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Network Slicing and Carrier Aggregation Architectures to support Small Cells and Ultradense Deployments

PhD Dissertation

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TeamUp5G-H2020-MSCA-ITN-2018 (Grant No: 813391)
2022

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Acknowledgements

I want to thank European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie ETN for funding the project New RAN **TE**chniques for 5G Ultr**A**-dense **M**obile networks (TeamUp5G) with the grant agreement No. 813391. It was a great opportunity and learning to be part of this project.

My gratitude toward Dr Albena Mihovska, my supervisor, cannot be expressed in words. I am grateful for her invaluable patience, feedback, support, and trust. Her experience and knowledge have encouraged me throughout my research journey and will keep inspiring me. I am also very grateful to DDrLuis Miguel Campos, my industrial supervisor, for his time, guidance, and expertise. DrDrampos's support throughout my industrial training was impeccable. This journey would not have been possible without the generous support and constant feedback from Prof. Fernando J. Velez.

I want to express my great appreciation to Prof Ramjee Prasad for providing me with the valuable exposure required to grow as a researcher and person. I would also like to thank the researchers and colleagues from Aarhus University BTECH Department and my project TeamUp5G for the thought-provoking discussions, collaborations, and support during my PhD. I am highly grateful to Prof Peter Lindgren, Dr Md. Bilal, Dr Purnima Lala Mehta, Dr Ambuj Kumar,and MrsGitte Kingo for their support, advice, and fruitful discussions. *Thank you all for providing me with a happy and cheerful environment to conduct my research*.

The names on the list of thanks are endless. I want to put special words to my parents, sisters, and brothers-in-law for standing with me through thick and thin. Their support and belief in my decisions mean a lot. I was fortunate to find the same love and support from my in-laws. During the Covid-19 period, their constant encouragement kept me motivated. "*I appreciate all the sacrifices you all have made on my behalf all these years*." Finally, a big shout-out to my husband, Nakul, for believing in me and supporting me unconditionally.

Although it's my PhD journey, it meant nothing without you all.

English Abstract

The world is moving at an exponential rate towards digitization and industrial expansion. The Fifth Generation (5G) networks have led the foundations for immersive and connected societies, offering higher bandwidth, lower latency, and a vast device density than the existing mobile network. The upcoming generations of wireless communication have predicted that around 2.5 billion 5G voice users to experience high-end interactive calling features by the end of 2026. There are endless opportunities for new business and value-chain models for providers and users. The Mobile Network Operators (MNOs) and vendors are coming together to have infrastructure and businesses to support the 5G and beyond ecosystem.

Our work is aimed to provide an adequate architecture for the coexistence of Network Slicing (NS) and Carrier Aggregation (CA) for the 5G New Radio (NR). CA is the technique to boost the data rate, while NS caters to individual demands for different user-centric services. NS allocates independent resources to provide end-to-end services. Three main service classes of network slicing have been defined as Enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), and ultra-Reliable and Low-Latency Communication (uRLLC). The Radio Access Network (RAN) resources for the slicing framework include link bandwidth, computing/processing capabilities, and spectrum.

We sub-divided the overall aim of achieving an integrated slicing framework for CA-enabled networks into four main verticals, namely: (i) identification of various combinations of Component Carriers (CC), (ii) implementation of CA in Small Cells (SC), (iii) radio resource management and scheduling techniques for CA and (iv) implementation of NS by creating slices based on user-applications. NS and CA are critical enablers for 5G and beyond networks to incorporate adaptability, scalability, and flexibility to support dynamic use case environments. We proposed to combine RAN resource management in NS and CA, considering different scheduling techniques like multi-band and cross-scheduling to cater to resource allocation among other slices. We achieved high throughput and goodput for eMBB and URLLC slices in CA-based environments. We identified resource isolation, abstraction, and virtualization as the challenges associated with RAN slicing. We proposed a radio resource virtualization technique to leverage resource abstraction and inter-slice resource isolation.

Also, we have proposed applying slicing as an extension of our work into the Open RAN (ORAN) interface as functional splits and immersive communications such as holographic communication. The scope of standardization requirements to facilitate 5G RAN disaggregation, CA, and NS is addressed. The thesis contributes to the design of an architecture for the coexistence of NS and CA to allow for the simultaneous use of component carriers from different and heterogeneous network nodes (e.g., base stations, WiFi access points, etc.), which could offer many benefits in terms of quality of service, energy efficiency, fairness, mobility, and spectrum and interference management.

Keywords: Network Slicing, Carrier Aggregation, Resource Management, Small Cells, Business Model.

Dansk Abstrakt

Verden bevæger sig med en eksponentiel hastighed mod digitalisering og industriel ekspansion. Femte generations (5G) netværk har ført grundlaget for fordybende og forbundne samfund og tilbyder højere båndbredde, lavere latenstid og en enorm enhedstæthed end det eksisterende mobilnetværk. De kommende generationer af trådløs kommunikation har forudsagt, at omkring 2,5 milliarder 5G-talebrugere vil opleve avancerede interaktive opkaldsfunktioner inden udgangen af 2026. Der er uendelige muligheder for nye forretnings- og værdikædemodeller for udbydere og brugere. Mobile Network Operators (MNO) og leverandører går sammen for at have infrastruktur og virksomheder til at understøtte videre 5G økosystem.

Vores arbejde er rettet mod at levere en passende arkitektur for sameksistensen af Network Slicing (NS) og Carrier Aggregation (CA) til 5G New Radio (NR). CA er teknikken til at øge datahastigheden, mens NS imødekommer individuelle krav til forskellige brugercentrerede tjenester. NS allokerer uafhængige ressourcer til at levere end-to-end-tjenester. Tre hovedserviceklasser af netværksslicing er blevet defineret som Enhanced Mobile Broadband (eMBB), massiv Machine Type Communication (mMTC) og ultra-Reliable and Low-Latency Communication (uRLLC). Radio Access Network (RAN)-ressourcerne til udskæringsrammerne inkluderer linkbåndbredde, computer-/behandlingskapaciteter og spektrum.

Vi underopdelte det overordnede mål med at opnå en integreret udskæringsramme for CA-aktiverede netværk i fire hovedvertikaler, nemlig: (i) identifikation af forskellige kombinationer af komponentbærere (CC), (ii) implementering af CA i små celler (SC)), (iii) radioressourcestyring og planlægningsteknikker for CA og (iv) implementering af NS ved at skabe udsnit baseret på brugerapplikationer. NS og CA er kritiske muligheder for 5G og videre netværk til at inkorporere tilpasningsevne, skalerbarhed og fleksibilitet for at understøtte dynamiske use case-miljøer. Vi foreslog at kombinere RAN-ressourcestyring i NS og CA, idet vi overvejede forskellige planlægningsteknikker som multi-band og krydsplanlægning for at imødekomme ressourceallokering blandt andre udsnit. Vi opnåede høj gennemstrømning og goodput for eMBB og URLLC udsnit i CA-baserede miljøer. Vi identificerede ressourceisolering, abstraktion og virtualisering som udfordringerne forbundet med RAN-slicing. Vi foreslog en radioressourcevirtualiseringsteknik til at udnytte ressourceabstraktion og ressourceisolering mellem skiver.

Vi har også foreslået at anvende slicing som en udvidelse af vores arbejde i Open RAN (ORAN)-grænsefladen som funktionelle opdelinger og fordybende kommunikation såsom holografisk kommunikation. Omfanget af standardiseringskrav for at lette 5G RAN-disaggregation, CA og NS behandles. Specialet bidrager til udformningen af en arkitektur til sameksistens mellem NS og CA, der muliggør samtidig brug af komponentbærere fra forskellige og heterogene netværksknuder (f.eks. basestationer, WiFi-adgangspunkter osv.), hvilket kan give mange fordele med hensyn til servicekvalitet, energieffektivitet, retfærdighed, mobilitet og frekvens- og interferensstyring.

Nøgleord: Network Slicing, Carrier Aggregation, Ressource Management, Small Cells, Business Model.

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Table of Acronyms

1G	First Generation of Mobile Wireless Communication	MIMO	Multiple Input Multiple Output
2G	Second Generation of Mobile Wireless Communication	ML	Machine Learning
3G	Third Generation of Mobile Wireless Communication	MME	Mobility Management Entity
3GPP	3rd Generation Partnership Project	mMTC	massive Machine Type Communication
4G	Fourth Generation of Mobile Wireless Communication	mmW	Millimeter Wave
4G-LTE	4G-Long Term Evolution	MNO	Mobile Network Operator
5G	Fifth Generation of Mobile Wireless Communication	MPR	Maximum Power Reductions
5G NR	5G New Radio	NAS	Non-Access Stratum
5GC	5G Core	NB	Node B
5G-EIR	5G Equipment Identity Register	NB-IoT	Node B IoT
5G-VCC	Vehicle Cloud Computing	NEF	Network Exposure Function
6G	Sixth Generation of Mobile Wireless Communication	NF	Network Function
AF	Application Function	NFV	Network Functions Virtualization
AI	Artificial Intelligence	NFV-MANO	NFV Management and Orchestration
AMF	Access & Mobility Management Function	NGMN	Next Generation Mobile Network
AMPS	Advanced Mobile Phone System	NG-RAN	Next Generation Radio Access Network
AP	Access Point	NMT	Nordic Mobile Telephone
API	Application Program Interface	NOMA	Non-Orthogonal Multiple Access
AR	Augmented Reality	NpRB	Number of pRB
ARP	Allocation Retention and Priority	NR	New Radio
AS	Access Stream	NRF	Network Repository Function
AUSF	Authentication Server Function	NS	Network Slicing
B2B	Business to Business	NSA	Non-Standalone
B2C	Business to Customer	NSI	Network Slice Instance
B5G	Beyond 5G	NSSF	Network Slice Selection Function
BBF	Broadband Forum	NTN	Non-Terrestrial Networks
BDMA	Beam Division Multiple Access	NWDA	Network Data Analytics Function
BM	Business Model	OFDM	Orthogonal Frequency Division Multiplexing
BS	Base Station	ONAP	Open Network Automation Platform

BSF	Binding Support Function
CA	Carrier Aggregation
CC	Component Carriers
CCS	Cross Carrier Scheduling
CDMA	Code Division Multiple Access
CHF	Charging Function
CM	Connection Management
CN	Core Network
CP	Control Plane
CP	Cyclic Prefix
CQI	Channel Quality Indicator
C-RAN	Cloud-RAN
CSI	Channel State Information
CSP	Communicaiton Service Provider
CU	Central Unit
CUPS	Control and User Plane Seperation
DCSG	Disaggregated Cell Site Router
DL	Downlink
DNN	Deep Neural Network
DP	Data Plane
DRB	Data Radio Bearer
DRL	Deep Reinforcement Learning
DSA	Dynamic Resource Allocation
DSS	Dynamic Spectrum Sharing
DU	Distributed Unit
E2E	End-to-End
EC	European Commission
eMBB	Enhanced Mobile Broadband
eMTC	enhanced Machine Type Communication
eNB	evolved NodeB
eNodeB	Evolved Node B
EPS	Evolved Packet System
ETSI	European Telecommunications Standards Institute
ETSI	European Telecommunications Standards Institute
ONF	Open Networking Foundation
ORAN	Open RAN
PAPR	Peak-to-Average Power Ratio
PCF	Policy Control Function
PDC	Personal Digial Cellular
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PGW	Packet Gateway
P-GW	Packet Data Network Gateway
PGW-U	Packet Gateway Uplink
PHS	Personal Handy-phone System
PHY	Physical Layer
PLMN	Public Land Mobile Network
pRB	Physical Resource Block
PS	Packet Scheduling
PTT	Push To Talk
QoE	Quality of Experience
QoS	Quality of Service
RAC	Radio Admission Control
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RedCap	Reduced Capability
RIS	Reconfigurable Intelligent Surfaces
RLC	Radio Link Control
RM	Remote Management
RRC	Radio Resource Control
RRH	Remote Radio Heads
RSPG	Radio Spectrum Policy Group
RU	Radio Unit
SA	Standalone
SBA	Service Based Architecture
SC	Small Cells
SCP	Service Communication Proxy

EU	European Union	SD	Subscriber Data
E-UTRA	Enhanced UMTS Terrestrial Radio Access	SDN	Software-Defined Network
FANS	Fixed Access Network Sharing	SDO	Standards Development Organization
FBMC	Filter Bank Multi-Carrier	SEPP	Security Edge Protection Proxy
FCC	Federal Communications Commission	S-GW	Serving-Gateway
FDD	Frequency Division Duplex	SINR	Signal to Noise plus Interference
FG	Focus Group	SLA	Service Level Agreement
FG-ML5G	FG on Machine Learning for Future Networks, Including 5G	SM	Subscriber Management
FR	Frequency Range	SMF	Session Management Function
FR1	Frequency Range 1	SMS	Session Management Signaling
FR2	Frequency Range 2	SMSF	Short Message Service Function
FWN	Future Wireless Networks	SO	Slice Orchestrator
GBR	Guaranteed Bit Rate	SP	Service Provider
GFBR	Guaranteed Flow Bit Rate	SRB	Signalling Radio Bearer
GMLC	Gateway Mobile Location Center	SRS	Sounding Reference Signals
gNB	5G's next-generation Node B	SVM	Support Vector Machine
gNodeB	5G's next-generation Node B	TACS	Total Access Communications System
GSM	Global System for Mobile Communication	Tbps	Terabit/second
GSMA	Global System for Mobile Communications Association	TDD	Time Division Duplexing
GST	Generic Network Slice Template	TDMA	Time Division Multiple Access
HetNets	Heterogenous Networks	THz	Terahertz
HSPA+	High Speed Packet Access	TIP	Telecom Infra Project
HSS	Home Subscriber Server	TN	Transport Network
IAB	Integrated Access Backhaul	TRP	Transmission and Reception Points
ICT	Information and Communication Technology	UAV	Unmanned Aerial Vehicle
iDEN	Integrated Dispatch Enhanced Network	UCMF	UE radio Capability ManagementFunction
IETF	Internet Engineering Task Force	UDM	Unified Data Management
IMT-2000	Internation Mobile Telecommunications 2000	UDN	Ultradense Network
IoT	Internet of Things	UDR	Unified Data Repository
Ipv6	Internet Protocol Version 6	UDSF	Unstructured Data Storage Function
ISG	Industry Standard Groups	UE	User Equipment
ITU	International Telecommunication Union	UMTS	Uninversall Mobile Telecommunications System

ITU-T	International Telecommunication Union - Telecommunication	UP	User Plane
KPI	Key Parameter Indicator	UPF	User Plane Function
LAA	Licensed Authorized Access	uRLLC	ultra-Reliable and Low-Latency Communication
LAN	Local Area Network	VAN	Virtual Access Nodes
LMF	Location Management Function	VM	Virtual Machine
LTE	Long Term Evolution	VNO	Virtual Network Operator
MAC	Medium Access Control	VPN	Virtual Private Network
MBB	Mobile Broadband	VR	Virtual Reality
WLAN	Wireless LAN	vRB	virtual Resource Block
WWAN	Wireless WAN	V-V2X	Cellular Vehicle-to-Everything
XR	Extended Reality	WAN	Wide Area Network
		WCDMA	Wideband Code Division Multiple Access

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1 Introduction

This thesis presents Network Slicing (NS) and Carrier Aggregation (CA) integration as key enablers beyond 5G and 6G networks. We intend to provide an adequate architecture for the coexistence of NS and CA in small cell deployments for the 5G New Radio (NR). CA is the technique to boost the data rate, while NS caters to individual demands for different user-centric services. NS allocates independent resources to provide end-to-end services. Three main service classes of network slicing have been defined as enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), and ultra-Reliable and Low-Latency Communication (uRLLC).

The thesis contributes to the design of an architecture for the coexistence of NS and CA to allow for the simultaneous use of component carriers from different and heterogeneous network nodes (e.g., base stations, WiFi access points, etc.), which could offer many benefits in terms of quality of service, energy efficiency, fairness, mobility, and spectrum and interference management. The adopted investigative scenario is small cells and ultradense deployments within 5G and Beyond networks.

The key contribution of this PhD thesis can be summarized as a novel proposal to combine NS and CA in a radio access network (RAN) slicing framework. Network slicing plays a crucial role in enabling service providers to offer innovative services to enter new markets and expand their business already today, therefore, the PhD thesis contributes to an enabling framework for new busi-ness model innovation across all industries. The research has addressed the technological challenges for enabling network slicing, in particular, end-to-end performance, which requires a way to manage the impact of resource sharing all along the path, even when it crosses management domains. Towards this end, the PhD thesis has proposed a novel cross-carrier scheduling algorithm to best use carriers to achieve high throughput for enhanced mobile broadband (eMBB) and ultra-reliable low latency communications (uRLLC) services as some of the open technology challenges.

1.1 Problem Definition

Before deep diving into the State-of-the-Art analysis, we formulated research questions to guide our way toward the problem statement, as illustrated in Figure 1-1.

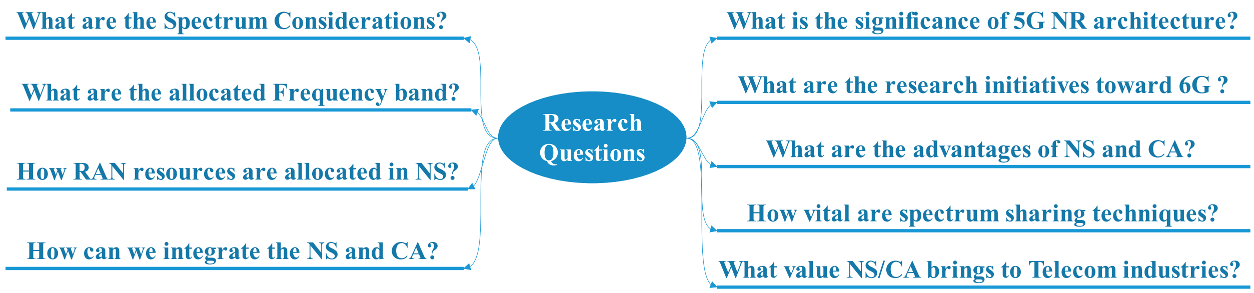

Figure 1-1 Identified Research Questions

These research questions were the foundation of this thesis and were developed considering various aspects to reflect the overall objective to present an architecture for the coexistence of NS and CA in small cell deployments for the 5G NR. In our systematic literature survey, we covered the evolution of 5G and 5G NR architectures, CA and NS competencies in LTE-Advanced and 5G networks, various resource allocation, management techniques, and most importantly, the importance of standardization and business value proposition for future networks. NS and CA bring promising results for the operators and vendors to deploy in 5G and beyond networks by enabling tailored network services. The operators can have a low-cost, flexible infrastructure to provide user-specific requests depending on the applications like high throughput, massive connectivity, low latency, high reliability, maybe clubbed together or individually.

To provide an integrated NS and CA framework to address the industrial requirements of high bandwidth and QoE, we identified challenges in various domains of NS and CA deployments. The goal is to improve network performance and introduce flexibility and greater utilization of network resources by accurately and dynamically provisioning the activated network slices with the appropriate resources to meet their diverse requirements. We identified individual challenges concerning NS and CA that are narrowed down as the following to be addressed in this work.

- Network Slicing
    - Deploying Network Slices is slicing the Radio Access Network (RAN).
    - Allocating resources to the network instances based on the demand for service (eMBB, uRLLC, and mMTC).
    - Managing RAN resources and sharing them among Network Slices is an increasingly tricky task that demands proper designing.
- Carrier Aggregation
    - Selection of Component Carriers (CC) to optimize the radio resource allocation
    - The impact of scheduling schemes on the resource allocation.
    - CA deployment in small cells and heterogeneous networks

1.2 Research Objective

Our main objective is to provide an adequate architecture for the coexistence of Network Slicing (NS) and Carrier Aggregation (CA) for the 5G New Radio (NR). We sub-divided the overall aim of achieving an integrated slicing framework for CA-enabled networks into five main verticals with an additional section to integrate potential research areas in other domains. Figure 1-2 represents the research objectives and outcomes.

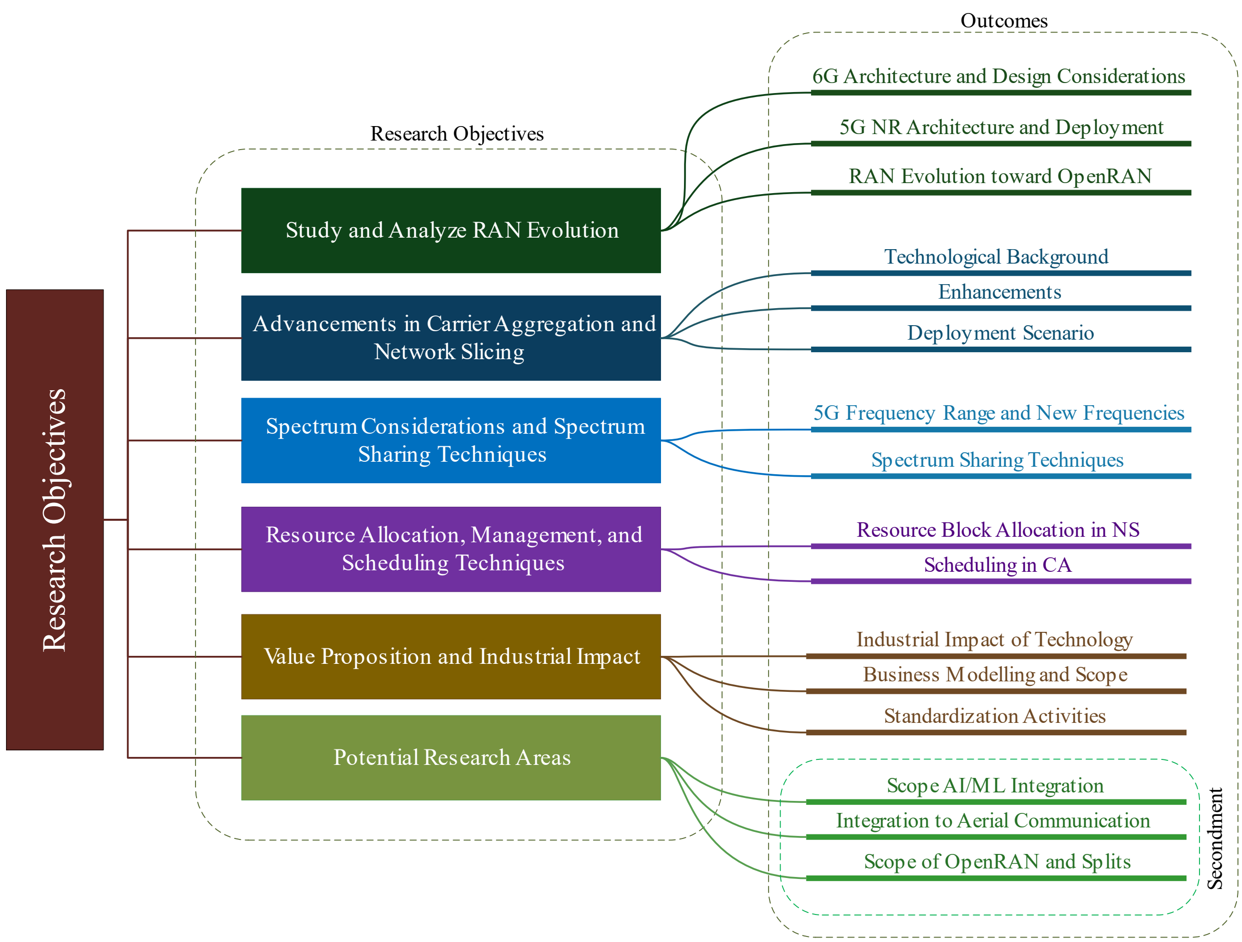

Figure 1-2 Research Objectives

The first three research objectives, → (i) Study and Analyze RAN Evolution, (ii) Advancements in CA and NS, and (iii) Spectrum Considerations and Spectrum Sharing Techniques, aims to provide a detailed analysis of the State-of-the-Art concerning 5G NR, CA, NS, 5G, and 6G networks.

The fourth research objective, *Resource Allocation, Management, and Scheduling Techniques*, aims to provide our contributions toward an integrated NS framework in CA-enabled networks. We analyzed RAN performance for different RAN slicing configurations based on L2 and L3 protocols, followed by a resource-sharing algorithm proposed to compute the necessary radio resources while deploying network slices. The resource allocations were based on the Channel Quality Indicator (CQI) values to meet the required throughput. We also evaluated CA component carrier selection schemes and scheduling algorithms in 5G NR and small cell deployments. Finally, we proposed an NS framework in CA-enabled networks.

The fifth objective, *Value Proposition and Industrial Impact,* aims to provide the technical readiness level of our proposal. We mapped our contribution to the industry requirements and detailed the technologies' ongoing and required standardization activities.

Finally, the last objective, *Potential Research Area* targets at the integration and collaboration among different verticals into our mainstream research. This objective was partially achieved during the industrial stay and will aim toward future research directions.

1.3 Contribution and Thesis Structure

We divided the thesis based on the research objectives into three sections and mapped the publications accordingly. Figure 1-3 illustrates the three main thesis sections as follows;

- RAN Evolution and 6G Networks;
- RAN Resource Allocation and Scheduling Techniques;
- Industrial and Business Impact;
- Conclusions and Future Scope.

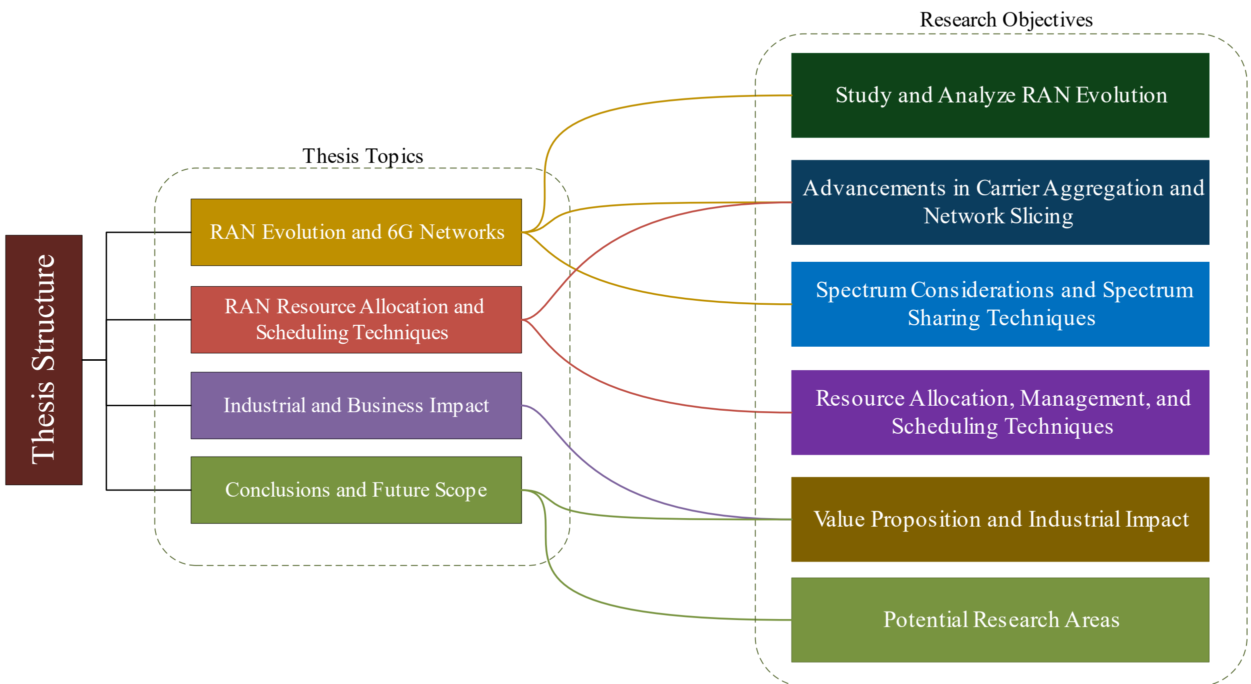

Figure 1-3 Thesis Structure

The first section – "RAN Evolution & 6G Networks," aims to cover the literature survey for the 5G and beyond networks. It introduces the state-of-the-art requirements, KPIs, and operating principles for 6G wireless networks with enabling technologies. We provided a structured summary of all the primary outcomes from the publications considered in this section concerning the literature. It encompasses research objectives 1, 2, and 3.

The second section – "RAN Resource Allocation and Scheduling Techniques," encompasses research objectives 2 and 4. It aims to provide our technical contributions toward an integrated NS framework in

CA-enabled networks. We proposed a novel resource-sharing algorithm to compute the necessary radio resources based on the CQI values to meet the required throughput. We also evaluated CA component carrier selection schemes and scheduling algorithms in 5G NR and small cell deployments. Finally, we proposed an NS framework in CA-enabled networks.

The second section – "Industrial and Business Impact," encompasses research objective 5, *Value Proposition and Industrial Impact.* This section will map our contributions toward the business model and standardization activities related to NS and CA.

The last section – "Conclusions and Future Scope"- encompasses the sixth objective. We will conclude our work with open research questions and directions. It will be a brief review of the thesis and a compilation of extracts from individual sections.

1.3.1 Key Contributions

The key contribution of this thesis can be summarized as a novel proposal to combine NS and CA in a RAN slicing framework. We employ a cross-carrier scheduling algorithm to best use carriers to achieve high throughput for eMBB and uRLLC services. The other contributions achieved are as follows:

- State-of-the-Art analysis and roadmap for 6G RAN evolution.
- Performance evaluation of RAN slicing functions using MATLAB, where we implemented different RAN slicing configurations to analyze radio resource distribution among slices based on L2/L3 parameters and different scheduling algorithms.
- A novel resource-sharing algorithm is proposed to compute the necessary radio resources while deploying network slices. The resource allocations were based on the Channel Quality Indicator (CQI) values to meet the required throughput.
- Proposed mapping of technology into businesses and industrial applications keeping in mind the generated value proposition from research.

Figure 1-4 maps our publications as contributions to the relevant research objectives.

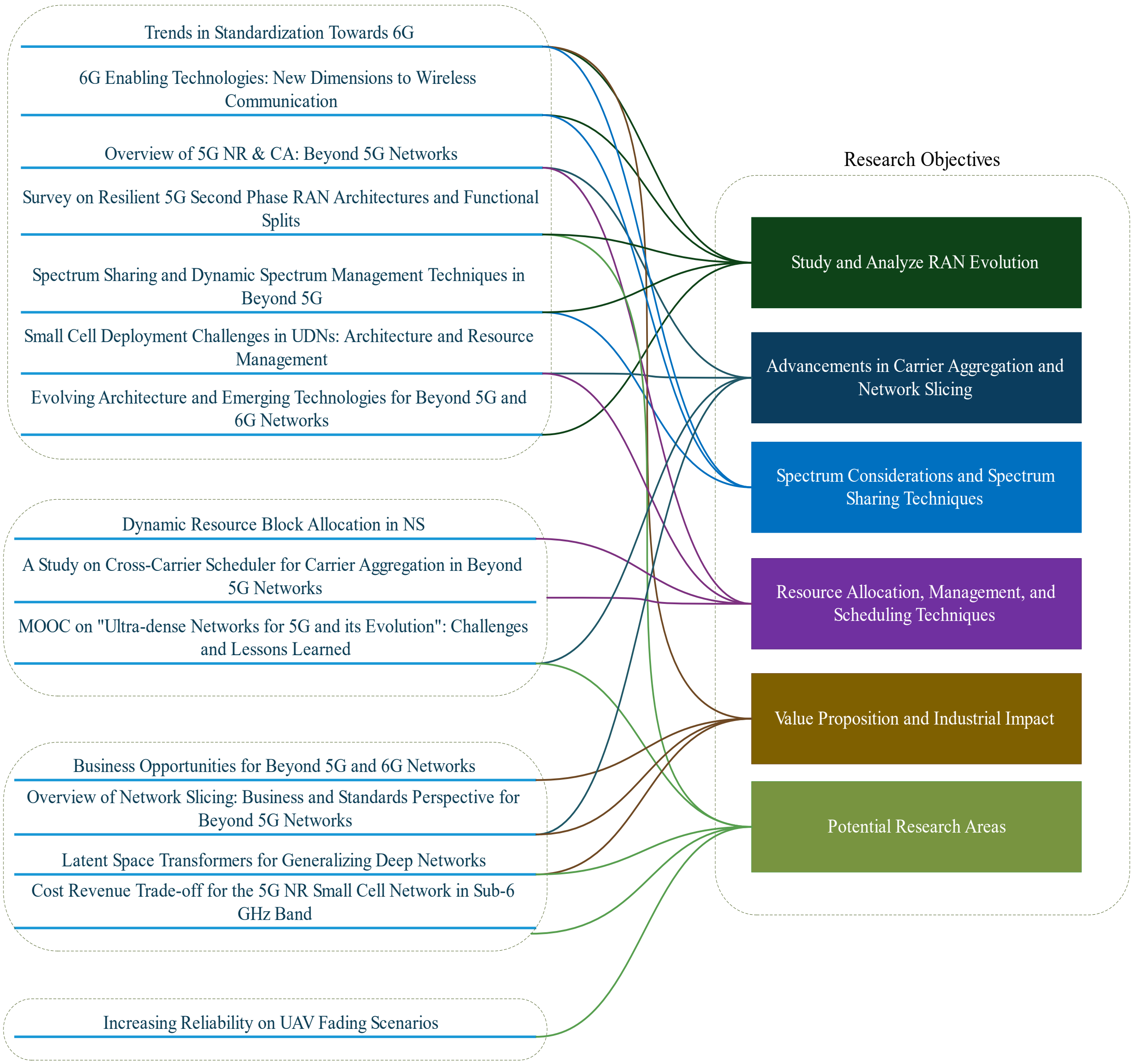

Figure 1-4 Mapping of Publications against the Research Questions

Contributions

2 RAN Evolution and 6G Networks

This section will map our publications to "Beyond 5G and 6G Networks". The focussed papers will provide detailed literature on the evolution of the 5G and 6G networks encompassing several aspects, from use cases, key parameter indicators (KPIs), deployment scenarios, key enablers, spectrum considerations, and sharing techniques. We will also provide insight into standardization activities going for 6G, Network Slicing, Artificial Intelligence (AI), and Machine Learning (ML). The contributions intend to serve the research objectives broadly with the sufficient literature drawn from the papers. Figure 2-1 illustrates the objective mapping with the publications considered under this section.

2.1 Objective and Contributions

The main objective of this section is to provide a State-of-the-Art analysis and a roadmap for evolving wireless mobile network generations.

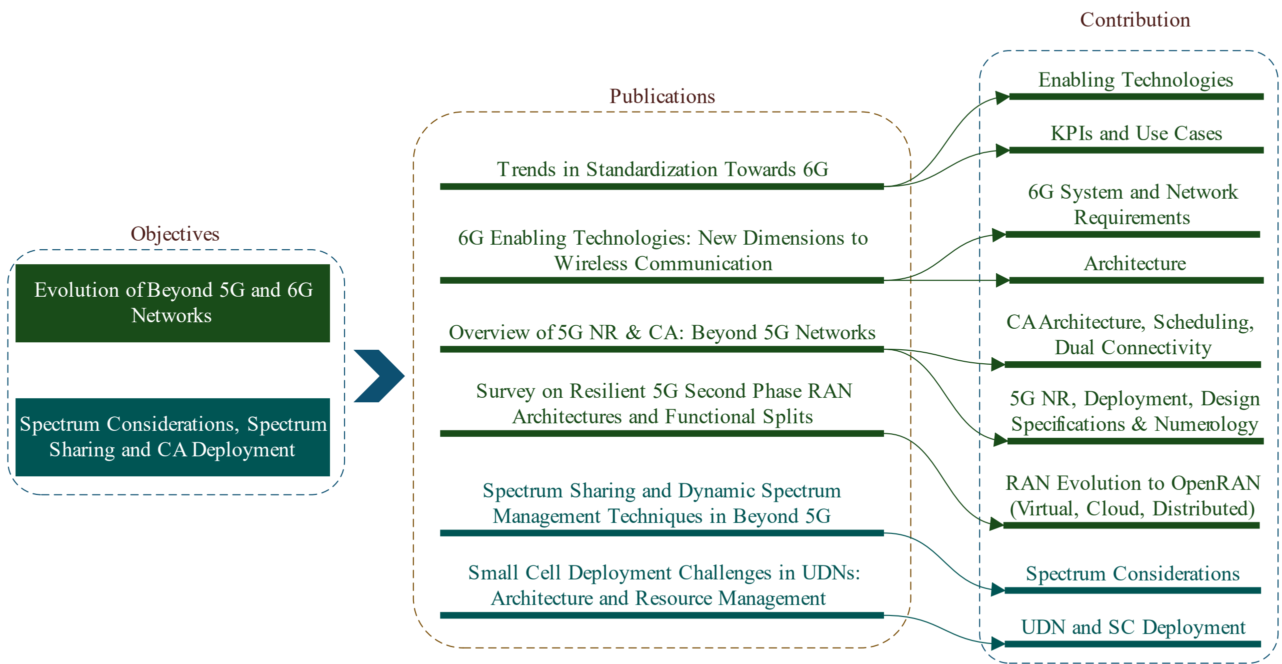

Figure 2-1 Objective Mapping to the Publications

2.2 Summary of Publications

1. **Trends in Standardization Towards 6G**
   Journal Article: Nidhi, Khan, B., Mihovska, A., Prasad, R., & Velez, F. J. (2021). Trends in Standardization Towards 6G. Journal of ICT Standardization, 327-348.

   The article discusses the advancements in wireless mobile broadband and the application cases for 6G. We presented anticipated KPIs and use cases for the 6G networks to offer the necessary infrastructure for several new devices and services. This study suggests the vision and requirements for beyond 5G (B5G) networks.

2. **6G Enabling Technologies: New Dimensions to Wireless Communication**
   Book Chapter: "Nidhi., Mihovska, A., Prasad, R. & Prasad, A. R., 10 Apr 2022, (Accepted/In press) River Publishers. Research output: Book/anthology/dissertation/ › Book › peer-review”

   This book chapter introduces the 6G of mobile wireless communication to provide a thorough overview of network research activities and the basic system needs, enabling technologies, influential drivers, advanced use cases, research requirements, and open research problems.

3. **Overview of 5G New Radio and Carrier Aggregation: 5G and beyond Networks**
   Conference Paper: Nidhi, A. Mihovska and R. Prasad, "Overview of 5G New Radio and Carrier Aggregation: 5G and Beyond Networks," 2020 23rd International Symposium on Wireless Personal Multimedia Communications (WPMC), 2020, pp. 1-6, doi: 10.1109/WPMC50192.2020.9309496.

   This paper, presented at the Wireless Personal Multimedia Communication conference-2020, provides a comprehensive overview of the development of NR, including deployment scenarios, numerologies, frame structure, and new waveforms. We provided an overview of CA, its requirements, and open research issues. We listed the enhancements made with 5G NR and CA through various 3GPP releases.

4. **Survey on Resilient 5G Second Phase RAN Architectures and Functional Splits**
   Journal Article: Khan, B., Nidhi., OdetAlla, H., Flizikowski, A., Mihovska, A. & Velez, F. J., 20 Nov 2021, (Submitted) In: IEEE Transactions on Network and Service Management. Special Issue, 18 p. Research output: Contribution to journal/Conference contribution in journal › Journal article › Research › peer-review

   This paper thoroughly covers the principles of the evolution of the RAN architecture, its essential components, and implementation issues. We explained the classic RAN architectural development to OpenRAN and discussed the significance of centralized, distributed, and virtualized RAN architectures. We elaborated on the benefits and challenges of RAN centralization (energy efficiency, reduced power costs, and fronthaul costs) and data traffic management among various data processing units and distributed antennas.

5. **Spectrum Sharing and Dynamic Spectrum Management Techniques in 5G and Beyond Networks: A Survey**
   Journal Article: Nidhi, Mihovska, Albena, and Ramjee Prasad. "Spectrum sharing and dynamic spectrum management techniques in 5G and beyond networks: A survey." Journal of Mobile Multimedia (2021): 65-78.

   This paper presents an overview of the various spectrum sharing and management techniques. This comparative study aims to provide a clear picture of designing a spectrum-efficient system for the 5G and beyond the network. We compared the featured spectrum bands with each generation of mobile communication and discussed different spectrum policies and allocation models (Licensed, Unlicensed and Shared).

6. **Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management**
   Conference Paper: Nidhi and A. Mihovska, "Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management," 2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2020, pp. 1-6, doi: 10.1109/CSNDSP49049.2020.9249560.

   The paper discussed various critical aspects of small cell and ultradense networks. The goal is to list numerous deployment issues and scenarios. The difficulties with managing resources, creating flexible architecture, controlling the available spectrum, employing unlicensed spectrum, etc., will be discussed. The inadequacies in available resource management, interference awareness techniques, spectrum management, etc., will be summed up with various prospective technologies.

7. **Evolving Architecture and Emerging Technologies for Beyond 5G and 6G Networks**
   Journal Article: Nidhi. & Mihovska, A., 2022, (In preparation) In: IEEE Communications Surveys & Tutorials. Research output: Contribution to journal/Conference contribution in journal/contribution to newspaper›Journal article›Research›peer-review.

   This paper includes updated literature for 5G, beyond 5G and 6G networks. This article will cover our findings and technical advancements in architecture, RAN design, CRAN Splitting, air interfaces, enablers, radio resource management, etc. We intend to provide a comparison landscape among various wireless mobile communication generations.

2.3 Introduction

Following 5G cellular technology, the sixth generation of wireless communication (6G) offers several technological and service-related opportunities to support greater capacity, throughput, and low latency (1s). 6G is anticipated to enable the use of the higher frequency spectrums and the fusion of numerous technologies, including artificial intelligence (AI), machine learning (ML), augmented/virtual reality (AR/VR), etc., to give users an immersive experience. 6G will mark the global transformation and innovation in terms of delay, data rate, level of intelligence, coverage, dependability, and capacity. Researchers are expected to look for innovations in present network architecture and communication theory to produce novel ideas that could be crucial for developing a brand-new system design that is "green" and addressing significant environmental issues, including climate change, is also essential.

The deployment phase of the fifth generation of wireless communication (5G) has begun, and it has established new guidelines to hasten 6G ambitions. The commercial deployment has created inadequacies in the current communication methods. Thus, it set forth the clear requirements for the 6G systems to allow applications for an improved user experience, ranging from autonomous systems to Extended Reality (XR)[1]. Numerous use cases and applications have been included in the definition of 6G[2], but its core network architecture and design are still missing. The wireless communication age will advance thanks to high-frequency bands and new access strategies. The possibility for different enabling technologies to meet the needs of a brand-new set of services are constantly under investigation and testing.

2.4 Evolution of Mobile Communication

Since the beginning, communication has been a crucial component of our lives. Modernizing technology supports the continual process of communication evolution. The transition from the wired telephone to real-time communication facilitated by AI[3] has significant significance for a better, more connected, and developing society. Due to its ongoing growth, the wireless communication business is regarded as a "Living" industry and is directly correlated with societal demands. There have been five generations of mobile communication, and there will be more in the future. The "G" stands for "Generation" in the First Generation (1G), Second Generation (2G), Third Generation (3G), and Fourth Generation (4G) of mobile communication. A new mobile communication generation is introduced every ten years, delivering unique features and services to satisfy user and network demand. Data traffic, data rate, throughput, latency,

[1] Jiang, W., Han, B., Habibi, M. A., & Schotten, H. D. (2021). The road towards 6G: A comprehensive survey. IEEE Open Journal of the Communications Society, 2, 334-366.
[2] Giordani, M., Polese, M., Mezzavilla, M., Rangan, S., & Zorzi, M. (2020). Toward 6G networks: Use cases and technologies. IEEE Com- munications Magazine, 58(3), 55-61.
[3] Letaief, K. B., Chen, W., Shi, Y., Zhang, J., & Zhang, Y. J. A. (2019). The roadmap to 6G: AI empowered wireless networks. IEEE communications magazine, 57(8), 84-90.

coverage, device density, reliability, and security are the key feature distinctions between mobile generations[4].

2.4.1 First-Generation Mobile Communication Technology (Analogue Systems)

In 1979, the first generation of cellular telephony, or 1G, was introduced. It was exclusively used for voice calls and was based on analog technology. It sends speech signals through narrowband frequency channels. With 1G, multiple regionally concurrent standards were created[5,6], including Total Access Communications System (TACS), Advanced Mobile Phone System (AMPS), and Nordic Mobile Telephone (NMT). For 1G systems, the fastest speed that could be reached was 2.4 Kbps, albeit with poorer voice quality, security, and battery life.

2.4.2 2G – Second Generation (Digital Systems)

Early in the 1990s, the second generation (2G) of mobile communication was introduced as mobile systems using digital radio signals. The goal of 2G was to strengthen the communication channel's security and dependability. There have been many distinct projects for 2G standard systems globally. Europe had Global System for Mobile Communications (GSM), Japan followed Personal Digital Cellular (PDC) and Integrated Dispatch Enhanced Network (iDEN) from Motorola standards, while in Asia, we had Personal Handy-phone System (PHS). The European Telecommunications Standards Institute (ETSI) launched GSM in 1987,[7] which used the Frequency Division Duplex (FDD) and Time Division Multiple Access (TDMA) systems. Qualcomm instead unveiled Code Division Multiple Access (CDMA)[8]. The usage of several users on a single channel was made possible by these multiplexing techniques in 2G networks. In addition to voice communications, 2G systems included data services, SMS, and improved features of traditional calling like call hold, conferencing, and call waiting.

2.4.3 Third Generation, or 3G

The emergence of 3G mobile systems was seen in 2001. The International Mobile Telecommunications 2000 (IMT-2000) framework[9] for the 3G cellular networks was established by the International Telecommunication Union (ITU). By providing features like web browsing, email, video downloading,

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[4]J. A. del Peral-Rosado, R. Raulefs, J. A. López-Salcedo and G. Seco-Granados, "Survey of Cellular Mobile Radio Localization Meth- ods: From 1G to 5G", in IEEE Communications Surveys & Tuto- rials, vol. 20, no. 2, pp. 1124-1148, Secondquarter 2018, doi: 10.1109/COMST.2017.2785181.
[5]T. Farley, "Mobile telephone history", Telektronikk, vol. 101, no. 3, pp. 22-34, 2005.
[6]F. Hillebrand, "The creation of standards for global mobile communication: GSM and UMTS standardization from 1982 to 2000", IEEE Wireless Commun., vol. 20, no. 5, pp. 24-33, Oct. 2013.
[7]GSM Memorandum of Understanding, Copenhagen, Denmark, Sep. 1987.
[8]EIA/TIA, IS-95, "Cellular System Recommended Minimum Performance Standards for Full-Rate Speech Codes", May 1992.
[9]IMT-2000 radio interface specifications approved in ITU meeting in Helsinki, Geneva, Switzerland, Nov. 1999.

image sharing, and fast internet speed at a rate of 200Kbps, 3G systems represented revolutionary developments in mobile communications. As a result, multimedia phones gave way to smartphones. It combined improved voice quality with a cost-effective increase in data rate. Along with 3G networks, the Universal Mobile Telecommunications System (UMTS) was launched. Wideband CDMA (WCDMA) was employed, and data rates of up to 2 Mbps (stationary) and 384 kbps were attained (mobility). HSPA+ may theoretically transmit data at a maximum speed of 21.6 Mbps. Data streaming is one of the most popular applications for 3G.

2.4.4 Fourth Generation (4G)

Based on the IMT-Advanced[10] specifications, 4G mobile systems were developed. The method taken by 4G systems was practical to provide users with high speed, good quality, and high capacity. With a 300ms to 100ms reduction in latency, it promised to attain 100 Mbps (mobile) and 1 Gbps (stationary) speeds. 4G systems significantly decreased the network congestion. It enhanced built-in security and introduced multimedia and the internet over IP concepts. Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) are the key enabling technologies (OFDM). Additionally, it specified Heterogeneous Networks (HetNets), Small Cells (SC)[11], and other features, including Coordinated Multipoint (CoMP), Advanced Multiple-Input Multiple-Output (MIMO) Transmissions, and Carrier Aggregation (CA)[12].

The following positioning approaches and advancements were made possible by the 4G systems[13];

- Positioning based on networks (Release 10[14,15])
- Matching radio frequency patterns (Release 9 - Release 12)[16]
- Improvements to positioning (Release 9[17] - Release 12[18])

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[10] “Requirements related to technical performance for IMT-Advanced radio interface(s)", 2008
[11] Nidhi and A. Mihovska, “Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management”, 2020 12th International Symposium on CSNDSP, 2020, pp. 1-6, doi: 10.1109/CSNDSP49049.2020.9249560.
[12]Nidhi, A. Mihovska and R. Prasad, “Overview of 5G New Radio and Carrier Aggregation: 5G and Beyond Networks”, 2020 23rd Interna- tional Symposium on WPMC, 2020, pp. 1-6, doi: 10.1109/WPMC50192.2020.9309496.
[13]A. Ghosh, R. Ratasuk, B. Mondal, N. Mangalvedhe and T. Thomas, “LTE-advanced: Next-generation wireless broadband technol- ogy [invited paper]”, IEEE Wireless Commun., vol. 17, no. 3, pp. 10-22, Jun. 2010.
[14] Network, E. U. T. R. A. (2011). S1 Application Protocol (S1AP)(Release 10). Technical Specification, 36.
[15] “LMU performance specification; network based positioning systems in E-UTRAN release 11 V11.4.0”, Oct. 2014.
[16] Johansson, T. (2013). 3GPP LTE Release 9 and 10 requirement analysis to physical layer UE testing.
[17] “New SI proposal: Positioning enhancements for E-UTRA”, Jun. 2013.
[18] “Requirements for support of radio resource management release 9 V9.22.0”, Dec. 2014.

2.4.5 Fifth Generation (5G)

In the commercial deployment stage, 5G systems aim to outperform their 4G predecessors regarding data speeds, connection density, latency, and other improvements. These systems took advantage of the millimeter wave (mmWave) spectrum between 30 and 300 GHz and SCs to reach a maximum data rate of 35.46 Gbps and enhanced coverage with reduced latency, respectively. Additionally, 5G systems made use of cutting-edge access technologies like Filter Bank Multi-Carrier (FBMC)[19], Non-Orthogonal Multiple Access (NOMA)[20], Quasi-Orthogonal Sequences, and Beam Division Multiple Access (BDMA), among others. By enabling antenna beam division based on base station location, the BDMA approach gives base stations multiple access. A scalable Orthogonal Frequency-Division Multiplexing (OFDM) results in extremely low latency in 5G networks. Additionally, Network Slicing (NS)[21] allows Mobile Network Operator (MNO) to cater tailored services based on the Service Level Agreement (SLA). Implementing AI, AR/VR, and XR created new use cases, apps, and services in terms of user experience.

The ongoing deployment of the Fifth-Generation (5G) mobile networks has parallelly seen the chaos among the research fraternity, industry, and academia for the Sixth Generation (6G) networks. The race is to facilitate requirements, use cases, and key enablers for developing 6G. The expectations from the 6G networks will be at least twice what 5G offered us in terms of connectivity, bandwidth, latency, services, and applications[22]. The foreseen use cases and requirements suggest new levels of immersive experiences associated with 6G, including real-time sensory and interactive communications incorporating holograms. We anticipate 6G as an energy-efficient and reliable platform where all our applications, services, and businesses can run seamlessly with built-in security capabilities. It can back multiple business verticals with mixed prerequisites and specifications. Built-in-Intelligence or Intelligence-by-design will be critical in 6G systems to optimize and blend multifarious techniques and algorithms. 6G networks, endorsed by Artificial Intelligence (AI), are expected to be deployed in early 2030[23] to address open challenges like system capacity, data rate, latency, security, and Quality of Service (QoS).

Higher frequencies from 6G networks, including spectrum/resource management techniques, will be critical to achieving higher data rates and lower latency. The anticipations made for 6G requirements have

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[19] C.-X. Wang et al., "Cellular architecture and key technologies for 5G wireless communication networks", IEEE Commun. Mag., vol. 52, no. 2, pp. 122-130, Feb. 2014.
[20] Henrique, P. S. R., & Prasad, R. (2021). 6G The Road to the Future Wireless Technologies 2030 (pp. i-xxvi). River Publishers.
[21] B. Khan, Nidhi, A. Mihovska, R. Prasad and F. J. Velez, "Overview of Network Slicing: Business and Standards Perspective for Beyond 5G Networks", 2021 IEEE Conference on Standards for Com- munications and Networking (CSCN), 2021, pp. 142-147, doi: 10.1109/CSCN53733.2021.9686125.
[22] Y. Jonsson. (2022) Designing the 6G networks of the future. [Online]. Available: https://www.chalmers.se/en/departments/e2/news/Pages/Designing-the-6G-networks-of-the-future.aspx
[23] M. Z. Chowdhury, M. Shahjalal, S. Ahmed and Y. M. Jang, "6G Wireless Communication Systems: Applications, Requirements, Technologies, Challenges, and Research Directions," in IEEE Open Journal of the Communications Society, vol. 1, pp. 957-975, 2020, doi: 10.1109/OJCOMS.2020.3010270.

marked the data rates in the scale of Terabit/second (Tbps) and the latency at 0.1 milliseconds[24]. 5G technologies will lead the foundation beyond 5G and 6G networks. The key 5G enablers will form the cornerstones in driving the research and development for the 6G networks. The technical advancements with the 6G networks will enhance various 5G architectural aspects, enabling technologies, and use cases.

This State-of-the-Art analysis aimed to bring forward the motivation for the proposed research and provided contributions. An extensive literature study has identified the open challenges, critical performance, and user requirements to be addressed. We intend to give an adequate architecture for the coexistence of Network Slicing (NS) and Carrier Aggregation (CA) for the 5G New Radio (NR) in Small Cell (SC) and Ultradense Networks (UDN). The considerations were made for the three main service classes defined as Enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), and ultra-Reliable and Low-Latency Communication (uRLLC) by International Telecommunications Union (ITU)[25]. The idea is to incorporate CA as the technique to boost the data rate in an infrastructure fostering NS that caters to individual demands for different user-centric services. Thus, the background section is divided into sub-sections, as illustrated in Figure 2-2

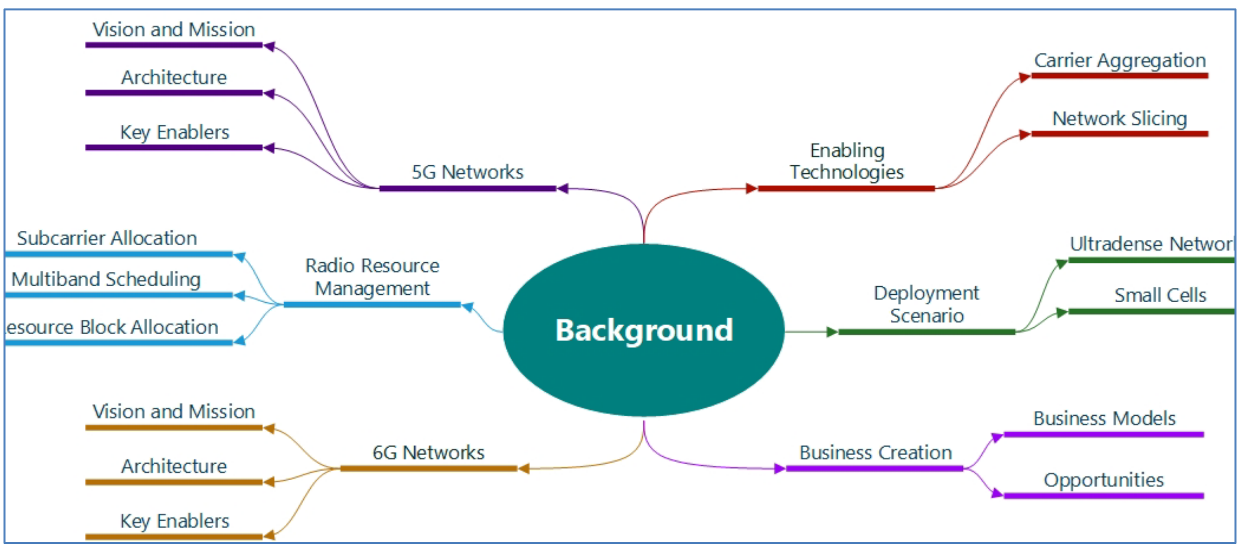

Figure 2-2 Structure for Background Literature

[24] Chowdhury, M. Z., Shahjalal, M., Ahmed, S., & Jang, Y. M. (2020). 6G wireless communication systems: Applications, requirements, technologies, challenges, and research directions. IEEE Open Journal of the Communications Society, 1, 957-975.
[25] ITU-R Press Release. (2021) ITU towards "IMT for 2020 and beyond". [Online]. Available: https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2020/Pages/default.aspx

2.5 5G Evolution and Architecture

The Internet of Things (IoT) and Internet Protocol version 6 (Ipv6) have led the foundation for 5G research and development for enabling multiple services and supporting the 'Smart World' concept. 5G systems were foreseen to provide Mobile Broadband (MBB) services, coexisting with the Fourth Generation (4G) 's Evolved Packet System (EPS) deployments. ITU-R has documented 5G requirements as IMT-2020 framework and vision[25,26]. 5G was introduced in Release-15 of the 3rd generation partnership project (3GPP)[27] in June 2018 and evolved gradually in various design aspects like air interface, protocol layers, etc., with later Releases.

2.5.1 IMT-2020 Vision: 5G Usage Scenarios

The enhanced Mobile Broadband (eMBB), ultra Reliable Low Latency Communications (uRLLC), and massive Machine Type Communications (mMTC)[28] are defined as three key 5G application areas. These three service classes with mapped applications are illustrated in Figure 2-3 IMT-2020 Vision and 5G Service Classes The eMBB service class describes the bandwidth-hungry applications demanding faster connections, higher throughput, and higher capacity, including high-definition telepresence, telemedicine, and remote surgery. The mMTC service class represents low-cost applications that require massive connectivity, low power, and less complexity. mMTC applications signify the fast-growing voluminous high-density environments to enable applications like smart metering, smart buildings, smart cities, etc. The uRLLC service class denotes the mission-critical services demanding ultra-low latency, high security, high reliability, and uninterrupted data transmission. Some of the uRLLC applications include autonomous vehicles, healthcare, industrial automation, etc.[28]

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[26] "IMT Vision –Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond", M.2083, 2015, [online] Available: www.itu.int/rec/R-REC-M.2083.
[27] https://www.3gpp.org/release-15
[28] "5G – It's Not Here Yet, But Closer Than You Think". October 31, 2017.

Figure 2-3 IMT-2020 Vision and 5G Service Classes

2.5.2 Evolution of 5G Architecture: Service-based Architecture

The ***5G Service Based Architecture*** (SBA)[29] by 3GPP has defined 5G as a platform that can reinforce heterogeneous network requirements. Technical specification 23.501[30] - "System Architecture for the 5G System" has provided a detailed catalog of SBA features and protocols. SBA allows simultaneous services to run on its scalable, flexible, cost-efficient, and programmable platform. A set of associated Network Functions (NFs) differentiates SBA's 5G core from the 4G architectures. The NFs enabling individual services can also access the services provided by another set of NFs. Figure 2-4 illustrates the 5G Core Service-Based Architecture[31,32].

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[29] J. Arkko. (2017) 5G for Business: A 2030 Market Compass. [Online]. Available: https://www.ericsson.com/en/blog/2017/9/service-based-architecture-in-5g
[30] 3GPP. (2022) Technical Specification Group Services and System Aspects; System architecture for the 5G System (5GS);Stage 2 (Release 17). [Online]. Available:https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3144.
[31] https://5g.security/5g-edge-miot-technology/5g-core-sba-components-architecture/
[32] https://www.metaswitch.com/knowledge-center/reference/what-is-the-5g-service-based-architecture-sba

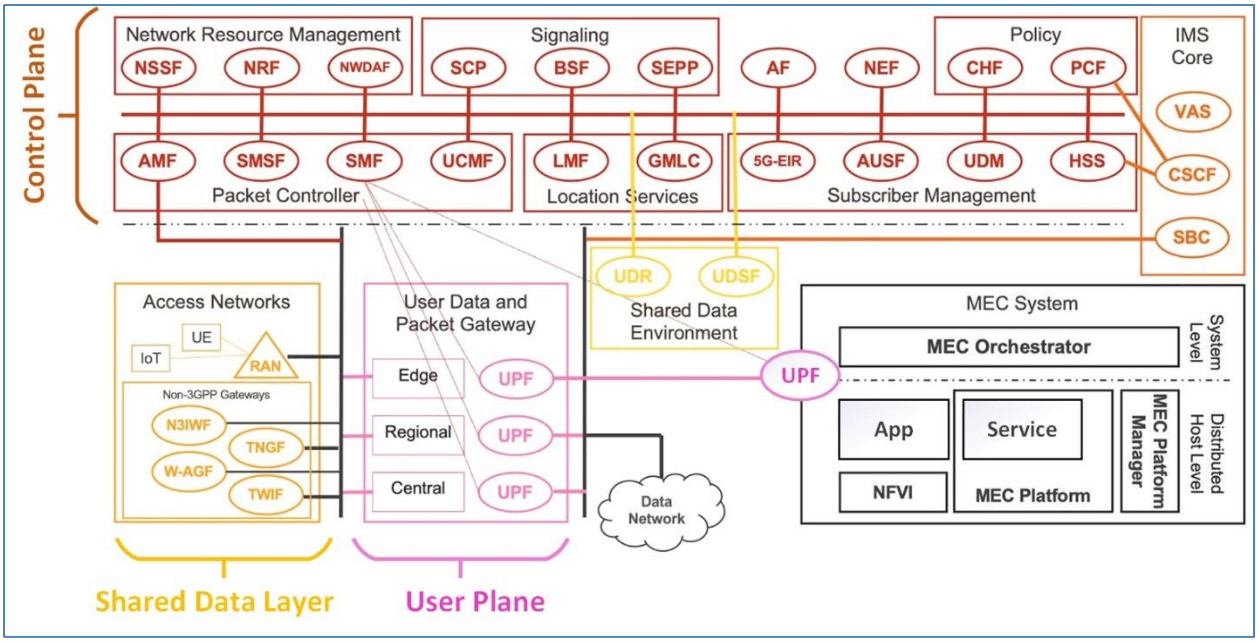

Figure 2-4 5G Core Service-Based Architecture

The Network and Resource Management consists of three parts: (i) Network Repository Function (NRF), (ii) Network Slice Selection Function (NSSF), and (iii) Network Data Analytics Function (NWDA). NRF enables NFs to identify other NFs' services and creates service repositories. NSSF selects Network Slice Instance (NSI) and redirects traffic accordingly to the slices. It is also responsible for providing AMF to grant access to UE. NWDA provides NFs the network analysis information[33].

The Signalling block consists of (i) Security Edge Protection Proxy (SEPP), (ii) Service Communication Proxy (SCP), and (iii) Binding Support Function(BSF). SEPP is responsible for providing security to the Control Plane (CP) traffic against various operators. SCP, composed of CP and Data Plane (DP), provides routing control and resiliency to the core network to cater NFs. BSF binds application-function requests to specific Policy Control Function (PCF) instances.

The Subscriber Data (SD) constitutes Unified Data Repository (UDR) and Unstructured Data Storage Function (UDSF). UDR stores structured subscriber-related data, whereas UDSF stores unstructured data that can be provided to NFs on request.

[33] ETSI, 5G; System architecture for the 5G System (5GS) (3GPP TS 23.501 version 16.6.0 Release 16)

Application Function (AF) facilitates traffic routing and policy framework interaction to support applications, while the Network Exposure Function (NEF) securely enables services and APIs from/to external systems.

Policy Control Function (PCF) and Charging Function (CHF) administer the policy framework's network and allow charging services to the NFs.

The Subscriber Management (SM) is composed of (i) Authentication Server Function (AUSF), (ii) Unified Data Management (UDM), (iii) Unified Data Management (UDM), (iv) Equipment Identity Register (5G-EIR), and (v) Home Subscriber Server (HSS). AUSF authenticates the UE while residing in a home network, while UDM stores subscriber information to cater NFs. 5G-EIR enables device authentication and protects against theft or unauthorized usage. HSS stores encrypted user-profiles and authentication data.

5G Location Services include Location Management Function (LMF) and Gateway Mobile Location Center (GMLC) to support UE location determination and send a location service request to AMF.

The CP is composed of (i) Access & Mobility Management Function (AMF), (ii) Session Management Function (SMF), (iii) Short Message Service Function (SMSF), and (iv) UE radio Capability Management Function (UCMF). AMF manages the mobility functionalities of the device, including authentication and connection, while SMF employs the functions required for establishing the sessions, including IP allocation and policy enforcement control. The UE is responsible for providing the connection and session-related information. SMSF enables SMS transfers over the Non-Access Stratum (NAS). The UCMF stores the UE IDs either by the Public Land Mobile Network (PLMN) or the manufacturer. PLMN refers to Earth's all mobile wireless networks other than satellites.

- In principle, 5G architectures are cloud- and service-based to facilitate automation, flexibility, programmability, and virtualization. The primary enhancements in the 5G core include the Control and User Plane Separation (CUPS)[34], Network Slicing (NS) support, and SBA. The following section details the network entities replaced in the 4G-Long Term Evolution (4G-LTE) architecture as mentioned below[31,35]:
- The 5 G's next-generation NB (gNB or gNodeB) that handles radio communications via NR air interface replaced the Evolved Node B (eNB or eNodeB) in 4G-LTE.
- The AMF and the SMF have replaced the Mobility Management Entity (MME) in LTE.
- The CUPS results in disassociated Packet Gateway (PGW) control and user plane functions leading to decentralized data forwarding entities (PGW-U). The Serving-Gateway (S-GW) and Packet Data Network (PDN) Gateway (P-GW) functionalities are integrated into PGW-U.

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[34] https://www.3gpp.org/news-events/1882-cups
[35] Alliance, N. G. M. N. (2018). Service-based architecture in 5G. Final deliverable (approved-P Public).

- The 5G User Plane (UP) maps the decentralized entities as a single entity referred to as the User Plane Function (UPF) that administers packet routing and forwarding functions.

Figure 2-5 depicts the various 5G system components.

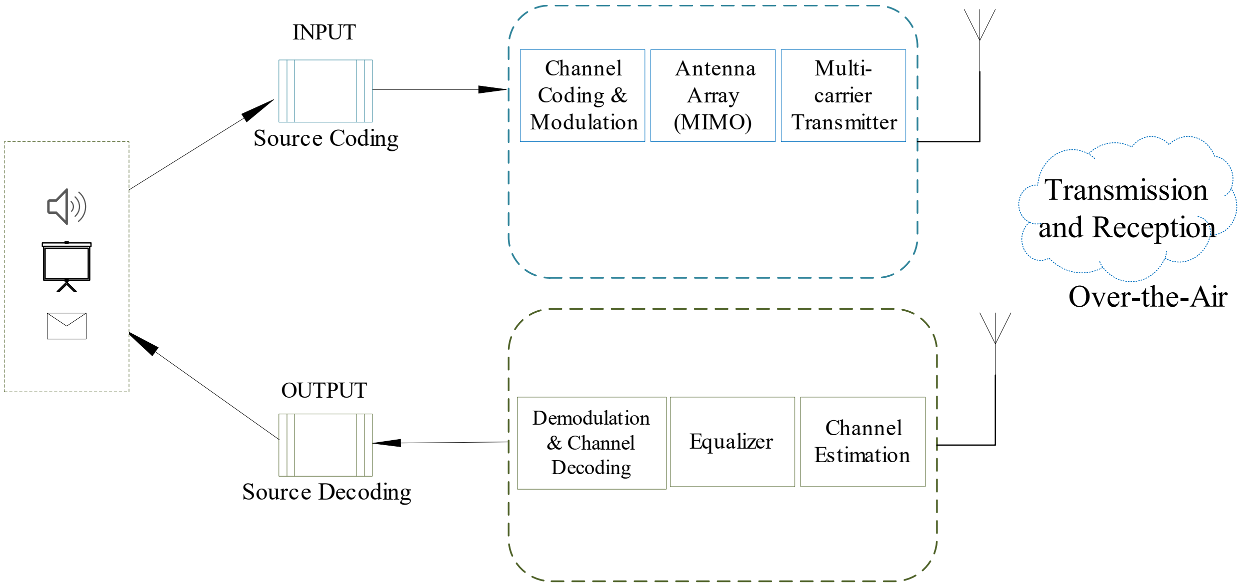

Figure 2-5 5G System Components

2.5.3 5G New Radio (NR)

Following SBA, the 3GPP's Release 15[27] defined a new Radio Access Technology (RAT) called 5G New Radio (5G NR) as a unified air interface for 5G systems. Its technical specification series 38[36] documents 5G NR requirements and enhancements studied under various scenarios. Making 5G NR a reality is incredibly complex. The aim behind the conception of 5G NR was to provide flexibility in connecting diverse requirements and applications. It has defined individual applications' specifications and requirements regarding techniques, spectrum, and bandwidth. It is a unified, scalable air interface that allows a wide range of 5G device classes to coexist, backed by the enhancements defined with 3GPP releases. 5G NR enhances the mobile broadband's electromagnetic radiation spectrum efficiency, enabling transmissions ranging from high (fiber-equivalent) to low bandwidth and ultra-low latency. The improvements, requirements, and benefits of 5G NR are mapped in Figure 2-6.

[36] https://www.3gpp.org/DynaReport/38-series.htm

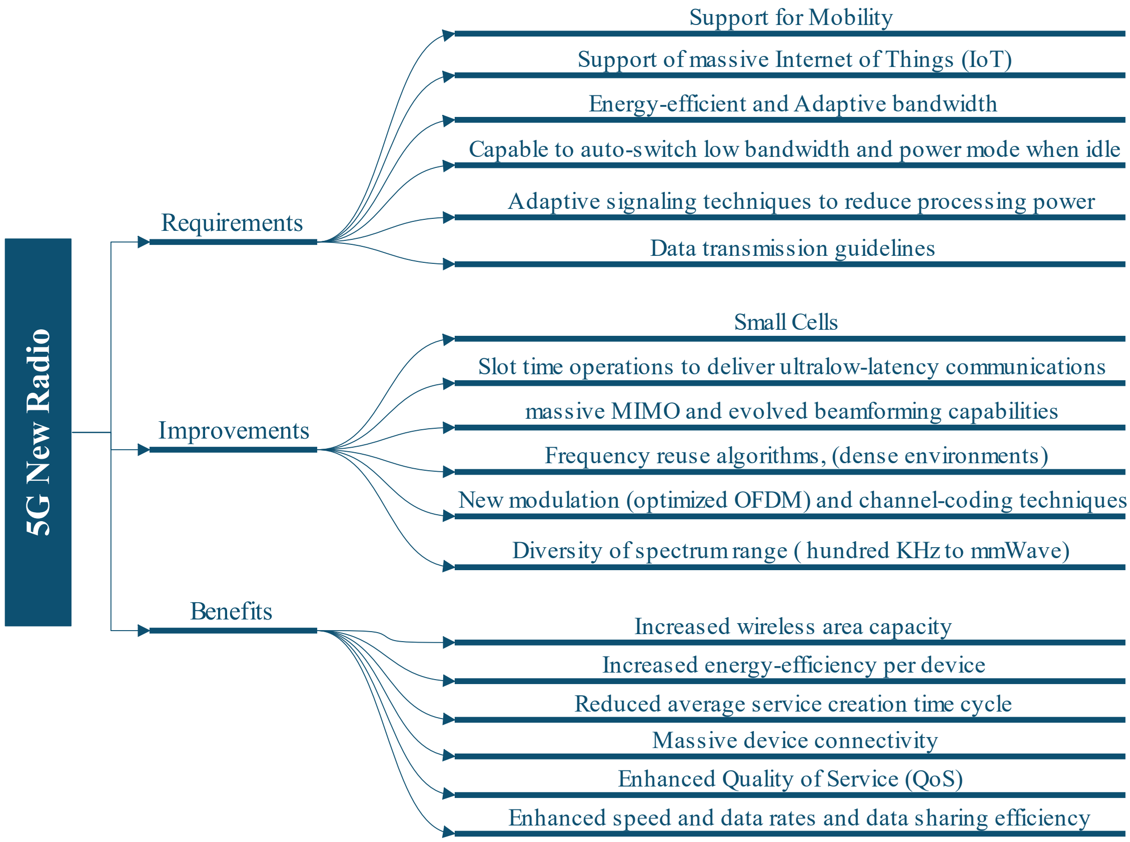

Figure 2-6 5G NR- Improvements, Requirements, and Benefits

2.5.3.1 5G NR Deployment Modes & Spectrum

5G NR introduced three deployment modes; (i) Standalone (SA), (ii) Non-Standalone (NSA), and (iii) Dynamic Spectrum Sharing (DSS). The SA mode enables full-fledged 5G gNBs for signaling and data transfer[37] without the LTE network[38]. The NSA mode refers to the hybrid deployment model[38] with the coexistence of LTE's CP for exhibiting control functions and the gNBs in the UP[37]. The DSS mode allows dynamic sharing of the carriers between LTE and 5G NR. It enables the same frequency in LTE and 5G modes by incorporating time-sliced duty and advanced antenna processing (no dedicated spectrum band)[39].

[37] "5G NR Deployment Scenarios or modes-NSA,SA,Homogeneous,Heterogeneous". rfwireless-world.com.
[38] "5G Non Standalone Solution Overview"
[39] "Spectrum sharing for fast & smooth 5G deployment". Ericsson. 18 March 2019.

5G NR's frequency bands are categorized into two different frequency ranges: Frequency Range (FR) 1 and FR 2. FR 1 includes sub-6 GHz and 410 MHz to 7125 MHz spectrum, whereas FR 2 includes 24.25 GHz to 71.0 GHz frequency bands[40]. The 3GPP technical specification TS 38.10 has published a list of all frequency bands and channel bandwidths. It supports five subcarrier spacing (15, 30, 60, 120, and 240 kHz), which determines the channel bandwidth and length of the Cyclic Prefix (CP).

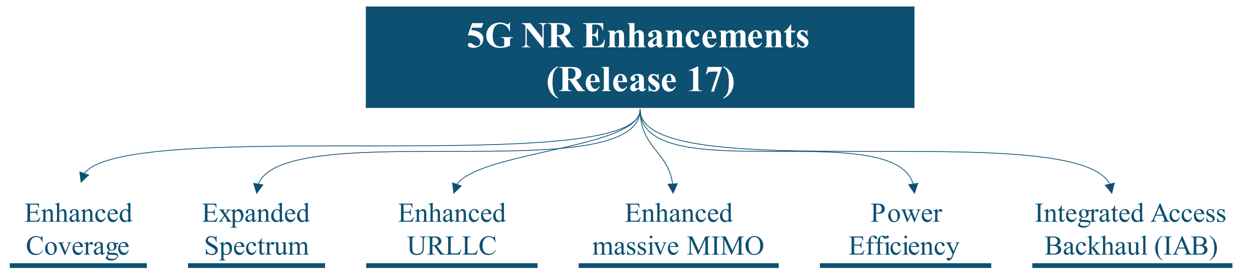

Figure 2-7 Key Areas of 5G NR Enhancements in Release 17

Release 17[41] published new and enhanced 5G system capabilities that concluded the 5G first phase evolution[41]. The key enhancements for 5G NR are explained based on the six main areas, as illustrated in Figure 2-7[42]. The enhancements can be summarized as follows;

- Expanded Spectrum
    - mmWave spectrum range expanded to the FR2 bands (from 24.25—52.6 GHz up to 71 GHz).
    - Unlicensed NR support extended to 60 GHz unlicensed band.
- Enhanced URLLC
    - Improved support to enable stringent applications.
    - Improved PHY feedback & compatibility for unlicensed band
    - Improved intra-device multiplexing and prioritization.
- Enhanced Coverage
    - Diverse deployments in sub-7 GHz, mmWave, and Non-Terrestrial Networks (NTN).
    - Enhanced uplink control and data channel design for reliability and joint channel estimation.
- Enhanced massive MIMO
    - Multi-transmission and reception points (TRP)

[40] "TS 38.101-1: NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone" (17.6.0 ed.). 3GPP. 2022-06-30.
[41] https://www.3gpp.org/release-17
[42] https://www.qualcomm.com/news/onq/2022/03/just-3gpp-completes-5g-nr-release-17

- Multi-beam operations
- Enhanced Sounding Reference Signals (SRS)
- Enhanced Channel State Information (CSI) calculations

- Power Efficiency
    - Reduction in unnecessary device paging receptions
    - Flexibility in device measurements (radio link)
- Integrated Access Backhaul (IAB)
    - Repeaters were introduced as amplifying and forward relay
    - Enhanced IAB to support simultaneous Tx and Rx

3GPP release 18[43] represents a significant evolution of the 5G System (5GS) and is the first release of the 5G-Advanced standard. The major enhancements focus on AI and XR to support evolving use cases. 3GPP has defined different study- and work-items responsible for the advanced 5G ecosystem. The identified Technical Specification Group (TSG) provide overall 3GPP system architecture and services, including User Equipment, Access Network, Core Network, and IP Multimedia Subsystem. The priorities are defined based on System Aspects (SA), RAN evolution and Core Networks and Terminals (CT) as illustrated in Figure 2-8. Release 18 aims further 5G system evolution and enhancements to support satellites, Personal IoT networks, enhanced AI/ML algorithms, XR applications, etc.

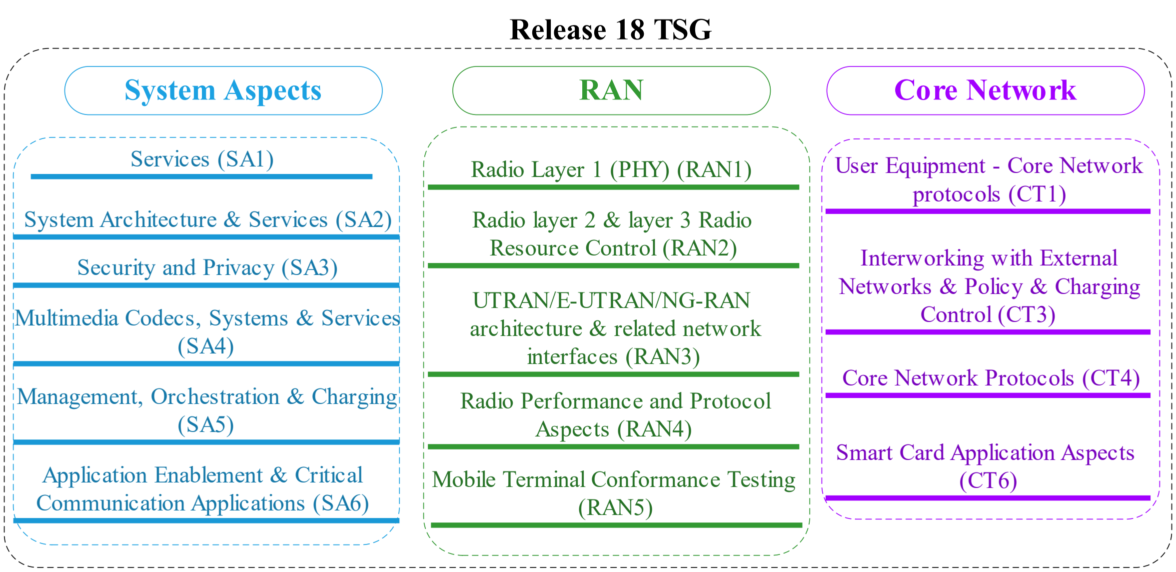

Figure 2-8 Technical Specification Groups for Release 18.

[43] https://www.3gpp.org/specifications-technologies/releases/release-18

2.5.3.2 5G Protocol Stack

The 5G protocol stack evolved from the 4G protocol stack by introducing the SDAP layer in UP[44]. User data is sent/ forwarded through the user plane. Stacks of both control and user plane have almost the same structure. They have the common structure for PHY, MAC, RLC, and PDCP layers, as shown in Figure 2-8. However, the layers above the PDCP layer are different. SDAP is the added layer in 5G NR. Carrier aggregation is supported in NR, and the data for each carrier is processed independently in SDAP, PDCP, and RLC and is multiplexed in the MAC layer.

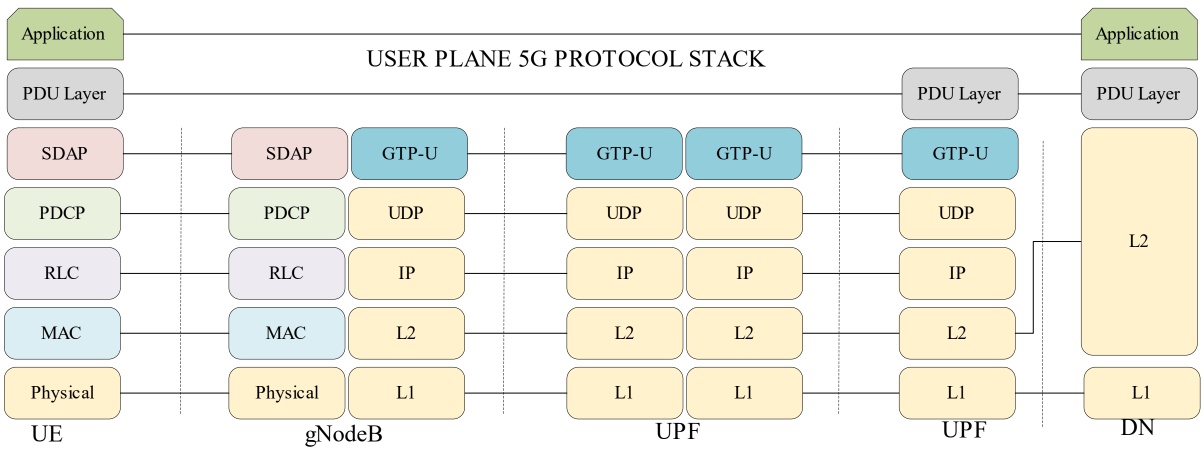

Figure 2-9 5G NR User Plane: Protocol Stack[44]

In the CP protocol stack, the NAS layer and the lower layer are the RRC; and transport layers PDCP, RLC, MAC, and PHYSICAL layer. The AMF has only the NAS layer. Between the UE and the 5G Core, a single N1 NAS signaling connection is used for each received entry to which the UE is attached. The single N1 endpoint is placed in the AMF. Single N1 NAS signaling connections are used for registration management, connection management (RM / CM), and SME-related messages and tactics for UEs. The NAS protocol on N1 includes the NAS-mobility management and NAS-session management components. There is more than one case of protocol between the UE and the core network function (excluding AMF) that needs to be carried over the N1 through the NAS-MM protocol. Examples include Session Management Signalling, SMS, UE Policy, and LCS. The CP protocol stack is illustrated in Figure 2-9.

[44] https://www.lteprotocol.com/2020/02/5g-protocol-stack.html

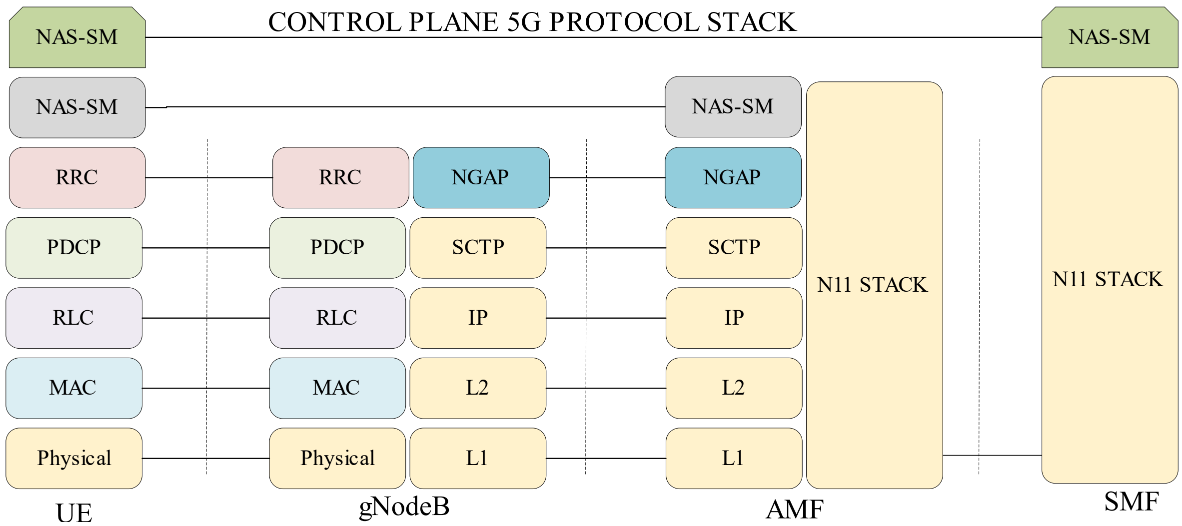

Figure 2-10 5G NR Control Plane: Protocol Stack

5G Protocol Stack's Layer 1 is the Physical Layer (PHY), Layer 2 consists of MAC, RLC, and PDCP, where Layer 3 is the Radio Remote Control (RRC) layer[45]. The main RRC functions include[46];

- Broadcast of System Information related to AS and NAS;
  - Paging initiated by 5GC or NG-RAN;
  - Establishment, maintenance, and release of an RRC connection between the UE and NG-RAN
  - Addition, modification, and release of carrier aggregation, Addition, modification, and release of Dual Connectivity in NR or between E-UTRA and NR.
- Security functions including
  - key management;
  - Establishment, configuration, maintenance, and release of Signalling Radio Bearers (SRBs) and Data Radio Bearers (DRBs);
- Mobility functions, including Handover and context transfer;
  - UE cell selection and reselection and control of cell selection and reselection; Inter-RAT mobility.
- QoS management functions;

[45] https://www.techplayon.com/5g-nr-radio-protocol-stack-layer-2-layer-3/
[46] https://www.rfwireless-world.com/Terminology/5G-Protocol-Stack-Layer-1-Layer-2-and-Layer-3.html

- UE measurement reporting and control of the reporting;
- Detection of and recovery from radio link failure;
- NAS message transfer to/from NAS from/to UE.

Layer 2 of the protocol stack has the following sub-layers;

- Service Data Adaptation Protocol (SDAP)
  - The SDAP offers 5GC QoS flows;
- Packet Data Convergence Protocol (PDCP)
  - The PDCP offers to the SDAP sublayer radio bearers;
- Radio Link Control (RLC)
  - The RLC offers to the PDCP sublayer RLC channels;
- Medium Access Control (MAC)
  - The MAC provides the RLC sublayer logical channels;
  - The physical layer offers the MAC sublayer transport channels;

2.5.4 CRAN and Splits

5G Radio Access Network (RAN) dis-aggregation has opened doors for new opportunities. 3GPP and Telecom industries have defined transport interfaces (backhaul, fronthaul, and mid-haul) and functional splits to incorporate network flexibility and openness. Network Functions Virtualization (NFV) enabled the Mobile Network Operators (MNOs) to implement fully–centralized Cloud–RAN (C–RAN) and dis-aggregated RAN architectures. 3GPP's Release 15 defines a flexible 5G RAN architecture with the gNodeB split into the Central Unit (CU), Distributed Unit (DU), and Radio Unit (RU), as shown in Figure \ref{function}. The operators use CU and DU to implement different split options. The high-level functions are distributed over the mid-haul (CU and DU). Among the eight main split options, split seven is further subdivided into 7.1, 7.2, and 7.3, as discussed in detail in the following section.

2.6 Sixth Generation (6G) Networks

Since its introduction in 1981, mobile communication technology has advanced from the first generation (1G) to the forthcoming fifth generation (5G)[47]. This evolution demonstrates that new mobile communication generations appear every ten years and provide users with new services. As a result, it is anticipated that 6G will develop and be operational around 2030[48]. Reliability, data speed, prices, available network functionalities, power efficiency, security, system performance, latency, network coverage, and

[47] I.-I. T. Union, "Report on Climate Change," ITU, 2008.
[48] G. Koutitas and P. Demestichas, "A review of energy efficiency in telecommunication networks," Proc. In Telecomm. Forum (TELFOR), November, 2009.

services were all improved with each iteration. As a result, each generation has seen the emergence of disruptive technologies, such as narrowband in 2G, broadband in 3G, 4G ultra-broadband, the present 5G wireless internet, and, as to be expected, the revolutionary terrestrial wideband in 6G.

Additionally, it has been discovered that the bandwidth must change for data to be transmitted. As bandwidth increased five times, or to 100 MHz in the case of 4G networks, it transitioned from an analog assembly at the beginning of the 1G to 25 MHz bandwidth usage for both 2G and 3G[49]. The 30-300 GHz spectral band bandwidth is designated for communication in the 5G use cases. According to estimates, the 6G would require increased bandwidth utilization, up to multiple THz levels and more than 300 GHz[50].

The rapidly expanding 5G networks have faced problems from the data-centric intelligent systems, future-oriented scenarios, networks, and applications[51]. Low latency, especially assured latency, which is needed for deterministic networking to reliably and precisely ensure end-to-end latency for future use cases, is the key defining feature of 5G. 5G is currently limited in several common scenarios, such as access in rural areas like villages or highways, which are not adequately covered. Some applications that incorporate real driverless cars won't be supported by the terrestrial 5G New radio. There is a need for satellite communication networks since they can provide better coverage than terrestrial networks. The communication network for unmanned aerial vehicles (UAVs) is crucial for quick reaction in demanding conditions. The maritime communication network can offer ships a high-quality communication service. Tbps will be needed for applications like virtual reality, VR mixed with augmented reality, high-quality three-dimensional VR, and so on; as a result, terahertz and optical frequency bands can be candidate bands.

Although 5G New Radio (5G NR) represents a significant advancement, it will not be sufficient to meet all network needs by 2030[52]. The network of the next generation is likely to support a variety of deployment scenarios for various applications, including robotic machines, integrating communication, sensing, computing, and high-touch virtual reality. Other deployment scenarios include coverage from space-air to ground-sea, communications coverage, high mobility, vehicle to everything, and robotic machine. As a result of heterogeneous networks, vast bandwidths, numerous antennas, and a variety of communication scenarios, 6G is intended to accommodate massive amounts of data and deliver approximately 100% geographic coverage, millisecond geolocation update rates, and sub-centimeter geolocation precision[51].

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[49] F. Times, “Gartner Report,” 2007.
[50] I. Cerutti, L. Valcarenghi and P. Castoldi, “Designing power-efficient WDM ring networks,” in ICST International Conference on Networks for Grid Applications, Athens, 2009.
[51] W.Vereecken and et al., “Energy Efficiency in thin client solutions,”in ICST International Conference on Networks for Grid Applications,,Athens, 2009.
[52] P. Henrique and R. Prasad, 6G The Road to the Future Wireless Technologies 2030, River Publishers, 2021.

6G networks are predicted to radically transform the current communication network to meet the demands of the coming data-driven society. The Key Performance Indicators (KPIs) from the 5G are generally still relevant for the 6G. The first wireless technology, 6G, is anticipated to require a per connection peak throughput of Tbps. For some use cases, such as factory automation, ultra-high reliability, ultra-low latency, and high accuracy synchrony would be required; in 6G, it is anticipated that there will be just one incorrect bit out of 1 billion that will reach the industrial control at the top. The key performance indicators for 6G are security and privacy, and it will require a high-end user with extreme security and industrial control. The sub-THz and THz bands will necessitate a larger bandwidth for the radio. Understanding how the research community is looking into and concentrating on the 6G wireless communication networks is crucial.

While using the spectrum has many drawbacks, it also offers opportunities for future networks. These high-frequency bands will be crucial to the network as a whole. The cost and energy limitations of many current IoT scenarios remain problems; however, in 6G, battery backup from the network is anticipated in some situations. CO2 molecule absorption substantially affects path loss, especially at a greater distance. When classifying the radio spectrum, it is essential to consider surface reflection and refraction via various materials.

The standards, whether open or not, are essential to accelerating the transition to 6G networks. It is beneficial to have a consistent strategy throughout the pre-development and development phases. Additionally, it speeds up invention and aids in teaming up against roadblocks. Numerous standardization organizations are engaged in related fields or areas with similar or distinct goals. There are many intersections and overlaps, so it is crucial to support the concept of cross-research. Additionally, these standard organizations determine when it is appropriate to take action concerning pre-standards or full-standards works.

2.6.1.1 Release 17 Enhancements toward 5G devices and applications

3GPP's Release 17[53] introduced new enhancements and features for system optimizations for a broad range of devices and applications, as illustrated in Figure 2-10. In addition to mentioned enhancements, other improvements include multi-radio dual connectivity, RAN Slicing, multi-SIM support, mini data transmission, higher-order modulation, etc.

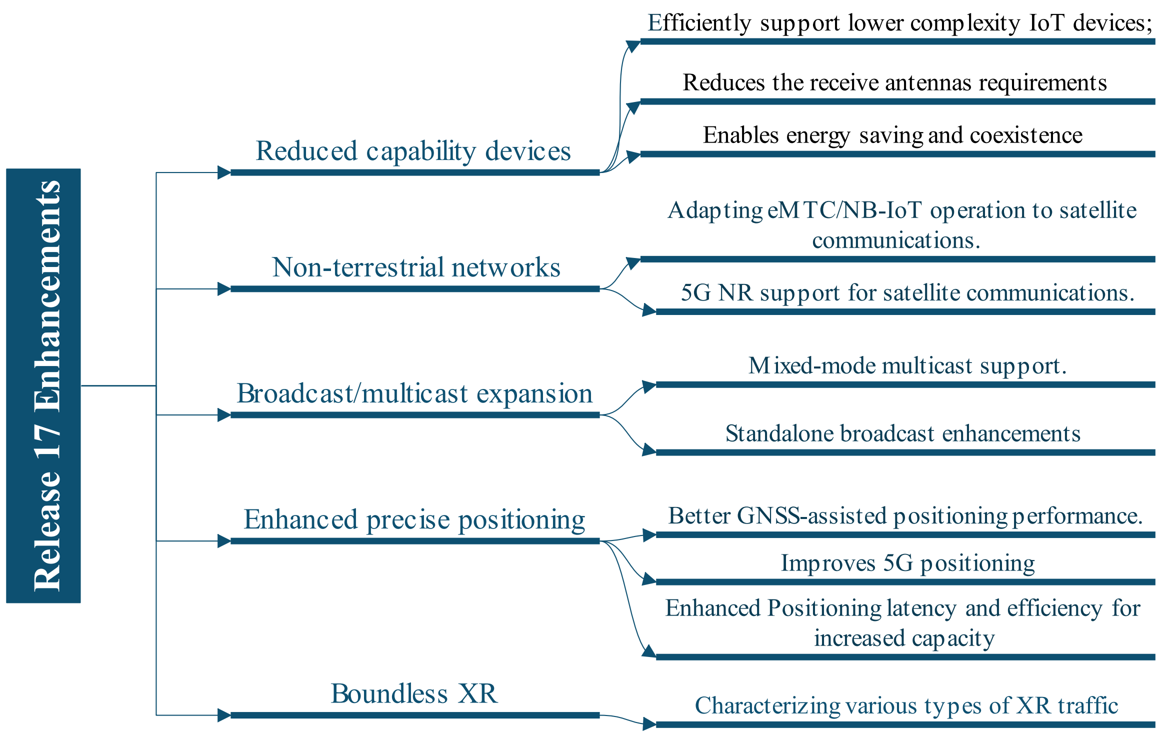

Figure 2-11 5G Enhancements with 3GPP Releases 17[54]

The development of 6G technology needs a holistic and multidimensional approach to integrate technologies and support businesses to flourish. 6G defines an integrated network with built-in control systems that execute technologies for societal, environmental, and economic benefit. 6G systems are advocating more towards a sustainable solution. Mobile Network Operators (MNOs) intend to create new

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[53] https://www.3gpp.org › release-17
[54] https://www.qualcomm.com/news/onq/2022/03/just-3gpp-completes-5g-nr-release-17

businesses and business models for the advancing technologies. A 5G and beyond network will have a user-centric approach toward business models and aim to solve the issues of the customers[55].

Changes in the Telecom landscape are evident and reflected through the value and supply chain revolution. The deployment of 5G is eminent among public networks and is being embraced in diversified industrial and consumer use cases. 6G development will drive the supply chain transformation to allow new verticals to establish. It is essential to focus on the business value creation in addition to the customers' needs and challenges. 6G will redefine the design, delivery, and consumption of network resources and services, irrespective of the verticals and applications[56]. Thus, this paper will address the business value creation through technology for the beyond 5G and 6G networks.

In the era of digitization and industrial expansion, Industry 4.0 is thriving on the foundation of the connected society and emerging technologies. The evolving industrial age will significantly advance the value-chain automation, security, and business models. Mobile operators worldwide are in the deployment phase of the Fifth Generation (5G) networks, which have become critical for the smart industries. 5G New Radio (NR) offers higher bandwidth, lower latency, and a huge device density than the existing mobile network.

2.6.2 6G Architecture

The 5G evolution starting with Release 18, is called 5G Advanced. This paper provides an overview of 5G Advanced to show the advantages of its technology components concerning network performance and capabilities. Guidance is provided on which features to expect in 5G Advanced and how those features enhance and enrich the already deployed 5G networks.

5G New Radio (NR) and 5G core (5GC) evolution is continuing in 3GPP toward 5G Advanced to ensure the success of 5G systems globally and to expand the usage of the 3GPP technology by supporting different use cases and verticals. AI/ML will play an important role in 5G Advanced systems and other technology components providing support for extended reality (XR), reduced capability (RedCap) devices, and network energy efficiency. While Ericsson 5G networks already support AI/ML and XR use cases and requirements in an energy-efficient manner, it is essential to enhance the 5G standards to improve multi-vendor support and provide a better device and network cooperation. The 5G Advanced standardization is a critical step for evolving cellular wireless access toward 6G.[57]

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[55] https://home.kpmg/uk/en/home/insights/2019/05/making-5g-a-reality.html
[56] S. Yrjola, P. Ahokangas, M. Matinmikko-Blue, R. Jurva, V. Kant, P. Karppinen, M. Kinnula, H. Koumaras, M. Rantakokko, V. Ziegler et al., "White paper on business of 6g," arXiv preprint arXiv:2005.06400, 2020
[57] https://www.ericsson.com/en/reports-and-papers/white-papers/5g-advanced-evolution-towards-6g

2.6.3 Key Enabling Technologies

New and modern technology must be incorporated into 6G to support the use cases and services mentioned above. These enabling technologies include carrier aggregation through multi-band scheduling, above 6 GHz Edge AI, communication with large, intelligent surfaces, integrated terrestrial, airborne, and satellite networks, energy transfer and harvesting, Terahertz communications, cell-free communication, and artificial intelligence (AI).

Carrier Aggregation: Coverage, throughput, resource reuse, system capacity, fairness, service quality, and user experience can all be enhanced through carrier aggregation (CA). Telecommunication service providers offer high data rate application services with high service quality that are economical and efficient in terms of energy use. Therefore, mobile applications will fulfill the client's expectations through carrier aggregation, one of the key contributors to fulfilling these needs. While CA has succeeded in Release 10 LTE- With Release 13 and later, advanced macro-cellular networks with up to five different non-contiguous carriers, bandwidths of hundreds of MHz for each carrier, and up to 32 different carriers can be supported[58]. This improved framework provides increased flexibility for aggregating many carriers in various bands and will also be useful for Licensed Authorized Access (LAA) operation in the unlicensed spectrum where there are many accessible spectrum blocks.

Communication with Large Intelligent Surfaces: Multiple-Input and Multiple-Output (MIMO) will be incorporated into the 6G standard to improve spectral and energy efficiency. MIMO will support huge, intelligent surfaces and novel surroundings supporting massive wireless communications surfaces[59].

Wireless Power Transfer and Energy Harvesting: Wireless energy transfer is becoming more sophisticated in line with the current wireless energy trend. It is clear from the 6G base station design that the base station will send the necessary power to a user's device. The process of using RF frequency to obtain electricity from a local environment is known as power harvesting. This wirelessly based power transfer offers an appealing option for users' batteries that have limited lifetime power. Low-power, energy-efficient wireless devices can be self-sufficient and environmentally benign by gathering energy from nearby or specialized energy sources[60].

[58] Z. Shen, A. Papasakellariou, J. Montojo, D. Gerstenberger and F. Xu, “Overview of 3GPP LTE-Advanced Carrier Aggregation for 4G Wireless Commnications,” IEEE Communications Magazine, pp. 122–130, 2012.
[59] W. Saad, M. Bennis and M. Chen, “A vision of 6G wireless systems: Applications, trends, technologies and open research problems,” IEEE Network, pp. 134–142, 2019.
[60] L. P. G. W. a. Y. Z. Yu Luo, “RF Energy Harvesting Wireless Communications: RF Environment, Device Hardware and Practical Issues,” Sensors, 2019.

Communication in the TeraHertz Band: In 6G, the THz band will have a significant impact. More bandwidth, greater capacity, secure transmission, high energy efficiency, small transceivers, terabit-per-second connection capacities, and extremely high data rates will be available in this range of 0.1 THz to 10 THz[61].

Cell-Free Communication: Previously, it was planned to utilize a UAV in an area without infrastructure, but, with 6G, it is anticipated that they will use it for dead zones as well, enabling cell-free communication. User equipment will be connected to the cell and to the entire network in 6G. As a result, problems with handover and coverage will be resolved.

Artificial Intelligence (AI) and Machine Learning (ML): AI and machine learning will ultimately enable 6G for automation. Especially for positioning and delay-sensitive applications, it will assume responsibility for network selection, resource allocation, and handover.

Integrated Terrestrial, Airborne, and Satellite Networks: By promoting hotspot connectivity, drones will outperform terrestrial networks. More terrestrial and drone base stations will make satellite connections for enhanced coverage. By combining high-altitude platforms, terrestrial base stations, and satellite stations, this method of communication attempts to increase user throughput and improve the services.

Network Slicing: Network Slicing (NS), a technology that allows for the creation of logically independent slices, enables end-to-end connectivity. By slicing with guaranteed Quality-of-Service, the Communication Service Providers (CSPs) can meet user-specific requests (QoS). The main benefit of using NS is that dedicated services don't require a new physical network. CSPs use network orchestration and virtualization to deliver real-time services following SLAs.

2.7 6G Networks: Considerations and Requirements

2.7.1 KPIs and Use Cases for 6G

Standards for the upcoming 6G networks have been established by numerous studies and research organizations, such as the 3rd Generation Partnership Project (3GPP) [62], based on factors such as bandwidth, data rate, latency, access technologies, energy and spectrum efficiency, connection density, etc.[63]. Key

[61] S. Elmeadawy and R. Shubair, "Enabling Technologies for 6G future wireless communications: Opportunities and Challenges," arXiv, 2020.
[62] K. Flynn, "A global partnership," Mar 2020. [Online]. Available: https://www.3gpp.org/release-16
[63]5GPPP, "B5G/6G Research with StandarizationPotential Roadmap,"5GPPP: 5G Infrastructure Public Private Partnership, November 2020.

Performance Indicators (KPIs), use cases, and specifications for 6G systems[64] are used to direct research efforts in academia and industry. For the development process to be validated, use cases are crucial. It establishes the outcomes and controls the behavior of the system.

2.7.2 Network Requirements

It's anticipated that 6G would build on the achievements of commercial 5G by making breakthroughs on a larger scale. New client markets with a wide range of services and parallel/vertical applications are expected to be made available by 6G installations. For 6G networks, AI will be necessary and serve as a tool to implement other interoperable technologies. Cloud and Big Data[65] will be essential in addition to AI for handling massive data. AR, VR, and XR immersive media applications will account for 85% of mobile broadband. The personalized technologies 6G will support the link of human emotions in hybrid spaces. Organizing, analyzing, storing, and using data from diverse devices will be difficult. Thus, the standards and policies must be following system requirements and user concerns.

The KPIs identified for the 2nd phase of 5G hold importance in 6G networks and are slightly modified based on the new 6G network requirements. A rich blend of use cases that explore 6G features can be identified to meet stringent requirements, including positioning, latency, device density, peak data rate, and energy efficiency. It ranges from human twins to manufacturing units (smart factory plus). The Human digital twin requires low latency and peak data rate, while the smart factory needs high security and low latency communication. Some of the use cases are defined as follows;

Human Digital Twin - The human body can be created to create a virtual human world that realizes the human health data and monitors it in real-time using interdisciplinary sciences and 6G technology digital twins. With time, 6G will reliably link a person's accurate statement of their health status to various procedures, including color Doppler ultrasound, blood tests, and urine biochemistry.

High-Speed Internet Access in the Air - The 6G will permit satellite transmission for its user to guarantee the service, but it is believed that the cost will be too high. 6G will be employing new network techniques to ensure air users.

New Smart City - Unified network architecture made possible by 6G will introduce new business situations. Deep integration and consideration of IA at all levels will be made in the 6G system for effective transmission, internal security, seamless networking, large-scale deployment, automatic maintenance, and

[64] S. Elmeadawy and R. Shubair, "Enabling Technologies for 6G future wireless communications: Opportunities and Challenges," arXiv, 2020.
[65] Lv, Z., Lou, R., Li, J., Singh, A. K., & Song, H. (2021). Big data analytics for 6G-enabled massive internet of things. IEEE Internet of Things Journal, 8(7), 5350-5359.

alarming hazards. Additionally, many sensors will be placed around the city and on structures; AI will enable many necessary procedures without human involvement.

XR (Extended Reality) is based on Holographic Communication - with the rapid growth of technology, it is anticipated that XR will replace augmented reality (AR) and virtual reality (VR) by 2030. The upgrade will be available to clients anytime, anywhere, using holographic communication and display. XR will enable the senses of hearing, smell, touch, taste, and emotion, as well as fully immersive holographic experiences such as concerts, sports, and painting.

Smart Factory Plus - 6G network will ensure full connectivity, stability, and security throughout the production cycle, not just for use in the factory. It will swiftly and adaptably link any intelligent devices that need to be connected inside the factory and use artificial intelligence to provide dynamic adjustment in accordance with production line requirements. Smart Factory PLUS will add an end-to-end closed loop over the 6G network.

By executing these use cases in real-time, it is anticipated that the 6G Ecosystem would open up the potential for new businesses. According to the Finnish 6G Flagship[66], these advancements can improve the use of the networks in a very innovative way and will open the door to Co-creation, which brings researchers and businesses together; Research to Business Process, which involves presenting research outputs to businesses; and Promoting research findings in relevant verticals/application areas while the players become leaders in digitalization.

[66] https://www.6gflagship.com/

2.7.3 Key Enablers and Challenges

Some key enablers for 6G are AI, NS, Edge/Fog Computing, and Self-evolving networks. AI is vital in streamlining and improving processes to minimize human involvement. The networks must be built on a data-driven architecture that uses vast amounts of data to support AI-based infrastructures. AI will define data transmission efficiency[67]. The latency, transmission weights, and data privacy concerns in standard Cloud networks incur overheads while accessing and processing data[68]. Thus, edge and fog computing solutions will eventually arise to offload the computational resources by moving the processing units near the user. NS[69] enables a flexible network on top of the shared physical infrastructure capable of specialized channels to suit user requests and the same functions[70] as the shared physical network. It accommodates specific user demands and specifications. It establishes rules for creating connections over the network and provides services with corresponding Service Level Agreements (SLAs)[71]. Figure 2-13 illustrates key challenges for the 6G network, while Figure 2-14 maps 6G KPIs, use cases, framework, and enabling technologies.

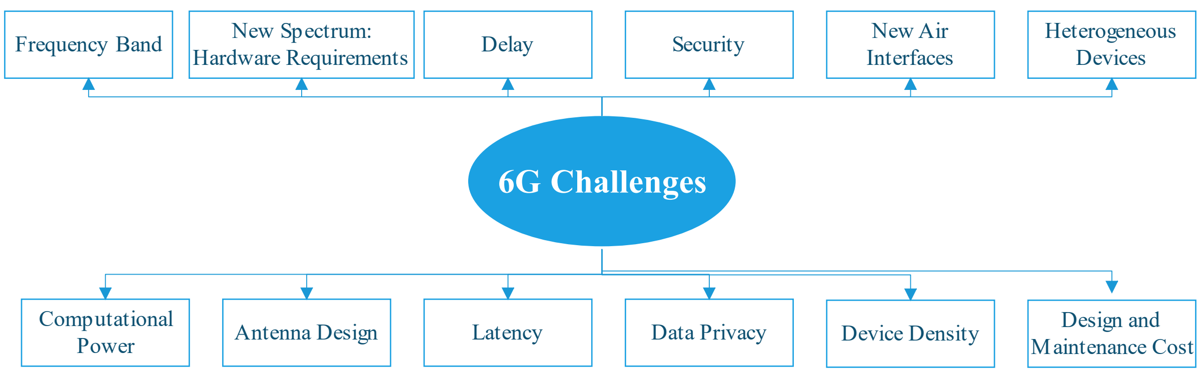

Figure 2-12 6G Challenges

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[67] Stoica, R. A., & de Abreu, G. T. F. (2019). 6G: the wireless commu- nications network for collaborative and AI applications. arXiv preprint arXiv:1904.03413.
[68] Lovén, L., Leppänen, T., Peltonen, E., Partala, J., Harjula, E., Poram- bage, P., ... & Riekki, J. (2019). EdgeAI: A vision for distributed, edge-native artificial intelligence in future 6G networks. The 1st 6G wireless summit, 1-2.
[69] N. Alliance, 5G White Paper (Final Deliverable), 2015.
[70] H. Zhang, N. Liu, X. Chu, K. Long, A.-H. Aghvami and V. C. Leung, "Network slicing based 5G and future mobile networks: mobility re- source management and challenges", IEEE communications magazine, vol. 55, no. 8, pp. 138-145, 2017.
[71] Network slicing explained, Nov 2020, [online] Available: https://www. nokia.com/about-us/newsroom/articles/network-slicing-explained/.

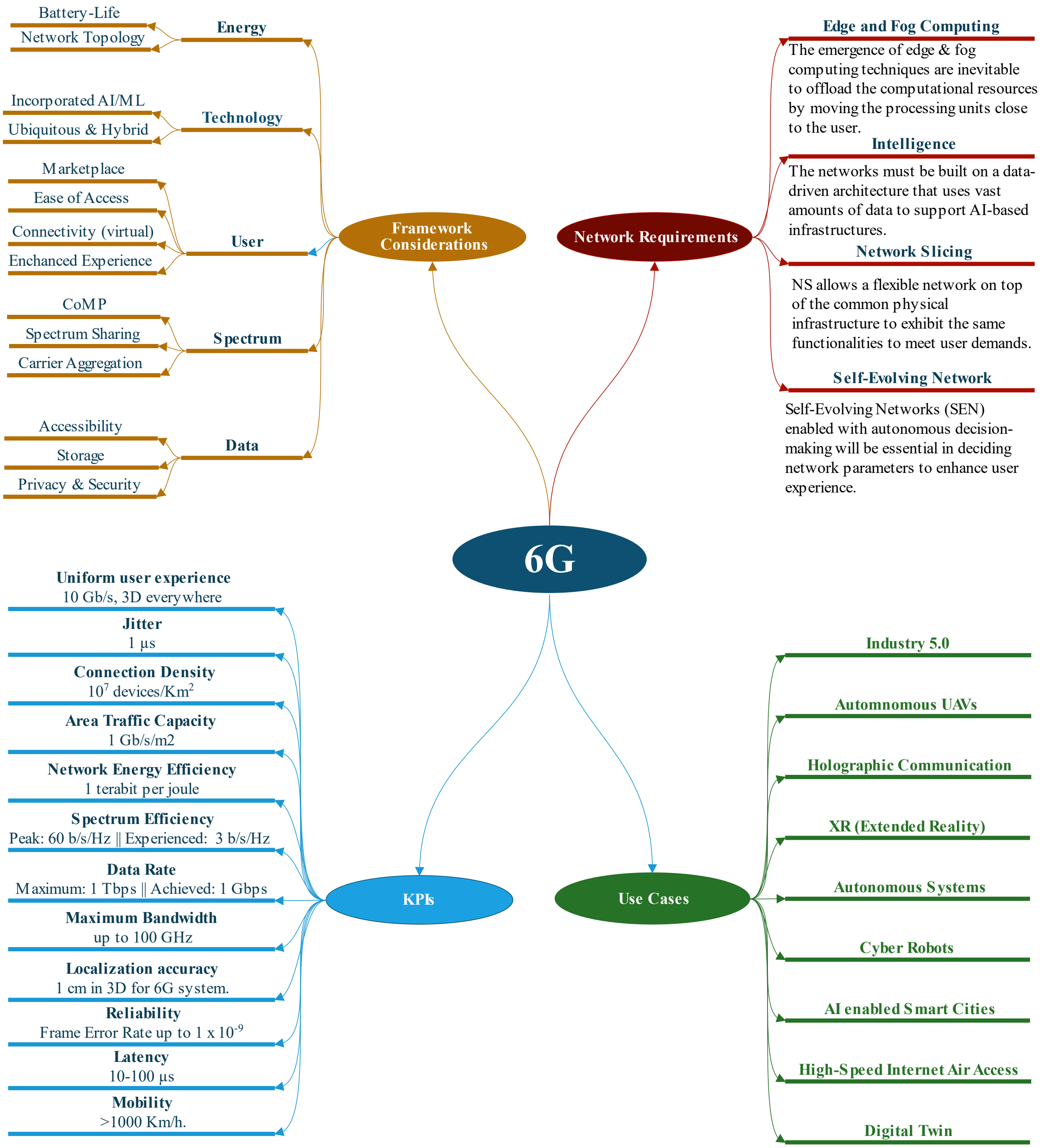

Figure 2-13 6G KPIs, Use Cases, Framework Considerations, and Enabling Technologies

2.8 Spectrum Management

The history of mobile communication networks has seen several spectrum management arrangements and strategies which effectively utilize available frequency bands[72]. It consists of spectrum allocation based on a market-specific allocation model, common unlicensed methods, and an administrative approach. There are currently very few specifics on 6G communication networks and their spectrum, and research is still in its early phases. The Terahertz (THz) frequency bands range, intended for mobile communication, is where 6G is anticipated to be deployed[73]. Since the frequencies for the 6G spectrum bands will be higher than previously, different spectrum management strategies will be used to separate the higher, mid, and lower bands.

It will be difficult to manage the spectrum of the 6G frequency bands, which will integrate communications and sensing. The use of AI in spectrum access decisions will pave the way for fully dynamic operation[74], in which the 6G network will perceive the radio environment and react to it in practical situations[75].

Table 2-1 lists the main characteristics of the 5G and 6G frequency bands that are currently in use. It explains that starting at 30 GHz, the free space loss increases slightly as one moves towards the THz area. The increase in antenna gain offsets the free space loss with a constant antenna area. Higher frequencies have drawbacks, including lower beam width, increased complexity and parallelism in RF hardware[76], and relative free space loss. These drawbacks make it difficult for mobile applications to acquire signals and track beams. The migration to higher frequencies won't cause the prices, operating distances, and battery restrictions of various IoT devices to scale quickly. To maximise resource reuse for communications, the THz spectrum needs to be handled based on absorption and following the characteristics of sub-bands reflection. In those cases where multiple applications are supported, careful frequency planning is required to avoid sub-channel overlap. Figure 2-15 demonstrates that the GHz provides a link distance of up to 10 km, whereas it is much less[77].

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[72] J. Peha, "Spectrum MAnagement Policy Options," *IEEE Communications Surveys*, vol. 1, no. 1, pp. 2–8, 1998.
[73] B. Hassan, S. Baig and M. Asif, "Key Technologies for Ultra-Reliable and Low-LAtency Communication," 6G IEEE Communications Standards Magazine, pp. 106–113, 2021.
[74] Nidhi, A. Mihovska and R. Prasad, "Spectrum Sharing and Dynamic Spectrum MAnagement Techniques in 5G and Beyond Networks: A survey," Journal of Mobile Multimedia, pp. 65–78, 2021.
[75] M. Matinmikko-Blue, S. Yrj¨ol¨a and P. Ahokangas, "Spectrum Management in the 6G er: The role of regulation and spectrum sharing," in 2nd 6G Wireless Summit, 2020.
[76] M. Latva-aho and K. Leppanen, "Key drivers and research challenges for 6G ubiquitous wireless intelligence (white paper)," 6G Flagship, University of Oulu, Oulu, 2019.
[77] www.oulu.fi/6gflagship/

FREQUENCY BAND	0.3-3 GHz	3-30 GHz	30-300 GHz	0.3-3 THz	3-30 THz
WAVELENGTH	100-10 cm	10-1 cm	10-1 mm	1000-100 µm	100-10 µm
DOMINANT PROPAGATION MECHANISM	LoS, Reflection, Diraction, Scattering, Penetration	LoS, Reflection, Diraction, Scattering	LoS, Reflection	LoS, Reflection	LoS, Reflection
DOMINANT ATTENUATION EFFECTS	Free Space Loss	Free Space Loss -Transmission Loss Through Materials High at Upper Band	Free Space Loss/ Molecular Absorption -O_2 @60 GHz -H_2O > 24 GHz	Free Space Loss/ Molecular Absorption -High H_2O Peaks	Free Space Loss/ Molecular Absorption -High H_2O Peaks
SUPPORTED LINK DISTANCES	10 km	1000 m	100 m	<10 m	<1 m
TX POWER LIMITING FACTOR	Regulation	Regulation	Technology	Technology	Technology
APPROXIMATE SYSTEM BANDWITH	up to 100 MHz	400 (or 800) MHz	Up to 30 GHz	Up to 300 GHz	> 100 GHz

Figure 2-14 Characteristics of the Spectrum Bands for 5G and 6G[78]

2.8.1 Spectrum Requirements for 6G

To encourage 6G research, the Federal Communications Commission (FCC)[79] opened a new spectrum in 2019. It calls it "the far frontier of spectrum regulation" and permits research on frequencies between 95 GHz and 3 THz. Propagation faces huge hurdles as 6G moves into such large regions of the spectrum while using ultra-high radio frequencies. Coexistence somehow plays a significant role in getting access to the frequency spectrum. A few of the technologies listed below will also be crucial in 6G networks.

2.8.1.1 Spectrum associated with 5G Networks

Enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable and low latency communications are the three megatrends identified by ITU in IMT 2020. (URLLC). The term "eMBB" refers to applications that consume a lot of bandwidth, including high-definition telepresence, telemedicine, remote surgery, and others. It also covers technologies such as carrier aggregation (CA), massive input massive output (MIMO), multiple access point technology (MRAT), etc. Smart metering, smart cities, asset tracking, and other dense, high-volume IoT nodes/applications are examples of mMTC. These are primarily the low-power, low-cost, and low-complexity applications. Mission-critical services,

[78] Nidhi, et al. "Trends in Standardization Towards 6G." Journal of ICT Standardization (2021): 327-348.
[79] S. Kinney, “Looking beyond 5G, FCC Opens up Terahertz Spectrum,” RCR Wireless News www.rcrwireless.com/20190319/policy/fcc-terahertz-spectrum, 19 March 2019.

such as those for industrial automation, driverless vehicles, and healthcare, are also included in URLLC. These applications are designed for Low Latency, String Security, and Ultra Reliability.

The application specified in Table 2-1determines how the spectrum will be used for 5G. Spectrum is a limited resource, making it difficult to find. To satisfy the increased bandwidth requirements of 6G, it is crucial to reuse the existing frequency bands. In the upcoming years, the standardisation efforts to utilise the licenced and unlicensed spectrum will undoubtedlynably be of utmost significance[80].

Table 2-1 5G Spectrum Allocation

Frequency Bands	***Range***	***Application***
Low bands	< 2 GHz	eMBB, URLLC & mMTC applications
Mid bands	2-8 GHz	
High bands	> 24 GHz	eMBB and URLLC applications

2.8.1.2 New Spectrum Beyond THz

To develop channel models and study the propagation conditions that the NTN (Non-Terrestrial Networks) elements will face in inter-node and non-terrestrial to terrestrial communications, it is necessary to collaborate closely with the terrestrial counterpart on the investigation of new spectral bands[81]. Additional bandwidth over 100 GHz and NTN, frequency bands beyond 50 GHz, and even spectrum above THz are anticipated to be used in conjunction with the 6G ecosystem for terrestrial applications. In addition, higher frequency bands can be used by NTN systems based on free-space optical communication (i.e., 150-300 THz). The architecture for evolutionary NTN systems will enable infrastructure reuse between terrestrial and non-terrestrial networks and a cost-effective network design[82]. Unmanned aerial vehicles (UAVs), equipped with processing, computing, and communication capabilities, can serve as flying nodes for the 6G network.

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[80] Nidhi, A. Mihovska and R. Prasad, "Spectrum Sharing and Dynamic Spectrum MAnagement Techniques in 5G and Beyond Networks: A survey," Journal of Mobile Multimedia, pp. 65–78, 2021.

[81] 5GPPP, "B5G/6G Research with Standarization Potential Roadmap," 5GPPP: 5G Infrastructure Public Private Partnership, November 2020.

[82] S. Kinney, "Looking beyond 5G, FCC Opens up Terahertz Spectrum," RCR Wireless News www.rcrwireless.com/20190319/policy/fcc-terahertz-spectrum, 19 March 2019.

Device behavior in homogeneous and heterogeneous networks differs significantly. Different technologies that operate in unlicensed bands coexist thanks to homogenous networks, which support the legal bands. The following are some of the significant issues and design considerations:

- An effective spectrum-sharing algorithm for demanding network configurations.
- The performance of spectrum sharing is impacted by the UEs' erratic movements and the frequent handovers in a crowded environment.
- Support for scalable data transmission over 5G and 6G networks. Thus, the spectrum sharing strategy needs to support the time-varying data requirements.
- Create algorithms for base stations and access points working together in heterogeneous networks.

2.9 Discussion and Conclusions

This analysis is focused on 6G standards requirements and outlines the standardization process. From a technological standpoint, 6G will give customers and MNOs a huge opportunity to experiment with various services and use cases. New difficulties will arise with the new spectrum. Along with the new characteristics of the 6G networks, services and enabling technologies have also been introduced. Numerous 6G standardization activities worldwide have also been addressed after generating newly developed KPIs and specifications. We now know that expanding the scope of standards and technology development is necessary to support upcoming ecosystems. Higher layers are now accessible for research, providing great opportunities and brand-new obstacles. Different organizations are developing the 6G guidelines, 100x data throughput, and sub-millisecond latency compared to 5G networks when crafting the specifications and standardization requirements.

Three worlds are included in the 6G vision: the physical world of objects and organisms, the digital world of data, communication, and computers, and the world of people as represented by our senses, bodies, minds, and values. Future network development and deployment also depend heavily on regulations and technological breakthroughs. The need for the accompanying services to be accessible to everyone and anywhere they are required thus one of the major concerns facing society due to the development of 6G enabling technologies. Global coverage and "easy-to-use technologies" are required for digital inclusion (at an affordable cost for deployment and the customer.

3 RAN Resource Allocation and Scheduling Techniques

This section maps our contributions beyond the State-of-the-Art analysis to provide solutions for the Radio Access Network (RAN) resource management, scheduling, and performance evaluation for NS, followed by scheduling techniques in CA. We will address the identified problems concerning RAN resource management and sharing while deploying network slices and carrier aggregation. The focussed papers will provide our contributions as a proposed solution to exhibit RAN resource slicing in NS deployments for URLLC and eMBB applications. In the case of CA deployments, we will elaborate on the cross-scheduling technique we implemented for resource allocation and management in Small Cells. Further, we will elaborate on our proposal for RAN slicing implementation in CA-enabled networks. This section will summarize our technical contributions.

3.1 Objective and Contributions

The contributions intend to broadly serve two of the six research objectives – (i) Advancements in Carrier Aggregation (CA) and Network Slicing (NS) and (ii) Resource Allocation, Management, and Scheduling Techniques. Figure 3-1 maps the research objectives to the publications considered under this section, with the main contributions.

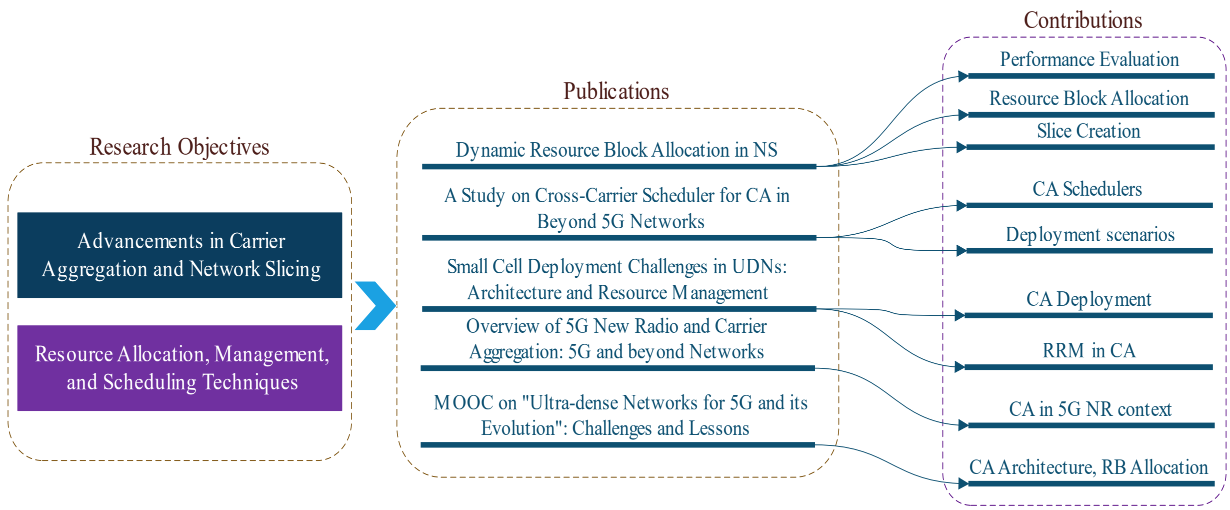

Figure 3-1 Objective Mapping to the Publications

The first part of this section will summarize our investigation and analysis to evaluate RAN slicing functions using MATLAB. We implemented different RAN slicing configurations to analyze radio resource distribution among slices based on Layer 2 (L2) and Layer 3 (L3) parameters and performed simulations for two network instances in a multi-service scenario with varying demands. Following the performance evaluation, we contributed toward our identified problem of RAN slicing in NS deployment. We proposed resource-sharing algorithms that compute radio resources for the individual created slice and adjust the allocated resource depending on achieved throughput estimates and Channel Quality Indicator (CQI) values. We explicitly explain the Resource Blocks (RB) allocation in the 5G NR.

Limitation: To this contribution, we identified significant overhead while extracting the CQI information from the base stations to feed the UEs. We discussed this challenge and potential solutions in the discussion section. The solution to mitigate the overhead issue is out of the scope of this work.

The second part details the CA techniques and analyzes cross-carrier and multiband scheduling schemes in CA-enabled 5G networks for the Downlink (DL). We considered 5G NR networks and discussed radio resource management and scheduling techniques in detail. We analyzed the performance of two different small cell deployments with the macro cell sites. Finally, we present an integrated CA-enabled slicing framework that promotes optimized channel utilization with guaranteed service requirements—for instance, high throughput in eMBB and ultra-low latency with high reliability in uRLLC slices.

Figure 3-2 illustrates the research questions we addressed in this section.

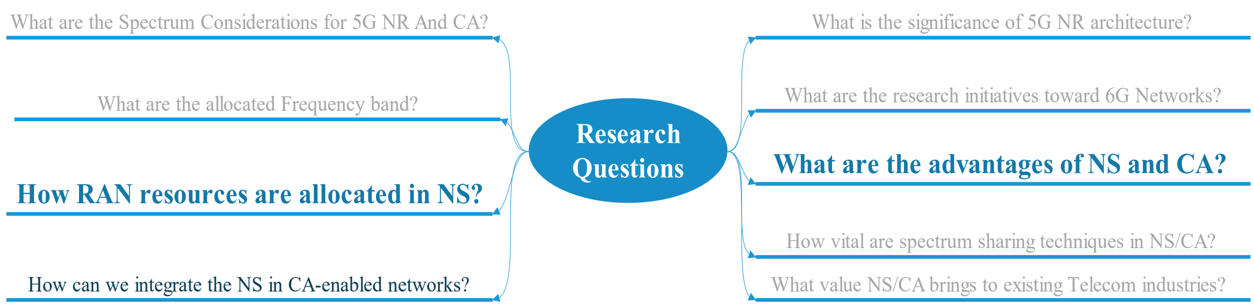

Figure 3-2 Addressed Research Questions

3.2 Summary of Publications

1. **Dynamic Resource Block Allocation in Network Slicing**
   Conference Paper: Nidhi., Khan, B., Mihovska, A., Poulkov, V., Prasad, R. & Velez, F., 27 Jun 2022, (Accepted/In press). 12th CONASENSE Symposium, 27th-29th June 2022, Munich, Germany.

   This study offers a thorough method for dividing a system into slices depending on the required services, resource virtualization, and isolation. The main emphasis is the Slice Orchestrator (SO) level resource sharing algorithms. The megatrends of Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (uRLLC), and Massive Machine-Type Communications (mMTC) are supported by various services and applications on these virtual network slices. In addition, the paper gives an overview of standardization efforts and changing specifications for use cases and services such as Holographic Telepresence and Automotives.

2. **A Study on Cross-Carrier Scheduler for Carrier Aggregation in Beyond 5G Networks**
   Conference Paper: Nidhi, B. Khan, A. Mihovska, R. Prasad and F. J. Velez, "A Study on Cross-Carrier Scheduler for Carrier Aggregation in Beyond 5G Networks," 2022 3rd URSI Atlantic and Asia Pacific Radio Science Meeting (AT-AP-RASC), 2022, pp. 1-4, doi: 10.23919/AT-AP-RASC54737.2022.9814320.

   This paper emphasizes CA deployment scenarios, CA-enabled 5G networks, resource management, and scheduling strategies for 5G New Radio (5G NR) networks. CA enables the User Equipment (UE) and the network to combine carrier frequencies in licensed, unlicensed, or Shared Access (SA) bands of the same or other spectrum bands to increase the data rates. We analyzed the cross-carrier and multi-band scheduling for Downlink resource allocation in CA-enabled networks. Resource Blocks (RBs) and Component Carriers (CCs) distribution address the requirements, challenges, and opportunities.

3. **Small Cell Deployment Challenges in UDNs: Architecture and Resource Management**
   Conference Paper: Nidhi and A. Mihovska, "Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management," 2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2020, pp. 1-6, doi: 10.1109/CSNDSP49049.2020.9249560.

   The paper discussed various critical aspects of small cell and ultradense networks. The goal is to list numerous deployment issues and scenarios. The difficulties with managing resources, creating flexible architecture, controlling the available spectrum, employing unlicensed spectrum, etc., will be discussed. The inadequacies in available resource management, interference awareness techniques, spectrum management, etc., will be summed up with various prospective technologies.

4. **Overview of 5G New Radio and Carrier Aggregation: 5G and beyond Networks**
   Conference Paper: Nidhi, A. Mihovska and R. Prasad, "Overview of 5G New Radio and Carrier Aggregation: 5G and Beyond Networks," 2020 23rd International Symposium on Wireless Personal Multimedia Communications (WPMC), 2020, pp. 1-6, doi: 10.1109/WPMC50192.2020.9309496.

   This paper, presented at the Wireless Personal Multimedia Communication conference-2020, provides a comprehensive overview of the development of NR, including deployment scenarios, numerologies, frame structure, and new waveforms. We provided an overview of CA, its requirements, and open research issues. We listed the enhancements made with 5G NR and CA through various 3GPP releases.

5. **MOOC on "Ultra-dense Networks for 5G and its Evolution": Challenges and Lessons Learnt**
   Conference Paper: M. J. Lopez-Morales et al., "MOOC on "Ultra-dense Networks for 5G and its Evolution": Challenges and Lessons Learned," 2022 31st Annual Conference of the European Association for Education in Electrical and Information Engineering (EAEEIE), 2022, pp. 1-6, doi: 10.1109/EAEEIE54893.2022.9819989.

   The published paper was an outcome of the Massive Open Online Course (MOOC) on the edX platform, created by the ESRs on the topic "Ultra-Dense Networks for 5G and its Evolution". We contributed to two modules out of six modules. Our contribution includes the basics of CA, the coexistence of small cells, and several spectrum-sharing architectures.

3.3 Advancements in Network Slicing and Carrier Aggregation

With the roll-out of the 5G mobile networks, the demand for advancing services and applications has increased significantly, with the required Quality of Service (QoS). Low latency and super reliability are also brought to the network by 5G, coupled with a significant leap in speed and data throughput[83]. It is anticipated that these demands will multiply exponentially in the coming era giving new research verticals and direction to hasten 6G ambitions. The 6G[84] systems must support numerous use cases and applications for an improved user experience, ranging from autonomous systems to Extended Reality (XR)[85]. The advancements in spectrum bands and new access strategies will drive different enabling technologies to meet the needs of a brand-new set of services.

Network Slicing (NS) and Carrier Aggregation (CA) are two of the key enablers for the upcoming wireless mobile networks. NS can be utilized to build several virtual networks, or "slices," to offer additional services to customers by the operators and creates new income opportunities. In contrast, CA is a technique to combine two or more channels to increase bandwidth and facilitates the telecom industry to lease infrastructure to enable local network access. The provider can leverage suppliers to lease access on a scale ranging from neighborhood marketplaces and regions to specific buildings. Both of these technologies came with the 4G networks and evolved gradually toward developing suitable architectures to support the advancing needs.

This objective aims to elaborate on the background of NS and CA, as illustrated in Figure 3-3, followed by different enhancements proposed by 3GPP[86] Releases.

Figure 3-3 Section Structure of the Objective

[83] https://www.nokia.com/about-us/newsroom/articles/network-slicing-explained/
[84] Giordani, M., Polese, M., Mezzavilla, M., Rangan, S., & Zorzi, M. (2020). Toward 6G networks: Use cases and technologies. IEEE Com- munications Magazine, 58(3), 55-61.
[85] Jiang, W., Han, B., Habibi, M. A., & Schotten, H. D. (2021). The road towards 6G: A comprehensive survey. IEEE Open Journal of the Communications Society, 2, 334-366.
[86] https://www.3gpp.org/

3.3.1 Network Slicing

The 5G wireless networks adopted NS as one of the fundamental technologies to provide End-to-End (E2E) connection for user-specific services. They enabled Communication Service Providers (CSPs) to meet a range of creative business models, use cases, and user-specific solutions. NS allows all the necessary functions of the shared physical network to be present in the slices establishing isolated virtual network layers; thus, it reduces implementation cost. 3GPP introduced the NS Framework in Release 15[87] and gradually enhanced it in further Releases. The Next Generation Mobile Network (NGMN)[88] first defined the NS framework as an E2E logical network on a shared physical/virtual infrastructure. The slices are isolated, programmable, and self-contained, with dedicated control and management characteristics to support multi-services. The framework consists of three essential layers; (i) Service Layer, (ii) Network Slice Instances, and (iii) Physical Infrastructure. The physical infrastructure layer acts as the resource layer. Figure 3-4 illustrates the NS Framework Blocks.

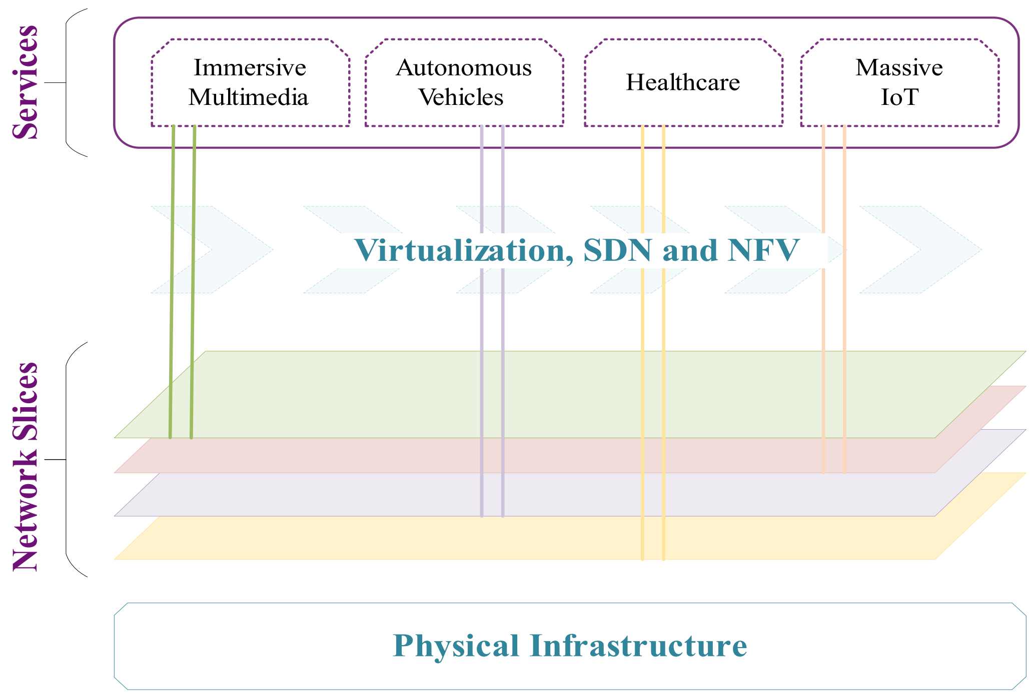

Figure 3-4 Network Slicing Framework

[87] https://www.3gpp.org/release-15
[88] NGMN 5G Initiative White Paper, February, 2015, https://www.ngmn.org/ wp-content/uploads/NGMN_5G_WhitePaperV1.pdf

In the technical specification 23.501, 3GPP introduced the 5G Service Based Architecture (SBA)[89] to facilitate the coexistence of heterogeneous network requirements. According to the technical specification TS28530-3GPP[90], network slicing refers to a logical network composed of three major network segments: RAN, Core Network (CN), and Transport Network (TN), with specific functionalities, capabilities, and characteristics. The network slice or instance comprehends the allocated computation and network resources in addition to the network functions. TN provides specified performance obligations while supplying the essential connectivity between RAN and CN. E2E network slice configurations affect TN's topology and performance requirements[91].

The 5G slicing framework exploits Software-Defined Network (SDN) and Network Function Virtualization (NFV) to enable specific functionalities and services[92]. Through Application Program Interfaces (APIs), SDN manages the CP data forwarding and traffic flow, configures resources, and facilitates user-specific services. It also enables slice creation and supports multiple sub-controllers. NFV manages the slice lifetime schedules and resource allocations. It allows Virtual Machines (VMs) to have the required network functionalities and share a common physical infrastructure.

From an operator's standpoint, offering customers network services in the 3GPP compliant and non-3GPP domains like the SGi LAN/N6 network and fixed access network is critical. Thus, E2E network slicing bridges the gap as a logical network crossing both 3GPP and non-3GPP domains[93] guided by the Service Level Agreements (SLAs). In conjunction with SLA, network orchestration aids CSPs in automating communication on and across the network to deliver customized services with assured QoS for various usage situations[94].

Using NS, CSPs can establish many virtual slices to accommodate massive increases in data traffic and unique user requirements. Each slice hosts unique network functions and application services in isolation, that is, without interfering with the coexisting slices[95]. NS enables all the virtual logical network levels to features of a shared physical network by offering a paradigm shift from the current traffic and network management method. Additionally, it splits the network into several separate virtual networks resulting in a specific channel that will offer resources to benefit the user requests. Slicing thereby strengthens traditional networks to accommodate a variety of business strategies and use scenarios. In addition, NS

[89] https://www.ericsson.com/en/blog/2017/9/servicebased-architecture-in-5g
[90] 3GPP TS28.530, https://portal.3gpp.org/desktopmodules/Specifications/ SpecificationDetails.aspx?specificationId=3273.
[91] https://www.ietf.org/id/draft-geng-teas-network-slice-mapping-05.html#name-introduction-3
[92] Ordonez-Lucena, J., Ameigeiras, P., Lopez, D., Ramos-Munoz, J. J., Lorca, J., & Folgueira, J. (2017). Network slicing for 5G with SDN/NFV: Concepts, architectures, and challenges. IEEE Communications Magazine, 55(5).
[93] https://www.gsma.com/newsroom/wp-content/uploads//NG.127-v2.0-3.pdf
[94] "Network slicing explained," 2020. https://www.nokia.com/about-us/newsroom/articles/networkslicing-explained/
[95] A. Nakao, P. Du, Y. Kiriha, F. Granelli, A. A. Gebremariam, T. Taleb, and M. Bagaa, "End-to-end network slicing for 5g mobile networks," Journal of Information Processing, vol. 25, pp. 153–163, 2017.

allows for improved service quality for user-specific custom solutions. For example, the Emergency services have stricter latency requirements than for uses focused on agriculture (to maintain crop health). It will therefore make current networks dynamic, adaptive, and scalable while allowing for increasing demand, from different applications, with different needs.

3.3.1.1 Core Network Slicing

3GPP[96] defined new architecture for the CN as the 5G Next Generation core to benefit from the SBA, incorporated virtualization and cloud integrations, and added 5G functionalities, including security, traffic control, and separate session management and access control[97]. There have been two deployment models defined for new CN architecture. The first phase deployment model was based on the LTE with a one-to-one mapping of the RAN entities, making reconfigurations mandatory with every added slice. The second phase deployments support SBA in a virtualized environment and use the NRF query method to discover and establish communication for available NFs. Figure 3-5 elaborates on the main functions of CN Slicing.

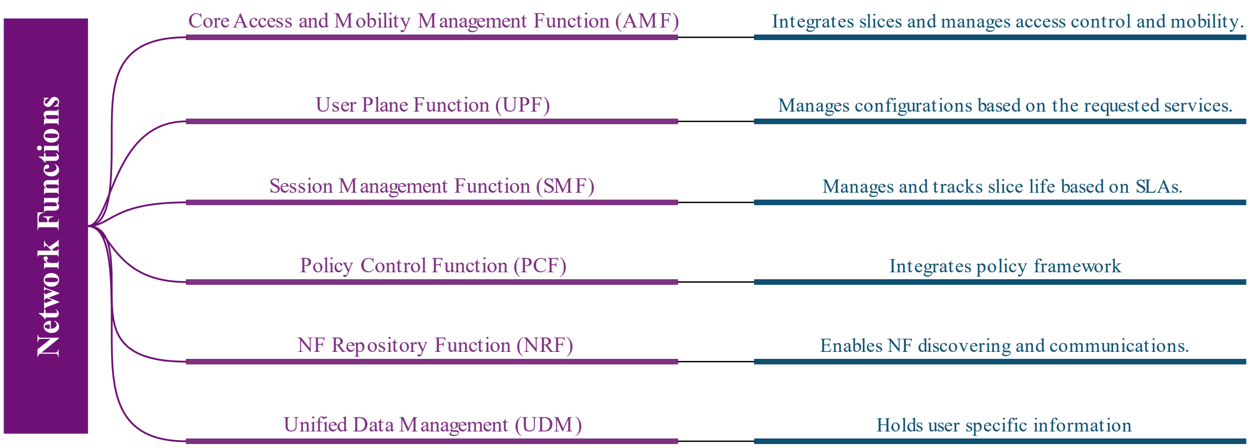

Figure 3-5 Network Functions defined by Core Network Slicing

[96] 3GPP, “Feasibility study on new services and markets technology enablers stage 1," vol. TR 22.891 release 14.
[97] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini, and H. Flinck, “Network slicing and softwarization: A survey on principles, enabling technologies, and solutions," IEEE Communications Surveys Tutorials, vol. 20, no. 3, pp. 2429-2453, 2018.

3.3.1.2 Transport Network Slicing

The TN carries data from the AN to the CN and consists of the backhaul and fronthaul. It provides connectivity among remote sites and devices. The backhaul network connects the Base Station (BS) to the AN where, the fronthaul facilitates the connections between the BS antennas and the remote Radio Frequency (RF) units. TN connects the NG-RAN functional modules and decides the configurations and deployment topologies. The migration of conventional 5G RAN to Centralized Radio Access Network (C-RAN) has introduced more flexibility and scalability with improved radio resource utilization. In C-RAN, the fronthaul networks transport the aggregated data from individual Radio Units (RU) and the Baseband (BBU). It also defines the logical split of the BBU into a Distributed Unit (DU) and a Centralized Unit (CU), incorporating added flexibility to support various 5G use cases.

At TN, two NS techniques are defined; (i) Fixed Access Network Sharing (FANS) and (ii) Fronthaul/Backhaul Network Slicing. The FANS allow the physical network sharing and allocation among CSPs and MNOs through the virtual network instance incorporating NFV technologies[98]. It enables slicing at the management level to update policy and configure Virtual Private Network (VPN). The NFV Management and Orchestration (NFV-MANO) approach facilitates resource allocation through the Virtual Access Nodes (VAN). MANO proceeds with slice requests as received to configure the network services using a hypervisor considering existing cloud computing platforms and routers. The Fronthaul/Backhaul Slicing introduces a transport architecture with integrated control and data plane forming an overlay network[99] to enable a programmable and flexible data plane.

3.3.1.3 Radio Access Network Slicing

The RAN resources are critical when considering the limitations of radio resources like bandwidth or frequency spectrum. Slicing on 5G RAN needs to address RAN-specific requirements[100] that primarily include service-aware resource allocation to prioritize demands[101], Intelligent traffic management to support multiservice slices, and a robust isolation mechanism to avoid inter-slice interferences[102]. The three

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98 B. Cornaglia, G. Young, & A. Marchetta, “Fixed access network sharing," Optical Fiber Technology, vol.26,pp. 2-11, Dec. 2015.
99 X. Li, R. Casellas, G. Landi, A. de la Oliva, X. Costa-Perez, A. Garcia-Saavedra, T. Deiss, L. Cominardi, and R. Vilalta, “5g-crosshaul network slicing:Enabling multi-tenancy in mobile transport networks," IEEE Communications Magazine, vol. 55, no. 8, pp. 128-137, 2017.
100 R. Ferrús, O. Sallent, J. Pérez-Romero, R. Agustí, “On 5G Radio Access Network Slicing: Radio Interface Protocol Features and Configuration”, IEEE Communications Magazine, September, 2017.
101 J. Pérez-Romero, O. Sallent, R. Ferrús, R. Agustí, “On the Configuration of Radio Resource Management in a Sliced RAN”, 2018.
102 I. Leonardo da Silva, G. Mildh, A. Trogolo, E. Buracchini, P. Spapis, A. Kaloxylos, G. Zimmemann, N. Bayer, “On the impact of network slicing on 5G radio Access networks”, IEEE Communications Magazines, September, 2016.

key aspects of RAN to incorporate an efficient resource sharing and dynamic isolation algorithm includes resource allocation and management, slice isolation techniques, and functional splits.

L3 Configuration

The Layer 3 configurations decide the slice capacity, associated RRM policies, and RRC protocol. The RRM protocols ensure that each slice meets the minimum resource criteria in multiple slice scenarios by allowing the UEs to identify individual slices marked with unique slice IDs.

L2 Configuration

Layer 2 signifies a Medium Access Control (MAC) scheduler configuration, including multiplexing and scheduling of the radio packet transmissions to employ slice isolation. It defines the Packet Scheduling (PS) features to manage and aggregate slice traffic for the Resource Blocks (RB).

L1 Configuration

Layer 1 is responsible for providing the transport channels with the associated services to enable RAN flexibility in Physical Layer (PHY). L1 defines the allocated number of Physical Resource Block (PRB) and the subcarrier separation (Δf) in addition to describing data processing and transferring mechanism, which varies with the slice type; thus, it also establishes radio resource partitioning.

3.3.1.4 Resource Block Allocation in Network Slicing

Dynamic Resource Allocation (DSA) of data packets is critical for dynamically active services like real-time (RT), non-real-time (NRT), and control signaling. The UE receives the bandwidth resources from the gNodeB (gNB) to enable data transmission and reception in both the downlink and the uplink. The smallest resource entity allotted to a single user is the Resource Block (RB). In 5G New Radio (5G NR), the assigned symbols (OFDM symbols) from various sub-carriers are defined by the time-domain resource allocation. In comparison, the Resource Block (RB) (sub-carriers) distribution to the UE is demonstrated by the frequency domain allocation. Contrary to LTE-A, an RB encompasses 12 sub-carriers in the frequency domain and has a variable RB bandwidth.

The gap between sub-carriers affects RB bandwidth. With a channel bandwidth of 100 MHz in the sub-6 GHz bands and 400 MHz in the mmWave range and no reserved Direct Current (DC, the sub-carrier whose frequency is equal to the RF center frequency of the transmitting station), NR offers a higher bandwidth efficiency (up to 99%)[103] than LTE (90%) and supports both uplink and downlink. The only thing the UEs need to determine the center of the OFDM frequency band is a DC subcarrier. The 5G New Radio

[103] X. You, C. Zhang, X. Tan, S. Jin, and H. Wu, "AI for 5G: research directions and paradigms," Science China Information Sciences, vol. 62, no. 2, pp. 1–13, 2019.

numerology is used to specify the maximum and minimum RBs. As a result, the channel bandwidth may be computed by knowing the RB's specified bandwidth. In the frequency domain, the 3GPP specifications distinguish between Resource Allocation Type #0 (RAT#0) and Resource Allocation Type #1 (RAT#1).

Sharing the same network resources is necessary for a network slicing deployment scenario when slices are formed across the same infrastructure. The task of assigning resources to specific slices while collaborating with the infrastructure providers falls under the Slice Manager (SM) purview. The slices, often called the slice tenants, are serviced by the virtual network operator (VNO). To control the required resources, a SLA is established between the SMs and the VNOs[104]. An effective method for allocating statistical resources among network slices with high SLAs[105] offers a more significant trade-off between the distribution of resources and system complexity and, as a result, raises new research issues on the data and cost continuum. In multi-tenant scenarios, the resource allocation strategy was centered on the optimum fairness index, utility gains, and capacity savings.

A flexible 5G network architecture to support cross-domain E2E slicing[106] with clearly defined inter-slice control and management functions and Deep Reinforcement Learning (DRL)[107] approach to assigning resources in dynamic multi-tenant systems are proposed to provide flexibility and scalability.

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[104] P. Caballero, A. Banchs, G. de Veciana, and X. Costa-P´erez, "Multi-Tenant Radio Access Network Slicing: Statistical Multiplexing of Spatial Loads," IEEE/ACM Transactions on Networking, vol. 25, no. 5, pp.3044–3058, 2017.
[105] A. Ksentini, P. A. Frangoudis, P. Amogh, and N. Nikaein, "Providing low latency guarantees for slicing-ready 5G systems via two-level MAC scheduling," IEEE Network, vol. 32, no. 6, pp. 116–123, 2018.
[106] M. Shariat, ˙O. Bulakci, A. De Domenico, C. Mannweiler, M. Gramaglia, Q. Wei, A. Gopalasingham, E. Pateromichelakis, F. Moggio, D. Tsolkas et al., "A flexible network architecture for 5G systems," Wireless Communications and Mobile Computing, vol. 2019, 2019.
[107] F. Mason, G. Nencioni, and A. Zanella, "A Multi-Agent Reinforcement Learning Architecture for Network Slicing Orchestration," in 2021 19th Mediterranean Communication and Computer Networking Conference (MedComNet). IEEE, 2021, pp. 1–8

3.3.2 Carrier Aggregation

By arranging the mobile terminal to be simultaneously connected with numerous cells of the serving base station, or making the mobile terminal, or user equipment (UE), function at various frequencies simultaneously, Carrier Aggregation (CA) is designed to increase the data rate per user. Dual Connectivity (DC) enables the mobile terminal to connect to two serving base stations simultaneously (known as the primary node, MN, and the secondary node, SN). In order to significantly increase the maximum bandwidth for the mobile terminal, dual connection and carrier aggregation can also be coupled. In this case, the UE is linked to two base stations and utilizes several cells in each of them[108].

A typical UE is not sending or receiving data to or from the network most of the time. To minimize signaling and energy consumption, it instead spends much time in what is known as dormant states, sometimes known as idle or inactive states. The terminal only returns to a connected state for data transmission when data comes; even then, it can take some time before it can begin functioning in CA and DC. This is because, in a normal network, the UE initially moves to the connected state where there is only one serving cell, after which it is set up to conduct measurements of other candidate frequencies/cells. The network won't set up the UE to use CA/DC and start functioning with it until the measurement results are reported.

3.3.2.1 CA Enhancements

Additional improvements for the early measurements feature have been added as part of the CA&DC upgrades work item in 3GPP Rel-16. For a speedy setup of DC, the capability has been expanded to include NR and early measurements. For both LTE and NR Rel-16, where the early measurement configuration can now include both LTE and NR carriers, the LTE Rel-15 euCA functionality discussed above has been employed as a baseline. By doing this, the UE is guaranteed to report measurement results for a speedy multi-Radio Dual Connectivity (MR-DC) setup, such as EN-DC, where the MN is in LTE and the SN is in NR, or NR-DC, when both the MN and secondary node (SN) are in NR.

One of the key benefits of carrier aggregation is that it allows mobile networks to use underutilized spectrum, which would otherwise go unused. As a result, the network's overall efficiency is enhanced, and its capacity is raised, which is crucial in heavily populated places. Additionally, carrier aggregation can enhance coverage in locations where the LTE signal is spotty or poor. The likelihood of finding a strong signal is increased by using various carriers, which can be a lifeline for people who live in remote areas or

[108] https://inseego.com/resources/5g-glossary/what-is-carrier-aggregation/

travel regularly. Carrier aggregation is a useful feature that can help LTE-Advanced networks function better[109].

Carrier Aggregation is the technology to enhance the data capacity, throughput, data rates, and improved network performance in the uplink, downlink, or both. It allows efficient spectrum utilization by combining two or more carriers in the same or different frequency bands into a single aggregated channel[110]. It enabled aggregation of FDD and TDD[111] and licensed and unlicensed carrier spectrums. Carriers can be aggregated in the following three ways:

- **Intra Band Contiguous CA**: It is a rare scenario with given frequency allocations today but can be possible with new spectrum bands like 3.5 GHz. This aggregation is the simplest in terms of hardware implementation. The contiguous channels are of the same size and in the same spectrum band.
- **Intra Band Non- Contiguous CA:** It is expected in countries where spectrum allocation is noncontiguous within a single band, when the middle carriers are loaded with other users, or when network sharing is considered. The non-contiguous channels are of different sizes within the same spectrum bands.
- **Inter Band Non- Contiguous CA:** It is the most realistic scenario since there is no contiguous wide spectrum to achieve the IMT-Advanced peak data rate. The channels are of the same size in different spectrum bands.

Carrier aggregation was introduced in Release 10 as a new feature to combine different component carriers to increase overall bandwidth and throughput. It played an important role in providing operators flexibility for making the best use of the available spectrum. Forty-four frequency bands are available, providing 700 MHz -2.7 GHz theoretically that can be aggregated, but commercial solutions can use up to three component carriers with an achieved downlink speed of up to 450Mbps.

Carrier aggregation technology is critical to allowing the coexistence of 4G and 5G by enabling operators to combine different 4G carriers with 4G or 5G carriers. The LTE-A standard specifies that each component

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[109] Z. Shen, A. Papasakellariou, J. Montojo, D. Gerstenberger and F. Xu, "Overview of 3GPP LTE-Advanced Carrier Aggregation for 4G Wireless Commnications," IEEE Communications Magazine, pp. 122–130, 2012.

[110] "A Global Partnership." Carrier Aggregation Explained, www.3gpp.org/technologies/keywords-acronyms/101-carrier-aggregation-explained.

[111] Jolly Parikh. "Scheduling Schemes For Carrier Aggregation In Lte-Advanced Systems." International Journal of Research in Engineering and Technology, vol. 03, no. 08, 2014, pp. 219–223., doi:10.15623/ijret.2014.0308036.

carrier (CCs) is limited to 20 MHz of bandwidth and aggregation of up to five allows a maximum of 100 MHz of total signal bandwidth, giving a fivefold increase in channel capacity and data speed[112].

3.3.2.2 Scheduling in Carrier Aggregation

This sub-section aims to analyze the scheduling schemes for CA deployments and evaluate the network performance. CA boosts a network's data capacity by combining two or more carriers into a single data channel and enables MNOs to offer higher uplink and downlink data speeds. The scheduling is critical in CA as the decisions are made for each sub-carrier and transmitted through the Scheduling Grants (SG) and Scheduling Assignments (SA), resulting in multiple receptions at the device's Physical Downlink Control Channels (PDCCHs).

3.3.2.3 Self and Cross-Carrier Scheduling

It is "Self-Scheduling" if the SG and SA are transmitted on the same cell as the data and each CC schedules for its carrier, whereas it is Cross-Carrier Scheduling (CCS) when SG and SA are sent on different cells from the data and the Primary Component Cell (PCC) or any specified serving cell schedules the resources for all the CCs. The Downlink Control Information (DCI) is received at another carrier, accommodating the SG[113]. The Carrier Indicator Field (CIF) is essential for aggregating multiple sub-carriers in CCS[114] , and the scheduled device receives multiple PDCCHs. The scheduling information uses higher layer signaling, Radio Resource Control (RRC) messages. Initially, the CIF was limited to 3 bits (5CC aggregation) which now is 5 bits to support 32CCs aggregation. A CIF value of 0 indicates Primary Cell (PC), while another shows the secondary cells (SCs).

3.3.2.4 Dynamic Spectrum Sharing

By enabling LTE and NR to share the same carrier, DSS offers a practical and affordable alternative for facilitating a seamless switch from 4G to 5G. Release 16 has expanded the rate-matching patterns available in NR to enable spectrum sharing when CA is utilized for LTE.

3.3.2.5 Dual Connectivity and Carrier Aggregation

Release 16 reduces latency for setup and activation of CA/DC, leading to improved system capacity and higher data rates. Unlike release 15, where measurement configuration and reporting do not occur until the UE enters the fully connected state, in Release 16, the connection can be resumed after periods of inactivity

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[112] Cao, Yuchen, et al. "Enhancing Carrier Aggregation: Design of BAW Quadplexer With Ultrahigh Cross-Band Isolation." IEEE Microwave Magazine, vol. 21, no. 3, 2020, pp. 101–110., doi:10.1109/mmm.2019.2958723.
[113] Nidhi, A. Mihovska, and R. Prasad, "Overview of 5G new radio and carrier aggregation: 5G and beyond networks," in 2020 23rd International Symposium on Wireless Personal Multimedia Communications (WPMC), 2020, pp. 1–6.
[114] https://www.3gpp.org/specifications/releases/70-release-10

without requiring extensive signaling for configuration and reporting]. According to TR 38.802, the following points are the highlights:

- The maximum number of Carrier Aggregation / Dual Carrier is 16
- The maximum aggregated bandwidth in phase 1 is around 1 GHz (contiguous or non-contiguous)
- Cross-carrier scheduling and joint UCI feedback are supported
- Per-carrier TB mapping is supported

3.3.2.6 Benefits of Carrier Aggregation

- Efficient use of available spectrum and leveraging of the underutilized spectrum.
- It allows MNOs to utilize the fragmented frequency resource efficiently.
- Network carrier load balancing: Enables intelligent and dynamic load balancing with real-time network load data.
- CA helps in the aggregation of frequencies irrespective of spectrum regulations. It can aggregate licensed and unlicensed and perform aggregation in shared spectrum scenarios.
- Increased uplink and downlink data rates with better network performance and higher throughput.
- The expanded coverage allows carriers to scale the networks resulting in enhanced scalability.

3.4 Resource Allocation, Management, and Scheduling Techniques

This sub-section will discuss our results to address the intended research objective and contributions, as illustrated in Figure 3-6.

- Our first discussion will elaborate on our investigation and analysis of RAN slicing functions using MATLAB, where we implemented different RAN slicing configurations to analyze radio resource distribution among slices based on Layer 2 (L2) and Layer 3 (L3) parameters. We performed simulations for two network instances in a multi-service scenario and analyzed network performance with varying demands.
- Following the performance evaluation, we contributed toward our identified problem of RAN slicing in NS deployment. We proposed resource-sharing algorithms that compute radio resources for the individual created slice and adjust the allocated resource depending on achieved throughput estimates and Channel Quality Indicator (CQI) values. We explicitly explain the Resource Blocks (RB) allocation in the 5G NR.
- The second part details the CA techniques and analyzes cross-carrier and multiband scheduling schemes in CA-enabled 5G networks for the Downlink (DL). We considered 5G NR networks and discussed radio resource management and scheduling techniques in detail. We analyzed the performance of two different small cell deployments with the macro cell sites.
- Finally, we present an integrated CA-enabled slicing framework that promotes optimized channel utilization with guaranteed service requirements—for instance, high throughput in eMBB and ultra-low latency with high reliability in uRLLC slices.

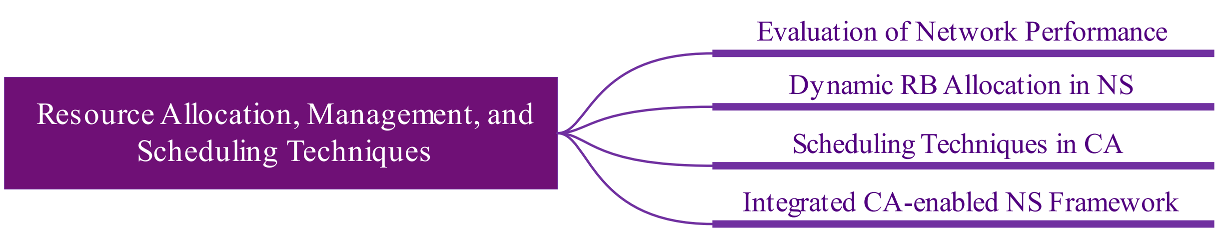

Figure 3-6 Section Structure of the Objective

3.4.1 Objective: Evaluate RAN slicing functions using MATLAB

Our first objective was to investigate and evaluate RAN slicing functions using MATLAB, where we implemented different RAN slicing configurations to analyze radio resource distribution among slices based on L2/L3 parameters and different scheduling algorithms. We performed simulations for two network instances in a multi-service scenario and studied network performance with varying demands.

3.4.1.1 Simulation Tool and Parameter Details

We simulated a multi-RAN slices deployment scenario in MATLAB and computed parameters helping us to understand the network's operation. The simulation scenario consists of a multiservice deployment with an NG-RAN configured with two RAN slices. RAN Slice 1 is for the eMBB services, and RAN Slice 2 is for the Mission Critical (uRLLC).

Network Performance with RAN Slicing

The simulations assumed the gNB at a 100 MHz channel (single cell) with 275 PRBs. We also considered 12 subcarriers at a separation, Δf of 30 kHz. Table 3-1 presents the considered simulation parameters, and Table 3-2 defines the RAN configurations. The Allocation Retention and Priority (ARP) is used to consider the Radio Admission Control (RAC) of each Data Radio Bearer (DRB). For PRB allocations, GBR bearers are given priority over non-GBR.

The Equation 1 defines the relation between GBR, DRB, and ARP to enable slice admission.

Equation 1 Relation between DRB, ARP and GBR

$$\rho_{occ}(ARP_i,s) + \Delta\rho(GFBR_i) \leq \rho_{max}(s)$$

where:

$\rho_{occ}(ARP_i,s)$, average PRB% for the slice s, occupied by the GBR with an ARP $\leq ARP_i$;

$\Delta\rho(GFBR_i)$, estimated PRB% to have bit rate equal to $GFBR_i$;

$\rho_{max}(s)$, admission control limit.

Table 3-1 Simulation Parameters

Parameters	Values
Path loss model	Urban micro-cell model (hexagonal layout)
Shadowing standard deviation	3 dB (LOS) and 4 dB (NLOS)
Base station antenna gain	5 dB
Frequency	3.6 GHz
Transmitted power per PRB	16.6 dBm
Number of PRBs	275
Max spectral efficiency	8.8 b/s/Hz
Slice Session	120 s
Activity factor of Non-GBR services	0.2
Simulation duration	20000 s

Parameter Assumptions/Summary:

- **Scenario**: A multiservice scenario with two RAN slices. (eMBB and uRRLC services).
- **RAN Configurations**:

Table 3-2 RAN Configurations

	Config #1		Config #2		Config #3	
	eMBB	**uRLLC**	**eMBB**	**uRLLC**	**eMBB**	**uRLLC**
L3 (Max PRB admission)	70%		50%	20%	50%	20%
L2 (Min PRB required for Guaranteed PS)	-	-	-	-	70%	30%
L1 Number of PRBs	275					
L1 Subcarrier Separation	30 kHz					

- **Constants**:
  - Allocation and Slicing algorithm
  - Scenario parameters (cell radio, number of cells, number of RBs, number of slices)
  - Propagation model parameters (frequency)
  - Parameter for the scheduling of Non-GBR UEs (GBR: Guaranteed BitRate)
  - Traffic and Admission parameters
- **UE check session**
  - Check session starts → Admission criteria (Pass)→Generate the new UE
  - Check session starts → Admission criteria (Fail)→Blocking
  - If the process is ended→ Remove UE from the list.
- **Allocation Session Checks**
  - The average number of RBs, estimated BER, and utilization for each slice
  - Estimate the bit rate per RB achieved in the cell
  - Average assigned bit rate per tenant
  - The congestion status per sliceSimulation Parameters

Simulation Results and Discussions

All the simulations are executed for the three defined configurations, as illustrated in Table 3-2 for the services as amrked in Table 3-3. ARP defines the rejection of new sessions in low resource scenarios where the Guaranteed Flow Bit Rate (GFBR) specifies the GBR service session.

Table 3-3 GBR and non-GBR Services

Slice Type	Service	Type	ARP	GFBR
eMBB	Premium HD Video	GBR	2	10 Mbps
	Premium Data	Non-GBR	2	-
	Basic Video	GBR	3	1 Mbps
	Basic Data	Non-GBR	3	-
uRLLC	Critical Video	GBR	2	2 Mbps
	Critical Data	Non-GBR	3	-
	PTT	GBR	1	10 Kbps

GBR Services:

The simulation results were obtained for Premium HD, Basic, and critical Video for eMBB slice. Figure 3-8, Figure 3-9, and Figure 3-10 shows that the blocking rate of these services increases with the slice load. We observed a higher blocking rate for the Basic Video because of its lower ARP value, increasing its priority levels.

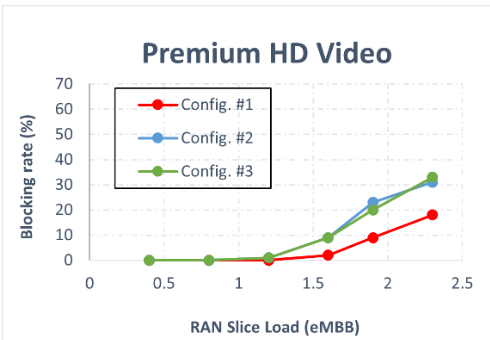

Figure 3-7 Rejection/Blocking rate variations for Premium HD Video for eMBB Services

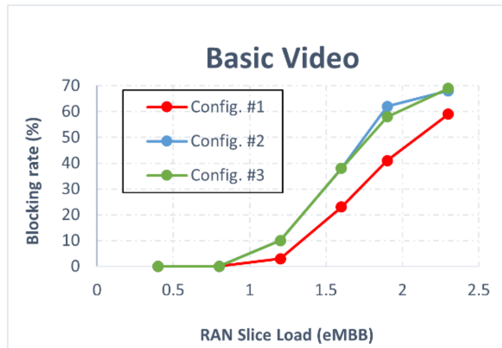

Figure 3-8 Rejection/Blocking rate variations for Basic Video for eMBB Services

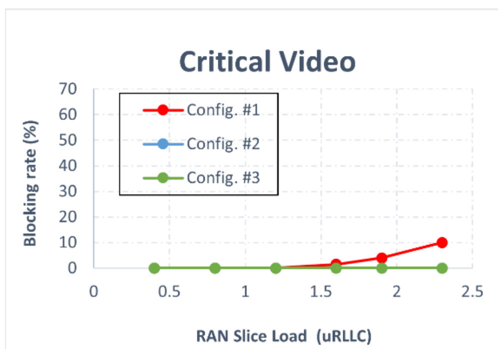

Figure 3-9 Rejection/Blocking rate variations for Critical Video for uRLLC Services

The admission control of L3 affects the blocking rate. Thus, config #2 and config #3 do not reflect a significant difference. For the Critical Video in the uRLLC slice in config #2 and #3, the blocking rate is negligible since the configured 20% is sufficient to provide services to both critical video and PTT. Since config #1 defines the total admission control limit of 70% irrespective of the slice type, config #2 and #3 (eMBB slice) are limited up to 50%. Thus it allows the Premium HD and Basic Videos to consume more than config #2 and #3. The blocking rate is always 0% based on priority for critical PTT services. In config #3 for the uRLLC slice, we observed a constant throughput which changes with config #1 and #2, whereas for the other two configurations, the throughput decreases as the load increases because the available PRBs are shared among the non-GBR services of the two slices.

Non-GBR Services:

The non-GBR services use the used PRBs after The GBR services, without any admission control criterion. It is significant from Figure 3-10, Figure 3-11, and Figure 3-12 that with the increase in load, the throughput per DRB decreases in all three configurations. GBR sessions are directly proportional to the increase in load. The throughput of Premium data is higher than the basic data for eMBB slices, depending on the priority. Since both configurations (config #1 and #2 for eMBB slice) do not use L2, their throughput reflects the same values. In config #3 for the uRLLC slice, the throughput increases to meet the minimum criterion of 70% PRBs.

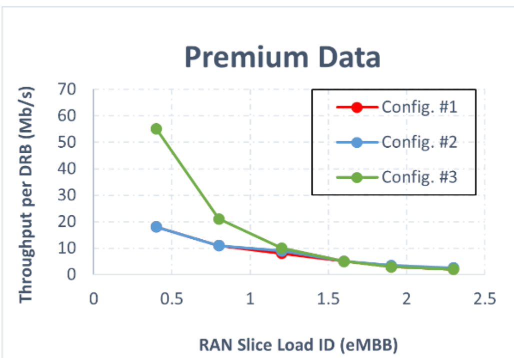

Figure 3-10 Average throughputs per DRB of Premium Data for eMBB Services

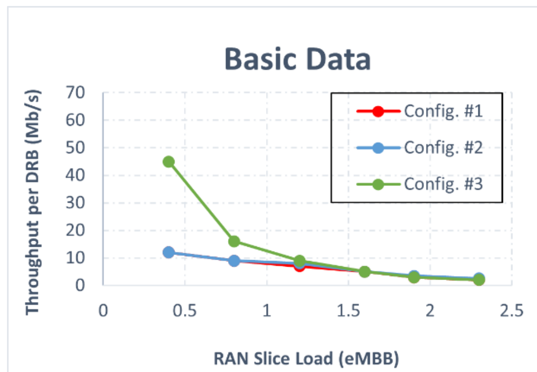

Figure 3-11 Average throughputs per DRB of Basic Data for eMBB Services

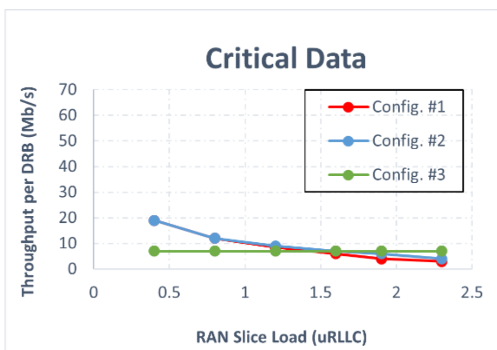

Figure 3-12 Average throughputs per DRB of Critical Data for uRLLC Services

Discussions

From our observation and analysis, we can conclude that the three configurations show almost the same pattern for the blocking rate for the eMBB slice. The blocking rate increases with an increase in the priority and a decrease in the PRBs assignment for eMBB slices. Also, the critical video in uRLLC services requires more sessions, increasing the blocking rate. We also observed an increase in the throughput (Premium

Data), where the decrease is recorded for the Basic and Critical Data throughput. The premium data has more sessions than Critical, thus the PRB distribution results into more assignments.

In addition, The performance for the critical video (uRLLC) increases with the increase in the sessions and priority.

3.4.2 Objective: Dynamic slicing of RAN Resources

Network slicing enabled the Infrastructure/Slice Providers (SP) to offer resources to the customers as a service for a given cost to maximize the resource usage by accepting slice requests. The customer requests a network slice from SP to get customized services. There is a need for a mechanism/scheduling scheme in which SPs can entertain the requests, as the SPs are subject to limited resources. Authors from[115] and [116] introduced a two-level scheduler to share the Physical Radio Blocks (pRBs) among slices by abstracting pRBs and using two scheduler levels. Two-level schedulers operation is as follows:

- The first level is slice-specific, allowing each slice to use its internal scheduler and schedule each UE with Virtual Resource Blocks (vRB).
- The second level considers the slice-specific (virtual) resource assignment and maps it to actual pRBs. It controls the number of pRBs (NpRBs) assigned to each slice and indicates the maximum NpRB to dedicate to each slice after executing an intra-slice physical resource sharing algorithm.

The aim is to compute the radio resources required in each slice. The resources are periodically adjusted based on the current Channel Quality Indicator (CQI) estimates from the users of the different slices. Assumptions are as follows:

- 5G network which including a SO, to initiate and configure slice resources based on the use case types (eMBB, mMTC or uRLLC) and a set of gNBs deployed covering an area.
- The SO communicates with the gNBs using a protocol that allows remote interaction and management.
- The gNB management process consists of
    - RAN information (CQI);
    - gNB configuration.
- A set of UEs is served by/associated with a network slice, spanning a set of gNBs (i.e., different physical locations).

[115] A. Ksentini, P. A. Frangoudis, P. Amogh, and N. Nikaein, “Providing low latency guarantees for slicing-ready 5G systems via two-level MAC scheduling,” IEEE Network, vol. 32, no. 6, pp. 116–123, 2018.
[116] A. Ksentini and N. Nikaein, “Toward enforcing network slicing on RAN: Flexibility and resources abstraction,” IEEE Communications Magazine, vol. 55, no. 6, pp. 102–108, 2017.

- There are three types of Slices: eMBB and URLLC Slices
- The SO receives the request to instantiate a slice. The Slice request includes
    - Slice type;
    - Duration;
    - Requirements like data rate, application, or latency;
    - List of associated UEs.

We simulated on MATLAB the two-level scheduler for eMBB and uRLLC slices for a varying number of users in each slice, keeping the other constant to observe CQI variations. The goal is to improve network performance and introduce flexibility and optimization of the network resources by accurately and dynamically provisioning the activated network slices with the appropriate resources to meet their diverse requirements. The aim is to have flexibility in RAN resource allocation concerning slicing.

3.4.2.1 Simulation Tool and Parameter Details

Slice Definition and Requirements

For each created slice instance, i

- eMBB Slice Requirements - High Data Rate

$$N_{pRB_{max}}(i) * d_{pRB} = N_{users}(i) * d_{App/user}$$

NpRBmax(i) ∗ dpRB = Nusers(i) ∗ dApp/user

- URLLC Slice Requirements: Ultra-Low Latency

$$\mu = \frac{N_{pRB} * d_{pRB}}{\text{Average packet size}}$$

where,

NpRBmax(i) : Required pRBs for each gNB;
dApp/user : Required Data rate per slice;
N_{users} : the number of active users;
dpRB : maximum data rate provided by one pRB;
pRB : Physical Radio Blocks.
Ideal channel conditions correspond to the maximum CQI = 15.

Simulation Results and Discussions

The performance has been evaluated in Matlab as an extension to the referenced work[115]. We modified the SO and considered eMBB and URLLC slice. We defined each slice with the required data rate, number of users and latency in URLLC slice. The simulations were carried out at varying CQI level, i.e. medium (7) to high (13). The eMBB slice users were fixed to 5 and varied users (up to 20 for medium CQI and up to 30 for high CQI values) in URLLC slice. In the view charts, lat stands for latency.

Figure 3-13 and Figure 3-14 present the throughput for the uRLLC slice at varying CQI values. Beyond the threshold, slice performance degrades (more in case of high CQI) but it guarantees the required bandwidth until 25 users.

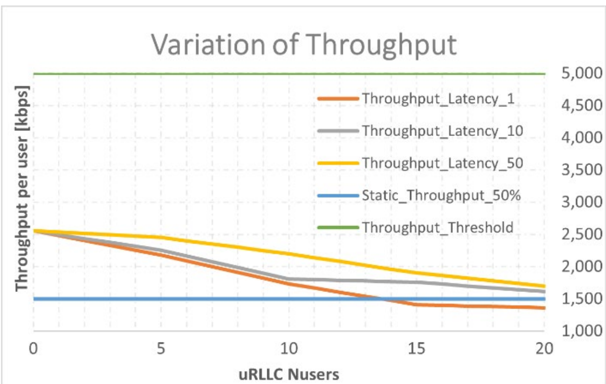

Figure 3-13 Variation of throughput per user as a function of the number of users with Medium CQI value

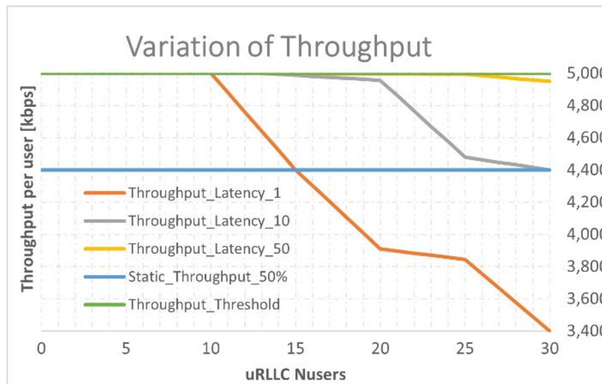

Figure 3-14 Variation of throughput per user as a function of the number of users (with High CQI value).

Figure 3-15 and Figure 3-16 show the experienced latency as a function of the number of uRLLC users for varying CQI values from 7 to 13. We considered different maximum values for latency, i.e., 1 ms, 10 ms and 50 ms. We observed that the max. latency value was near about maintained for both the value of CQI. High CQI allows higher NpRB compared with the medium CQI by allowing more users. We also observed that fixed number of PRBs cannot guarantee the very low latency requirement.

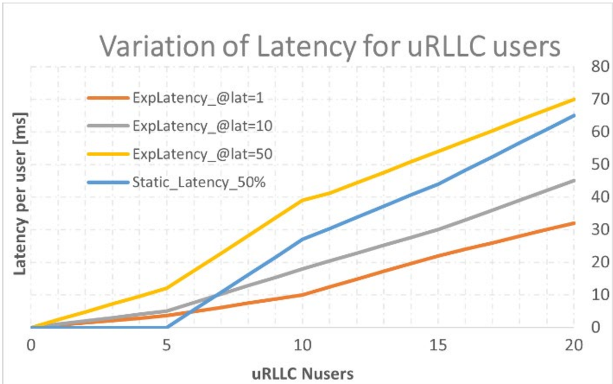

Figure 3-15 Variation of latency as a function of the number of users (with Medium CQI value).

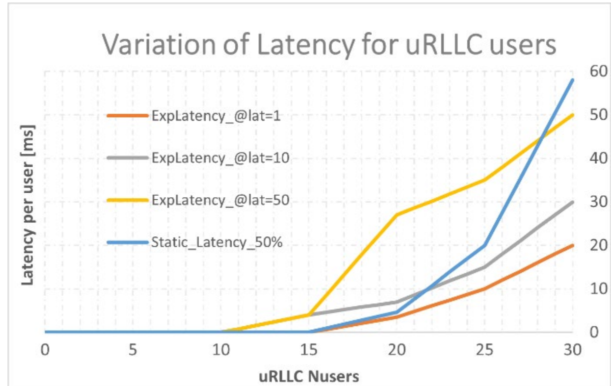

Figure 3-16 Variation of latency as a function of the number of users (with High CQI value).

The results in Figure 3-17 and Figure 3-18 show the estimated NpRB and used by the gNBs for the URLLC slices with varied CQI values. We observed that the estimated NpRB is similar to the one communicated to the gNB until reaching the identified thresholds as shown in Figure 3-10 and Figure 3-11. The communicated NpRB to gNB is lower than the estimated value on increasing the threshold values.

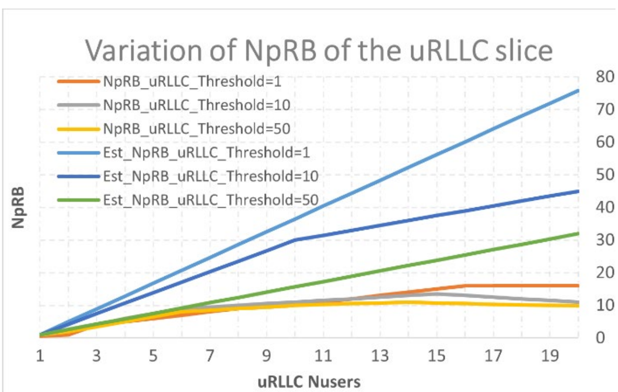

Figure 3-17 Variation of NpRB of the URLLC slice as a function of the number of users.

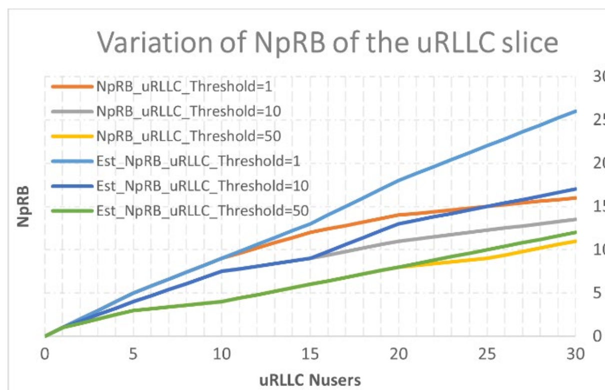

Figure 3-18 Variation of NpRB of the URLLC slice as a function of the number of users.

The results in Figure 3-19 and Figure 3-20 show the estimated NpRB per user within the gNBs for eMBB slices with varied CQI values. We observed that the estimated NpRB could not be satisfied in case of medium channel quality and required NpRB is higher. Lower dpRB is expected at higher CQI values.

The results show that our proposed algorithm to estimate the required NpRB for eMBB and URLLC slices is accurate and permits sharing of the RAN resources among slices. Hence, the practical feasibility of our proposed solution is verified. We observed that when there is saturation, a reduction of the throughput and NpRBs per user, corresponding to an inflection in the curves for the total NpRBS.

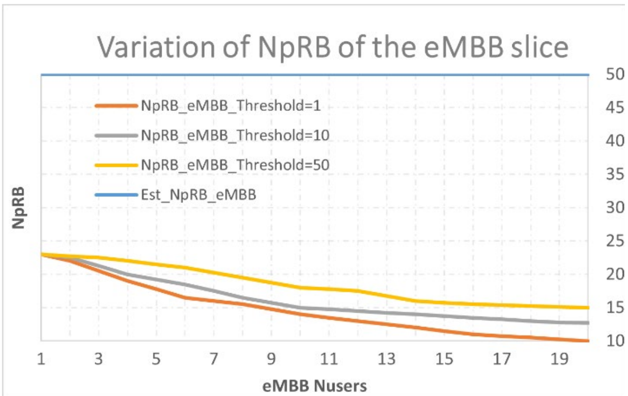

Figure 3-19 NpRB per user of the eMBB slice as a function of the number of users.

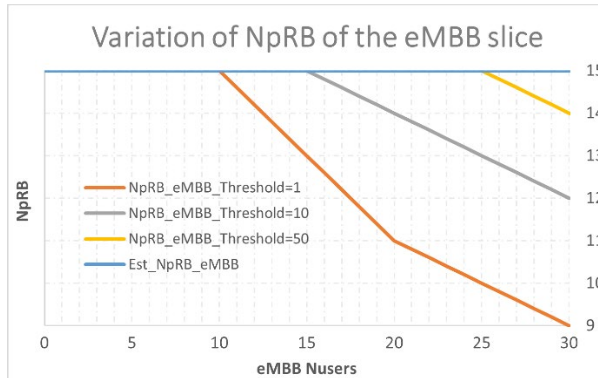

Figure 3-20 NpRB per user of the eMBB slice as a function of the number of users.

Discussions

In the above simulations, we proposed slice creation and allocation of resource blocks while isolating the slices for eMBB and URLLC by using the two-level scheduling introduced in the referenced work. We have introduced algorithms to estimate the required RAN resources for the eMBB and URLLC slices while evaluating the performance under varying CQI values at the SO level. Heterogeneous Networks (HetNets) optimization is an open research area concerning Network Slicing. Also, 3GPP's functional splits[117] have huge potentials to be implemented with slicing to manage the network function virtualization and softwarization of RAN resources. Besides, there is a need to develop novel meta-learning models for ML-enabled network slicing, an open research area.

The main foreseen challenge in 5G New Radio dynamic resource allocation is the associated overhead when we extract the information from the base station (UE provides CQI to the base stations) to the SO. Thus, to eliminate/ minimize the communication overhead, we will simultaneously propose the following steps:

- A machine learning approach to infer the stability of UE channel conditions;
- Propose a predictive scheme to efficiently reduce the dependency on the network's configuration to address the various service and demands;

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[117] GSMA. (2021) E2E Network Slicing Architecture Version 1.0. [Online]. Available: https://www.gsma.com/newsroom/wpcontent/uploads//NG.127-v1.0-2.pdf

- Admission Control Policy/ Decision based on Q-Learning and Regret Matching for the SP to manage the slice requests (we will validate the mechanism concerning the SP serving the network requests).

Further, we obtained the results to illustrate our proposed algorithm for estimating the number of physical resource blocks by the eMBB and URLLC slices. We successfully demonstrated slice creation and resource allocation. Our future work will enhance the algorithm by employing deep reinforcement learning and intelligence in resource-sharing mechanisms.

3.4.3 Objective: Integrated NS in CA-Enabled Scenario

The technical requirements for 5G and beyond networks need to support the exponential growth in connected devices and evolving use cases in the Ultra-Reliable Low-Latency Communication (uRLLC) and improved Mobile Broadband (eMBB) scenarios. Acknowledging the potential in Network Slicing and Carrier Aggregation in offering low latency, flexibility, and multi-gigabit per second wireless communications and network adaptability to any specific use case setting. We propose to employ Carrier Aggregation in the RAN slicing framework. We proposed a cross-carrier scheduling algorithm to allocate and manage radio resources, specifically in eMBB (throughput) and uRLLC (ultra-low latency) services. The proposed algorithm maximizes resource utilization by dynamically controlling the packet dispatch rate and QoS. We compared the result for the same scenarios, with and without CA.

We lack enough literature to support the integration of CA and NS to cater high demands of heterogeneous traffic. Taking into account our contributions to slice creation and resource allocation followed by cross-carrier scheduling in CA, we proposed to have an integrated algorithm that can allocate the network instances resources employing aggregated frequencies. We aim to have high QoS, throughput, and low latency. CA is used to distribute the carriers with uRLLC and eMBB services. These carriers can act as slices themselves. We incorporated frequency diversity, a technique allowing the same transmission at different frequencies to provide the carrier per their requirements. For instance, a network slice with high-reliability needs can utilize a low-band spectrum to reduce path loss and increase reliability.

3.4.3.1 Simulation and Network Parameters

- Densely populated Urban Scenario of Cell Radius 200m;
- Single serving gNB deployed at the cell center;
- User N_u, with a speed of 1 - 10 m/s
- Target Applications: eMBB and uRLLC Services. The rest is the list in Table 3-1.

Table 3-4 Simulation Parameters

Parameter	Value
Total System Bandwidth B	500 MHz
CC0 center frequency f_0	28 GHz
CC1 center frequency f_1	10 GHz
eMBB primary CC	CC0
uRLLC primary CC	CC1
RLC Mode	Yes
BSR timer	1 ms
cc_{ratio}	0.5
Number of uRLLC UEs	10
Number of eMBB UEs	10
eMBB source rate	[80; 100; 120;140; 160] Mbit/s
URLLC source rate	[1; 1.5; 2] Mbit/s
Radius r	200 m
UE speed	[1; 10] m/s
R_{uRLLC}	1 packet
R_{eMBB}	0

3.4.3.2 Network Configurations

Examining the average end-to-end delay, aggregated throughput, and packet loss ratio attained at the application layer for both the eMBB and URLLC data flows. We assessed the performance of the proposed framework. Our proposal was put to the test and evaluated under two conditions;

- Without CA and Slicing; (single carrier with the total system bandwidth *B*.)
- With CA; (NS + CA, but without the adaptive cross-carrier scheduling,)

3.4.3.3 Results and Discussion

Figure 3-21, Figure 3-22, and Figure 3-23 show the result of simulations performed for different values of eMBB source rate with the uRLLC data rate fixed at 1 Mbps. These simulations give us the per-user performance metrics.

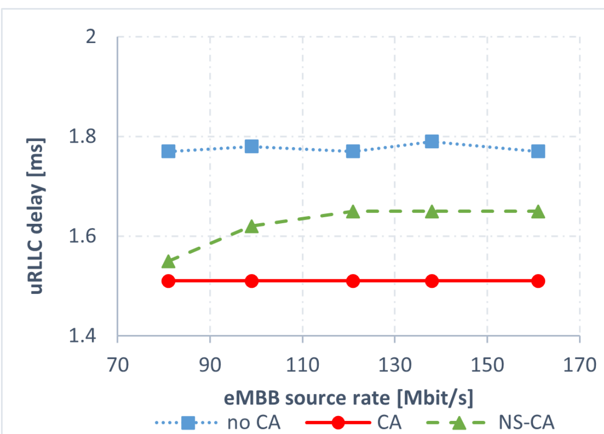

Figure 3-21 Per user Performance for Average uRLLC Delay

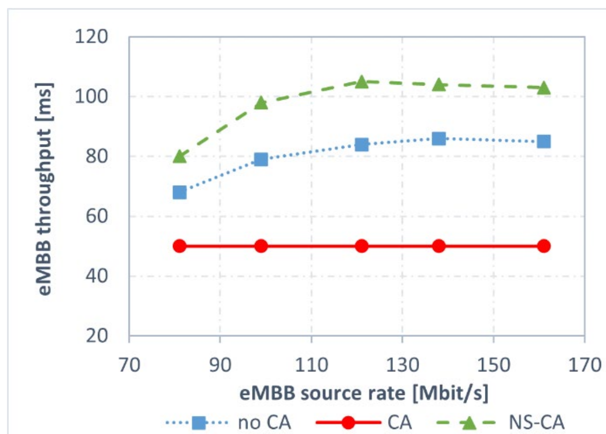

Figure 3-22 Per user Performance for Average eMBB Throughput

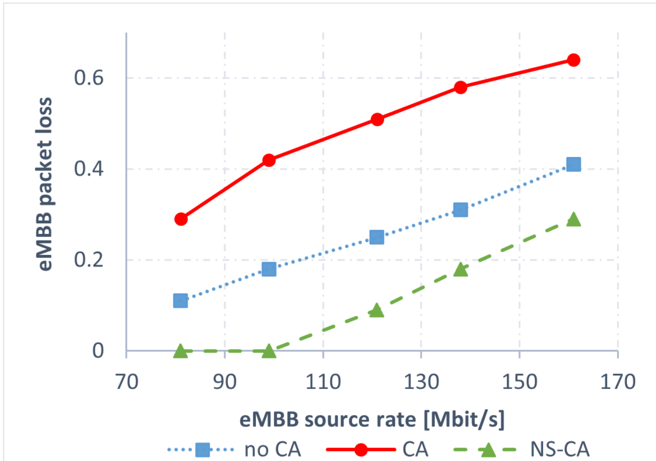

Figure 3-23 Per user Performance for Average eMBB Packet Loss

We compare the performance achieved by the three strategies, namely (i) without CA, (ii) With CA and (iii) With CA and NS. We found that all three simulations guarantee a reliable URLLC traffic delivery. Introducing RAN slicing through carrier aggregation improves the delay. The lowest delay is achieved when the two services are isolated because of independent uRLLC transmissions. The presence of eMBB doesn't affect the delay. We also observed that low-frequency bands guarantee higher reliability. Figure 3-22 exhibits lower throughput and packet loss than Figure 3-23.

Figure 3-24, Figure 3-25, and Figure 3-26 show the simulations for per-user performance at a fixed eMBB data rate of 100 Mbps and varying uRLLC source rate.

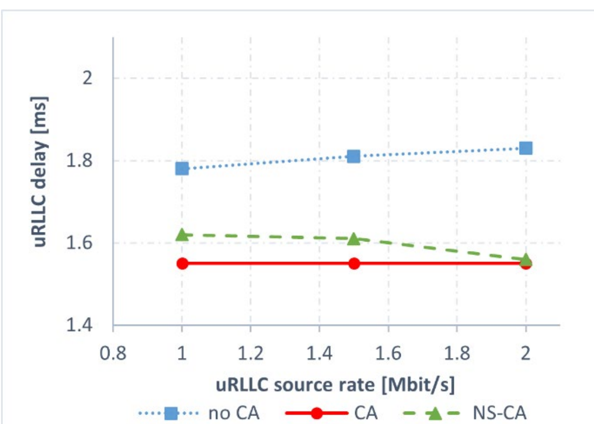

Figure 3-24 Per user Performance for Average uRLLC Delay

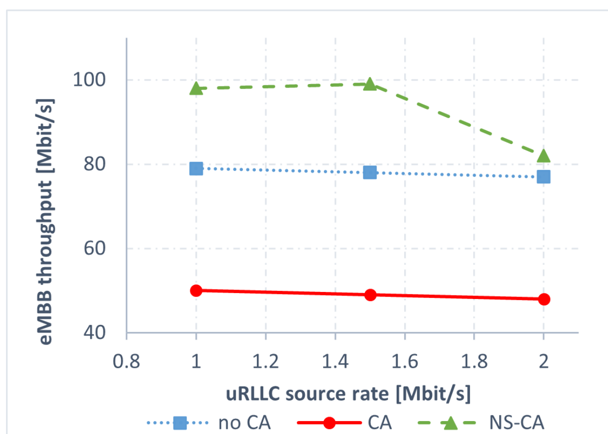

Figure 3-25 Per user Performance for Average eMBB Throughput

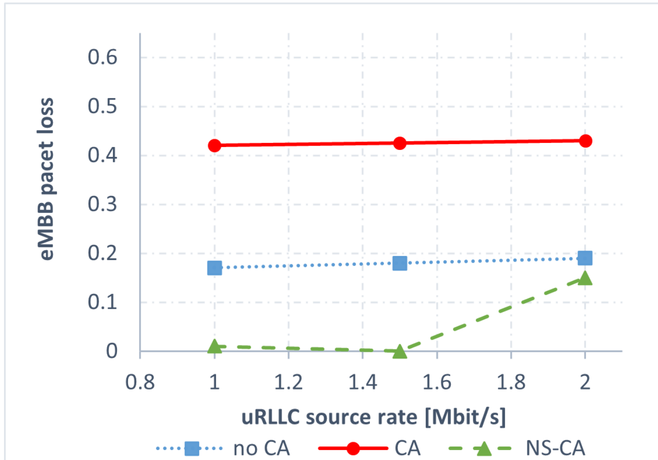

Figure 3-26 Per-user performance metrics for Average eMBB Packet Loss Ratio

We observed that the combined NS and CA scheme shows better efficiency than the other two states for different uRLLC source data rates. We found that the proposed solution exhibits a higher throughput, lower packet loss for the eMBB service, and lower latency. The gain in the proposed solution is inversely proportional to the uRLLC rate. Thus, it decreases with the increase in uRLLC source rates.

3.4.3.4 Key Contributions

- Employing CA mechanism to achieve network slicing at the RAN. Implemented slicing through CA.
  - Advantages
    - Facilitates multi-CC aggregation, which allows telecom operators to use chunks of the spectrum with more flexibility.
    - CA enables slice isolation by incorporating different carriers per slice.
    - This mechanism allocates carriers with the best use capacity, i.e., e low-bands are used to exhibit services with low path loss tolerance and high bandwidth.

4 Industrial and Business Impact

This section will map our contributions emphasizing the industrial application of our research. We will map the industrial requirements to our findings and present technical and business aspects of network slicing and carrier aggregation. We have identified and presented the need for standardization towards 6G, NS, and AI/ML. Slicing and CA, in conjunction with VNFs, open up many opportunities for the service providers. CSPs can provide as much capacity for specialized services as is necessary to meet the needs of paying consumers based on generic wireless infrastructure and general-purpose computation and storage resources. Even complex and specialized customer environments can be quickly spun up by utilizing built-in capacity slicing tools and all virtual service platforms. These techniques reduce costs as they don't require dedicated hardware. Additionally, since the capacity to constantly try new ideas enables the best use of resources, an increased return on investment is likely.

The telecom operators must choose where they create their technology and where they want to lease the use of equipment built and maintained by other providers—including their rivals—due to the high expense of building telecom infrastructure to service a particular market. Carrier aggregation, a term used in the telecom industry to describe leasing infrastructure to enable local network access, is a crucial part of the business models for both carriers and solution providers.

Similarly, Slicing in conjunction with VNFs can provide the service providers with an enormous capacity for user-specific services. Presently, the wireless infrastructure is based on a generic computation and storage model that must meet the demands of the paying consumers.

For instance, solution providers can employ CA to create a regional or national telecom infrastructure network and deploy NS to meet user-specific demands. The provider can then leverage suppliers to lease access on a scale ranging from neighborhood marketplaces and regions to specific buildings. On the other hand, carriers rely on aggregators as a demand generator to justify enlarging their service footprint and boosting their market share in specific geographic areas.

4.1 Objective and Contributions

The contributions will be mapped to the research objective – "Value Proposition and Industrial Impact." which intends to reflect the transition of technology from academia to industry. We want to present our research's Technical Readiness Level (TRL). We will integrate our research findings into industrial requirements for new business opportunities. Our contributions from the research papers are illustrated in Figure 4-1, which maps the research objectives and publications with the main contributions.

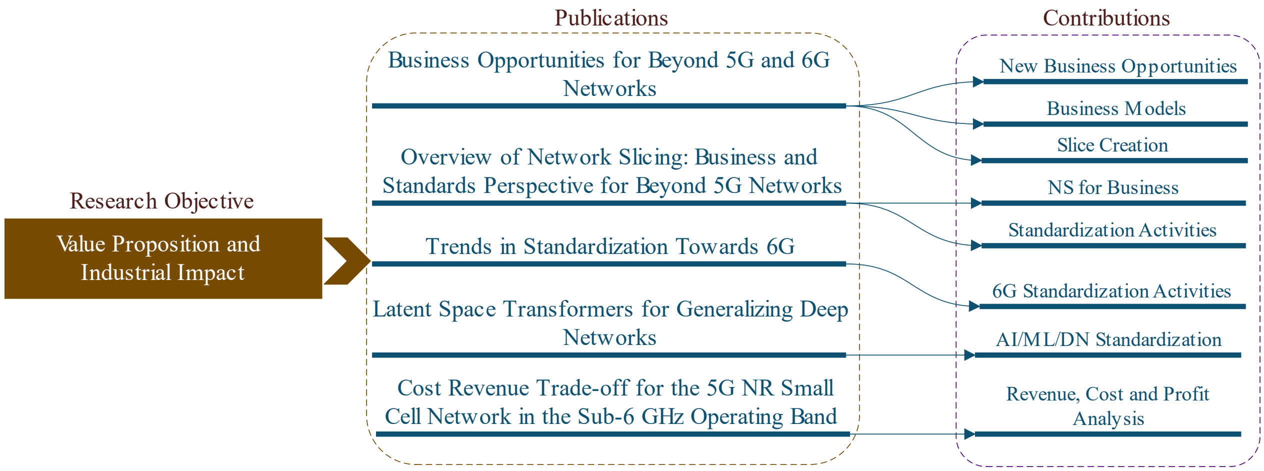

Figure 4-1 Objective Mapping to the Publications

Figure 4-2 shows the research question we addressed in this section to emphasize the value this thesis can bring to the industry.

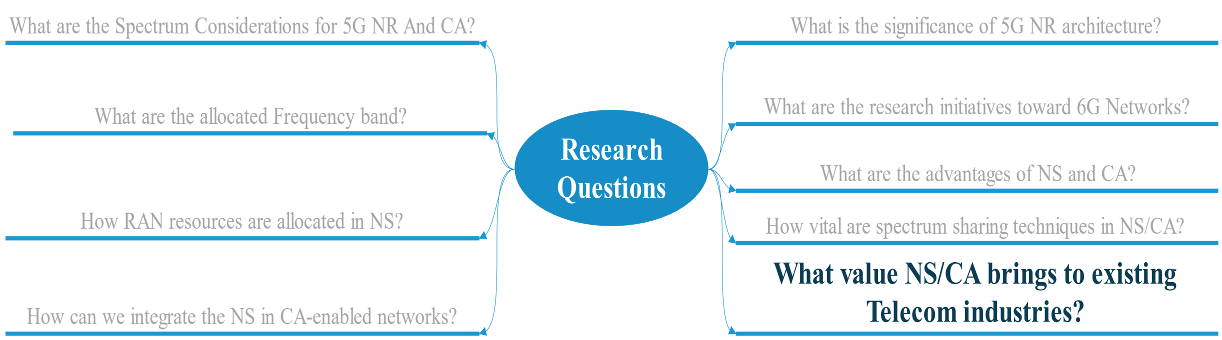

Figure 4-2 Addressed Research Question

4.2 Summary of Publications

Business Opportunities for Beyond 5G and 6G Networks
Conference Paper: (Submitted) Nidhi., A. Mihovska, A. Kumar and R. Prasad, "Business Opportunities for Beyond 5G and 6G Networks" 25th International Symposium on Wireless Personal Multimedia Communications (WPMC) 2022.

In this work, we illustrated many facets of the technology-related business model and thoroughly explained network requirements beyond 5G and 6G, along with possible use cases and applications. We incorporated NS in the business model and mapped the use cases to different potential business opportunities. We also described why Network slicing is an essential enabler for future networks and its importance for creating new businesses. We stressed the multi-business model approach to defining the business model concerning Network slicing and other applications. Thus, this paper will address the business value creation through technology for the beyond 5G and 6G networks.

Overview of Network Slicing: Business and Standards Perspective for Beyond 5G Networks
Conference Paper: B. Khan, Nidhi, A. Mihovska, R. Prasad and F. J. Velez, "Overview of Network Slicing: Business and Standards Perspective for Beyond 5G Networks," 2021 IEEE Conference on Standards for Communications and Networking (CSCN), 2021, pp. 142-147, doi: 10.1109/CSCN53733.2021.9686125.

In this paper, we presented NS as a critical technique that can help service providers to expand their service catalog with better QoE. It provides detailed literature on the slicing framework and insights into the ongoing and required standardization activities.

Trends in Standardization Towards 6G
Journal Article: Nidhi, Khan, B., Mihovska, A., Prasad, R., & Velez, F. J. (2021). Trends in Standardization Towards 6G. Journal of ICT Standardization, 327-348.

This study presents the need for standards to attain a fully functional and interoperable 6G era and gives the vision and requirements for beyond 5G (B5G) networks. We highlighted vital B5G network supporting technologies, initiatives, and standardization efforts addressing difficulties with spectrum use are covered in detail.

Latent Space Transformers for Generalizing Deep Networks

Conference Paper: H. Farkhari et al., "Latent Space Transformers for Generalizing Deep Networks," 2021 IEEE Conference on Standards for Communications and Networking (CSCN), 2021, pp. 130-135, doi: 10.1109/CSCN53733.2021.9686099.

This paper was published at IEEE Conference on Standards for Communications and Networking (CSCN), 2021, proposing a brand-new idea for Deep Network (DN) interoperability. Our contribution to this publication is to the general standardization of deep neural networks and artificial intelligence. Finally, we provide various 5G use cases that support the suggested paradigm.

Cost Revenue Trade-off for the 5G NR Small Cell Network in the Sub-6 GHz Operating Band

Conference Paper: (Submitted) Khan, B., Nidhi., Rui Paulo, A. Mihovska and Fernando J. Velez, " B Cost Revenue Trade-off for the 5G NR Small Cell Network in the Sub-6 GHz Operating Band" 25th International Symposium on Wireless Personal Multimedia Communications (WPMC) 2022.

This paper provided a study showing opportunities in industries incorporating 5G RAN dis-aggregation. We offered a cost-revenue-profit trade-off implementing small cells with splits 6 and 7 (7.2) of 3GPP in sub-6 GHz networks. We discussed in detail the revenue-profit model for deployments with and without splitting, assuming cost parameters and traffic costs.

4.3 Introduction

5G and future networks must offer a future technology-proof platform and enable the expansion of current business models in commercial operations. It should also make it possible to develop new business models without affecting network infrastructure. Operators should be able to adapt and economically enable new business models without having an architectural impact. Third-party service providers should be able to offer their services using 5G networks with very little lead time and based on shared SLAs. Operators will also assist vertical industries and help to mobilize the industrial processes. Partnerships will be built on various layers to integrate partners' services into the 5G system, from sharing infrastructure to providing specific network capabilities as an end-to-end service.

Over the last decade, Meta[118] has invested billions in partnerships with telecom companies, OEMs, policymakers, and the wider industry to improve connectivity worldwide. From ongoing collaborative efforts such as the Telecom Infra Project (TIP)[119], country-specific and international spectrum advocacy, and work with the Wi-Fi Alliance; to technologies like Magma[120], an open-source software platform that helps operators deploy mobile networks. The move to the Metaverse is an unprecedented opportunity for the connectivity industry. It must be built on a foundation of openness and interoperability and be accessible to as many people as possible. The Meta Connectivity team makes the bleeding edge technologies that will allow our subsequent billion users to access Metaverse.

Our integrated NS in CA-enabled networks aims to provide an adaptable and flexible platform to cater to user-specific demands and services with existing network infrastructures. We exhibited the advantages of both NS and CA from both user and service provider ends. Our objectives are to provide an adequate solution enabling concepts like Metaverse to become a reality via significant advancements in network latency, symmetrical bandwidth, and overall speed of networks.

4.4 Industrial Impact of Intended Technology

We proposed a novel resource-sharing algorithm to compute the necessary radio resources based on the CQI values to meet the required throughput. We also evaluated CA component carrier selection schemes and scheduling algorithms in 5G NR and small cell deployments. Finally, we proposed an NS framework in CA-enabled networks that can integrate NS and CA in a RAN slicing framework by employing a cross-carrier scheduling algorithm to best use carriers to achieve high throughput for eMBB and uRLLC services.

[118] https://s21.q4cdn.com/399680738/files/doc_financials/2021/q4/FB-12.31.2021-Exhibit-99.1-Final.pdf
[119] https://telecominfraproject.com/
[120] https://magmacore.org/

The resources are dynamically allocated to the demanded services. The other relevant contributions achieved are as follows:

- Performance evaluation of RAN slicing functions using MATLAB, where we implemented different RAN slicing configurations to analyze radio resource distribution among slices based on L2/L3 parameters and different scheduling algorithms.
- A novel resource-sharing algorithm is proposed to compute the necessary radio resources while deploying network slices. The resource allocations were based on the Channel Quality Indicator (CQI) values to meet the required throughput.

4.4.1 Mapping of thesis Outcome to Industry

We proposed that Solution providers have more freedom in designing their network infrastructure, employing slicing and carrier aggregation. Suppliers might strategically decide where and when to develop their own technology to serve clients and when they would be better off renting access from other providers. CA allows leasing the network as a cost-efficient technique instead of infrastructure development. The CSPs can create sizable networks with high customer availability by fusing their infrastructure with services gathered from various carriers.

Key Contribution:

- Employing CA mechanism to achieve network slicing at the RAN. Implemented slicing through CA.
    - Advantages
        - Facilitates multi-CC aggregation, which allows **telecom operators** to use chunks of the spectrum with more flexibility.
        - CA enables slice isolation by incorporating different carriers per slice.
        - This mechanism allocates carriers with the best use capacity, i.e., e low-bands are used to exhibit services with low path loss tolerance and high bandwidth.

CA and NS can also serve larger commercial customers demanding vast infrastructure by making the existing resources available. Thus, the service providers can offer significantly securer telecom service contracts, particularly at numerous locations. Before investing in their last-mile infrastructure, solution providers can use CA-NS to test out new markets. Their success in attracting and keeping clients can predict how successful they will be in boosting revenues and market share.

Telecom services will become more user-friendly for consumers and end-users. Instead of dealing with several bills and points of contact during a single service contract, aggregation enables customers to manage all of their telecom services through a single account and single customer support. The advantage of having access to several service technology options is also enjoyed by customers. In addition to boosting availability at any place and support for a more extensive range of telecom needs, this gives their service more flexibility. For instance, CA and NS can facilitate greater access and performance when employing cloud-based applications and managed services.

4.5 Industrial Requirements

Current job requirements in the telecom sector reflect the vast demand and void created to fill the gap between academia and industry. The success of any technology depends on its implementation and practical usage. We investigated NS and CA and proposed an integrated platform to support NS in CA-enabled networks. Some of the key industrial requirements are mapped in Figure 4-3.

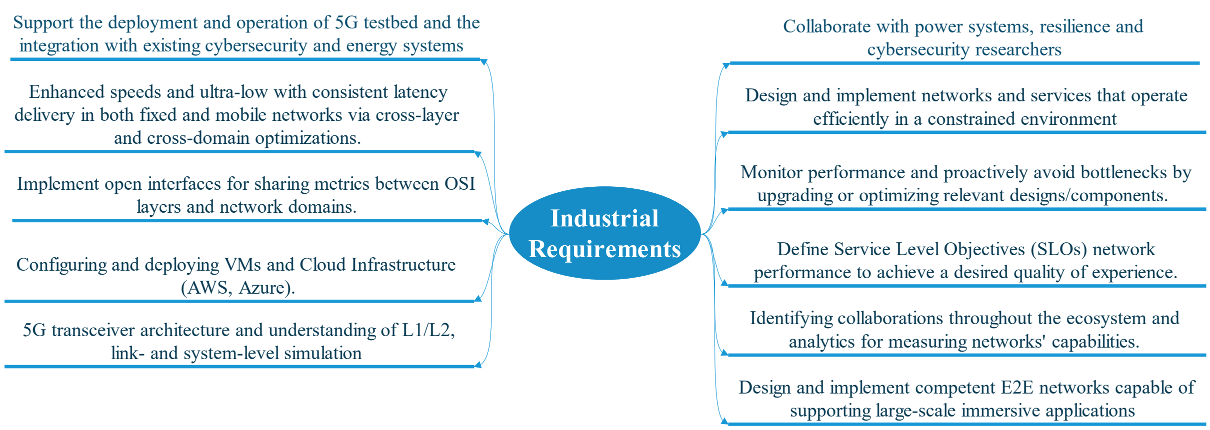

Figure 4-3 Industrial Requirements for deploying 5G and beyond Networks

4.6 Business Opportunities

The development of 6G technology needs a holistic and multidimensional approach to integrate technologies and support businesses to flourish. 6G defines an integrated network with built-in control systems that execute technologies for societal, environmental, and economic benefit. 6G systems are advocating more towards a sustainable solution. Mobile Network Operators (MNOs) intend to create new businesses and business models for the advancing technologies. A 5G and beyond network will have a user-centric approach toward business models and aim to solve the issues of the customers.

Changes in the Telecom landscape are evident and reflected through the value and supply chain revolution. The deployment of 5G is eminent among public networks and is being embraced in diversified industrial and consumer use cases. 6G development will drive the supply chain transformation to allow new verticals to establish. It is essential to focus on the business value creation in addition to the customers' needs and challenges. 6G will redefine the design, delivery, and consumption of network resources and services, irrespective of the verticals and applications. The recent advancements have resulted in the multidimensional integration of industrial verticals. There are enormous opportunities for businesses to grow and integrate cutting-edge technologies. Incorporating technology in business to provide solutions intends to bring added value to customers and industries. NS enables affordable customization that benefits the service providers with new income opportunities and flexibility in the service catalog without additional hardware costs.

Concerning performance and security management, enterprises and smaller companies find network segmentation and SD-WAN technologies appealing options for slicing. Slicing boosts the usefulness of a wireless WAN (WWAN)[121] and a corporate wireless LAN (WLAN) as 5G networks continue to develop and spread. Some of the essential use cases and applications[122] with substantial business potentials beyond 5G and 6G networks are illustrated in Figure 4-4[123].

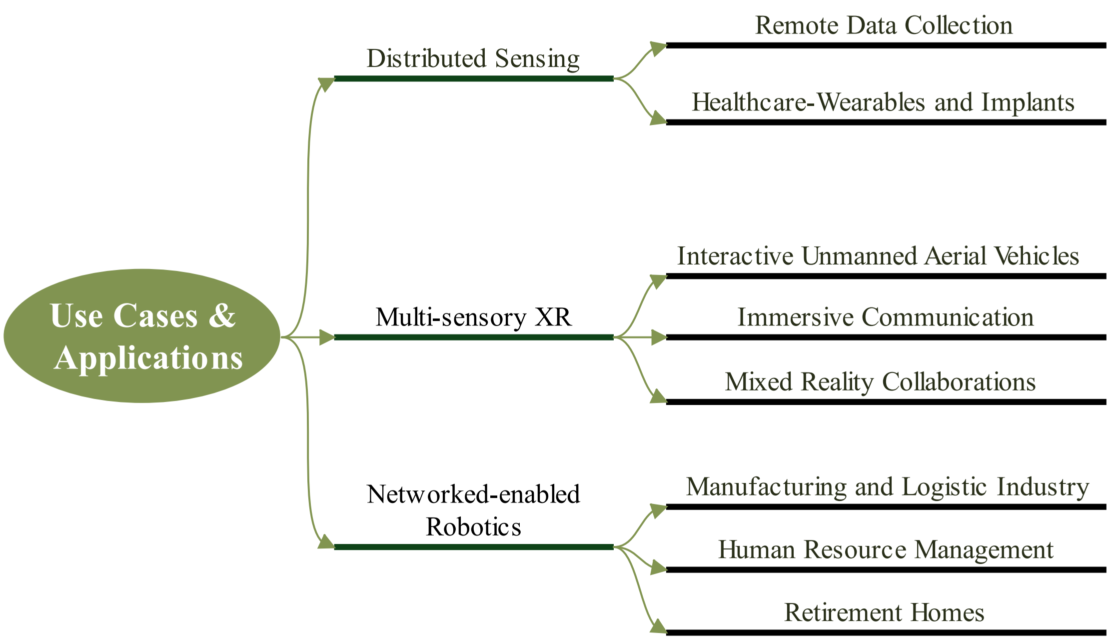

Figure 4-4 Essential Business Use Cases and Applications

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[121] https://www.techtarget.com/whatis/definition/network-slicing
[122] https://nextgalliance.org/white papers/6g-applications-and-use-cases
[123] N. Alliance. (2022) 6G Technologies. [Online]. Available:https://nextgalliance.org/white papers/6g-technologies/

4.7 Business Models

Enterprises are searching for cutting-edge solutions to fulfill their demands and take advantage of new chances as 5G introduces new technology and generates new business opportunities across all industries. Enterprise users expect all business and operational operations to be automated, including ordering, activating, delivering, and decommissioning services. They anticipate receiving services more quickly and with more security.

End-to-end network slicing opens up new income potential for communication service providers and encourages the development of new business models and use cases across all industries. It offers flexibility and the capacity to deliver services more quickly while maintaining high security, isolation, and necessary features to achieve the agreed-upon SLA. By effectively using and managing network resources, network slicing enables operators to maximize return on investment and deliver scale-up differentiated services.

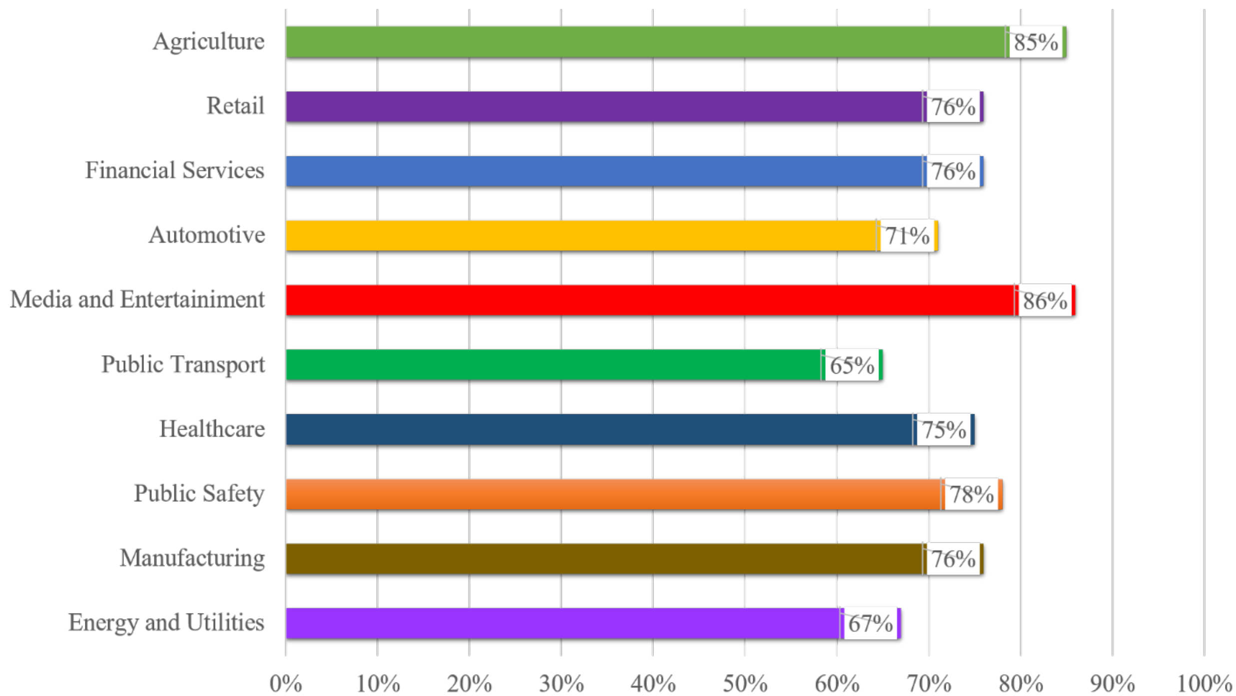

Figure 4-5 Business Opportunities in different Industries

A Business Model (BM) represents a business in an abstract form to depict a company's plan to maximize its profit[124]. It entails an organization's blueprint to create, deliver, and capture value, considering various factors. As cited by Ericsson[125] , beyond 5G and 6G networks enable various new business opportunities in the telecom sector sectors in the top 60%. Figure 4-5 illustrates different industries with business opportunities. BM represents a high-level business plan based on the target market. A value proposition, an essential entity of a BM, describes the offered services/products considering customers' requirements and overall impact. It refers to the promises made by the company toward customers.

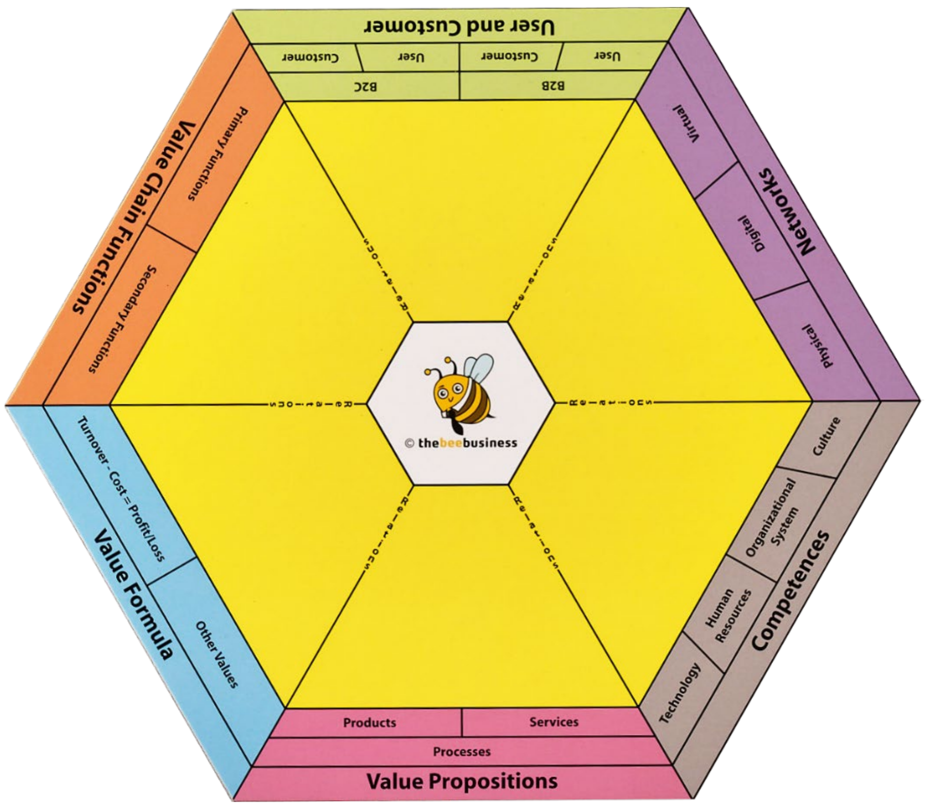

Figure 4-6 Multi Business Model Innovation Illustration

We described the Multi Business Model Innovation Approach[126] to map business opportunities associated with 6G networks and network slicing. Figure 4-6 illustrates various verticals of a business model from the

[124] A. Osterwalder and Y. Pigneur, Business model generation: a handbook for visionaries, game changers, and challengers. John Wiley & Sons, 2010, vol. 1.
[125] https://www.ericsson.com/en/5g/5g-for-business/5g-for-business-a-2030-market-compass
[126] P. Lindgren, The Multi Business Model Innovation Approach. River Publishers, 2018.

customer-end to the provider-end. This model helps create and capture the essentials of the "AS IS" BM and maps the requirements of "TO BE" BMs. It explains a general model for running a business with profit. Its different arms, as mentioned below and in Figure 4-6[126] shows perspective to create BM from different angles.

- **Value Propositions** include the promises made by the MNOs and CSPs toward customers. It involves the processes and different products and services offered to customers—for instance, ultra-high bandwidth support to enable a real-time multiplayer gaming experience.
- **Value Formula** covers the company's expenses and gives profit or loss numbers. It also includes installation and maintenance costs.
- **Value Chain Functions** describe all the tasks involved in creating a product or service.
- **User and Customer** include either or both B2B or B2C models to capture the relationship matrix between users and providers.
- **Networks** denote the channel through which services or products reach their desired customers.
- **Competencies** capture technological advancements, including tangible and non-tangible resources.

4.8 Role of Standardization in Commercialization

4.8.1 Standards and Standardization Bodies

Any research's results are based on the guidelines that have been established for its conduct. Standards are described as the conditions and guidelines for a good, procedure, or service[127]. It defines a recognized design to ensure quality control. Standards are becoming more and more necessary as technology advances. Global information and communication technology (ICT) standards are becoming more and more essential as technology develops[128]. To guarantee compatibility between its processors and successors, a set of standards that will guide the entire development process is a must. The process of ICT standardization for telecommunication networks is extensive and crucial in and of itself[129].

Standards and requirements support early Research and Development (R&D) processes to prevent delays and identify fallbacks. The development of standardization and research activities occurs concurrently and inside a tightly woven system. Standards can play a significant role throughout the development cycle, depending on the environment. A pre-standard is necessary for innovation activities to direct the applied research. For instance, the ETSI Industry Standardization Groups (ISGs) offer pre-standards to enable analysis before formal standards are established[130]. Standards outline what constitutes safety, safe practices, security, etc., following legal and regulatory requirements.

4.8.2 Standards Development Organizations (SDOs)

Stakeholders from many industry verticals, such as manufacturers, providers, customers, and regulators, come together to form SDOs, organizations, alliances, or conferences that develop standards and rules. Universities and businesses are essential in defining needs and offering compelling justifications for developing a prototype. Additionally, they found a set of rules to ensure a genuine development process.

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[127] A. Akins, "6G Wireless: What it is and when it's coming," March 2021. [Online]. Available: www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/6g-wireless-what-it-is-and-when-it-is-coming-62956538.

[128] 5GPPP, "B5G/6G Research with Standarization Potential Roadmap," 5GPPP: 5G Infrastructure Public Private Partnership, November 2020.

[129] C.J. Lanting and A. Rodriguez-Ascaso, "ETSI: Understanding ICT Standardization: Principles and Practice," 2021. Available: https://www.etsi.org/images/files/Education/Understanding_ICT_Standardization_LoResWeb_20190524.pdf.

[130] T. Spanjaard, "WhoWill Standardize 6G? Smartinsights," Smartinsights www.smartinsights.net/single-post/who-will-standardize-6g, 11 December 2020.

SDOs come in a variety of forms according to several classes. The European Telecommunications Standards Institute (ETSI) taxonomy and types of SDOs are shown in Figure 4-4.

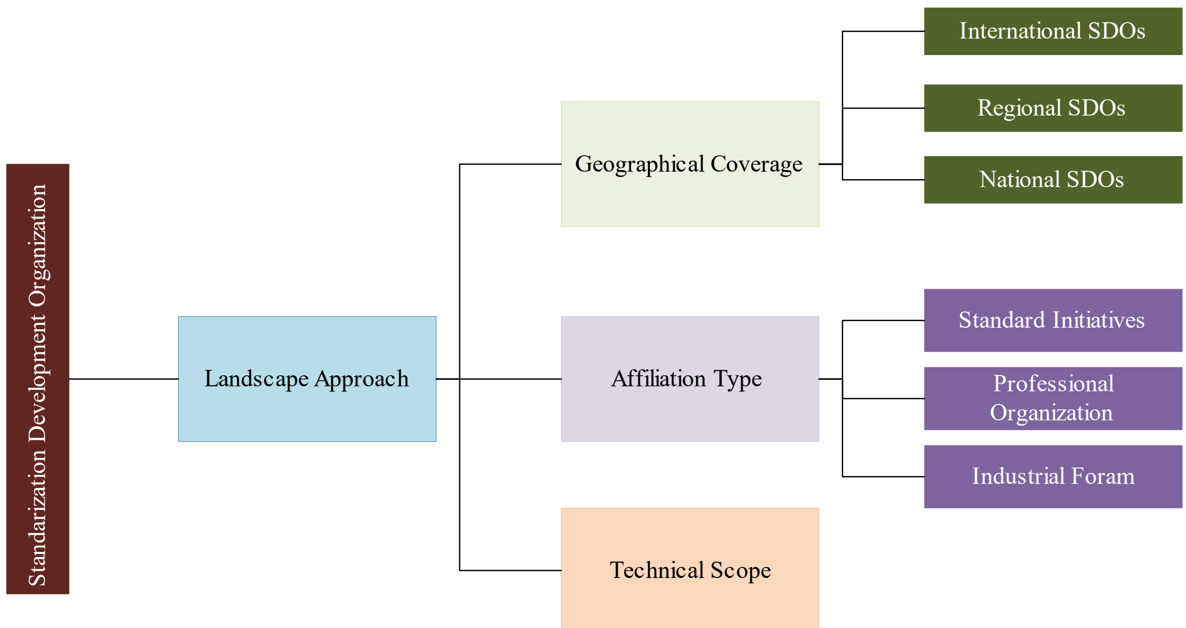

Figure 4-7 Types of Standardization Organizations

4.8.3 6G Standardization

With the help of extensive innovation and research efforts, the globe is heading toward the Beyond 5G communications ecosystem. Different study groups are producing an initial set of standards based on various use cases and KPIs. Beyond 2023, the 3GPP anticipates publishing 6G specifications[128]. Thus, it will take around ten years for 6G systems to reach their full potential. Technologies like Millimeter Wave (mmW), TeraHertz (THz) Communications, Reconfigurable Intelligent Surfaces (RISs), Incorporating Machine Learning (ML) at the radio interface, Holographic Communications, etc. are all being developed by both academia and industry. ITU unveiled the IMT 2030 idea in May 2019 to characterize B5G as a hybrid network. Several major corporations, including AT&T Inc., Facebook Inc., and QUALCOMM Inc., collaborate to develop and deploy 6G standards. While the Next G Alliance[128], established in 2020, is working toward a 6G rollout from a different angle, encompassing deployment, R&D, and manufacturing standardization, it is approaching the project differently. China created alliances in the east to start early 6G research[130].

The European Commission Radio Spectrum Policy Group (RSPG)[131] suggests that the Member States and the European Commission (EC) support the 6G initiatives. It allows for the flexible use of the new THz harmonized spectrum as well as the use of the harmonized spectrum of the European Union (EU) to support fixed wireless access and wireless backhauling[130]. The University of Oulu in Finland is the home of the 6G Flagship project, which focuses on 6G technology[132]. A 6G research & development facility has been announced by Vodafone Germany [26] near Dresden. The "Hexa-X" project, sponsored by the EU and led by Nokia, is looking into potential 6G future technologies.

Japan[130] NTT Docomo plans to have the 6G specs available by 2025 and is spending significant money to establish a 6G research infrastructure. As a sign of its participation in 6G activities[127], Samsung-South Korea has shown an end-to-end 140 GHz wireless link employing a completely digital beamforming technology in the Terahertz frequency[133]. The research and development organization NIIR[134] consented to work with Ericsson to test 5G technology and the Skolkovo Institute of Science and Technology on 6G R&D.

Release 18[135], 3GPP is anticipated to bring new features and capabilities to 5G by 2023. The following releases are expected to focus on B5G and 6G specifications. The Roadmap for 5G NR NTNs is expected to have products available with the finalization of 3GPP Rel. 17, and by 2023, 5G NR NTN systems will be operational. By 2025, the new frequency bands, i.e., >50 GHz and beyond THz, will be applicable for NTN systems.

[131] E. R. S. P. Group, "RSPG Additional spectrum needs and guidance on the fast rollout of future wireless broadband networks," March 2021. [Online]. Available: https://rspg-spectrum.eu/wp-content/uploads/2021/02/RSPG21-008final Draft RSPG Opin.
[132] O. University, "6G Flagship," 12 July 2021. [Online]. Available: www.oulu.fi/6gflagship/.
[133] M. Lennighan, "Vodafone Germany Launches a Network Offensive," June 2021. [Online]. Available: https://Telecoms.com/, 26 May 2021.
[134] A. Hernandez, "Techaeris: "South Korea Eyes 2028 to LAUNCH 6G,
Samsung Leads the Charge."," 23 June 2021. [Online]. Available: techaeris.com/2021/06/23/south-korea-eyes-2028-to-launch-6g-samsungleads-the-charge/.
[135] https://www.3gpp.org/release18

4.8.4 Standardization Activities in Network Slicing

Global System for Mobile Communications Association (GSMA)[136] and Next Generation Mobile Network (NGMN)[137] contribute to the investigation of high-level requirements and architecture, as well as to the creation of the concepts of E2E 5G network slicing and business initiatives. The industry is researching network slicing needs and examining their impact on various network levels, such as the core network or RAN. Various SDOs have defined standardization activities based different technical requirements concerning Slicing. Some of key activities are mentioned below;

- GSMA is an international organization that creates a unified mobile ecosystem that promotes industry solutions like network slicing while fostering research and innovation in the mobile communications sector. For instance, the recently released white paper on "E2E Network Slicing Architecture[138]" outlines the needs of various industries, operators, and vendors and the necessity of working together in standardization efforts to produce a comprehensive answer for the NS architecture. The white paper further explains the E2E NS design, high-level requirements, and continuing projects from multiple SDOs.
- 3GPP: To facilitate 5G network slicing, 3GPP, one of the primary standards organizations, has several active working and study groups. For instance, the SA1 group of the 3GPP focuses on use cases and requirements. The architecture choice to facilitate network slicing is defined by the SA2 working group. Security is covered by the SA3 working group, while SA5 covers slice management[139]. Releases 16[140] and 17[141] of the 3GPP improved the NS idea, which was first presented in Release 15[142]. Release 16 improved network automation, provided controls for identity and permission and brought a service-based architecture to the 5G slicing. Release 17 specifies compatibility for the GSMA-mandated Generic Network Slice Template (GST) features and offers improvements for phase 2 of the NS architecture.
- The European Telecommunications Standards Institute (ETSI) initiatives for 5G network slicing focus on the configuration, delivery, and assurance of deployment and the optimization of 5G services, enabling total automation. Additionally, it offers a solution for computing and storage[143].

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[136] https://www.gsma.com/futurenetworks/ip_services/understanding-5g/network-slicing/
[137] N. Alliance, "Description of network slicing concept," NGMN 5G P, vol. 1, no. 1, 2016
[138] GSMA. (2021) E2E Network Slicing Architecture Version 1.0. [Online]. Available: https://www.gsma.com/newsroom/wp-content/uploads//NG.127-v1.0-2.pdf
[139] P. Rost, C. Mannweiler, D. S. Michalopoulos, C. Sartori, V. Sciancale-pore, N. Sastry, O. Holland, S. Tayade, B. Han, D. Bega et al., "Network slicing to enable scalability and flexibility in 5G mobile networks," IEEE Communications Magazine, vol. 55, no. 5, pp. 72–79, 2017.
[140] https://www.3gpp.org/release-16
[141] https://www.3gpp.org/release-17
[142] https://www.3gpp.org/release-15
[143] N. ETSI, "Network functions virtualisation (NFV); terminology for main concepts in NFV," Group Specification, Dec, 2014

- The development of the 5G network slicing architecture and its broad needs are addressed through the Internet Engineering Task Force (IETF) standardization activities. Additionally, they take into account network slice management and orchestration technologies. Their most recent work involves traffic-engineered networks' control of network slicing, abstraction applicability, and gateway function for network slicing.
- The activities to define the slicing management architecture for transport networks are done by the Broadband Forum (BBF). Additionally, the BBF standardization operations include resource control assistance and sharing broadband network infrastructure among various service providers[144].
- The International Telecommunication Union-Telecommunication (ITU-T) promotes various E2E network slicing functionalities to give clients reliability. ITU-T features include softwarization, network capability exposure, mobility needs, a variety of E2E Quality of Service (QoS) with distributed nature, support for edge clouds, control, and user plane separations. ITU-T Study Group 13 (SG13)[145] carries out standardization work in orchestration, network management, and horizontal slicing. Additionally, it specifies high-level network softwarization and discusses data plane programmability. The deliverable of an ITU-T SG13 Focus Group (FG) on Machine Learning for Future Networks, Including 5G (FG-ML5G),[146] had specified requirements, including information on interfacing, network architectures, protocols, algorithms, and data formats.
- The Open Networking Foundation (ONF) examines the network's low latency and secure virtual subsets when researching network slicing connections for high-capacity 5G services[147].
- The Open Network Automation Platform (ONAP) is a community of next-generation network automation technologies created by operators. It emphasizes bringing together open source initiatives and standards while encouraging cross-organizational partnerships. The technological difficulties posed by 5G slices have been the subject of a recent series of white papers produced by ONAP[148].

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[144] C.-Y. Chang and N. Nikaein, "Closing in on 5G control apps: enabling multiservice programmability in a disaggregated radio access network,"IEEE vehicular technology magazine, vol. 13, no. 4, pp. 80–93, 2018
[145] ITU-T. (2019) Progress of 5G studies in ITU-T: overview of SG13 standardization activities . [Online]. Available: https://www.itu.int/en/ITU-T/Workshops-and-Seminars/20180604/ Documents/Session1.pdf
[146] "Focus Group on Machine Learning for Future Networks including 5G." [Online]. Available: https://www.itu.int/en/ITU-T/focusgroups/ml5g/Pages/default.aspx
[147] ONF. (2019) Transport API (TAPI) 2.0 Overview Version 0.0 August. [Online]. Available: https://opennetworking.org/wp-content/uploads/2017/08/TAPI-2-WP DRAFT.pdf
[148]https://www.onap.org/wp-content/uploads/sites/20/2020/03/ONAP_HarmonizingOpenSourceStandards031520.pdf

4.8.5 Standards in Artificial Intelligence

The standardization projects for AI/ML architectures and methods are shown in Table 4-1. Standards and specifications are essential to the AI ecosystem because they guarantee a more secure and dependable future. Additionally, intelligent, connected gadgets produce a vast amount of data and the data needed to train the models. Data is also crucial and necessary in intelligent environments because it contains personal and professional information. For instance, data cannot be shared or used for training in healthcare contexts. Therefore, it is crucial to have a clear need to govern data exchange and analysis. Both the General Data Protection Regulation (GDPR) of the European Union (EU) and IEEE are striving toward an AI design that is ethically aligned.

Table 4-1 Standardization Activities for AI/ML/DL

Summarized Standardization Activities for AI/ML/DL
ITU T Y.3172[149], IEEE P2830 provides a technical framework & requirements for Shared ML algorithms. In a trusted third-party context, it defines the structure and architecture for the training model using multi-source encrypted data. Its focus is on processing encrypted data in a third-party execution environment. It also covers functional components, workflows, security, technical requirements, and protocols to provide a verifiable foundation for trust and security.
P3333.1.3/D2[150] -IEEE Draft Standard for the DL-Based Assessment of Visual Experience defines deep learning-based metrics for visual content QoE evaluation and content analysis. It concentrates on perceptual quality and VR cybersickness to attain good QoE considering human factors, a trustworthy test methodology, and a database development process. It also specifies situations for in-depth personal preference study of visual contents, creating image and video databases, and thorough clinical and psychophysical data analysis.
ITU-T Y.3176 provides high-level specifications and the architecture for integrating ML marketplaces based on the standards in ITU-T Y.3172 and supports integration in future networks.
ITU-T Y.3172[151] provides a foundation for machine learning architecture that can be used in future networks, such as IMT-2020. It outlines several architectural specifications and the components' integration rules. It outlines ML management, orchestration, and pipeline functionalities.

[149] "IEEE Draft Standard for Technical Framework and Requirements of Trusted Execution Environment based Shared Machine Learning," IEEE P2830/D1, October 2020, pp. 1–21, 2021.
[150] IEEE-SA, "IEEE Draft Standard for the Deep Learning-Based As- sessment of Visual Experience Based on Human Factors," IEEE P3333.1.3/D2, August 2021, pp. 1–47, 2021.
[151] ITU, "Architectural framework for machine learning in future networks including IMT-2020," Jun 2019. [Online]. Available: https://www.itu.int/rec/T-REC-Y.3172/en

▪ FG-ML-5G is an ITU-T Study Group 13 (SG13)**152** on Machine Learning for Future Networks. Ten technical specifications, including interfaces, network architectures, protocols, algorithms, and data formats, have been documented for ML for future networks. From January 2018 to July 2020, it was operational. Here are a few of the focus group's pertinent comments on the suggested work, including IMT-2020. ▪ ITU-T Y.3172: a foundation for machine learning architecture in upcoming networks; ▪ ITU-T Y.3173: Framework for assessing future networks' intelligence levels; ▪ ITU-T Y.3174: Data handling framework to support machine learning in future networks; ▪ ITU-T Y.3176: Integration of the market for machine learning in future networks; ▪ Framework for serving ML models on upcoming networks.
ITU-T Y.3173[153] offers a method for assessing the intelligence levels of future networks, including IMT-2020, and specifies a framework for evaluating network intelligence. Based on ITU-T Y.3172 recommendations, it defines an architectural paradigm for assessing network intelligence levels.
ITU-T Y.3174[154] offers a data processing framework to support ML in upcoming networks. It outlines the specifications for data collecting and processing methods in various ML usage situations, creates a general framework for data handling, and illustrates how it has been implemented on multiple underlying networks.
IEC and ISO organized a workshop on the **AI Ecosystem Standardization Program**[155] to utilize AI across Europe effectively and ensure Europe's leadership position in AI. It provides an initial picture of the European AI environment while summarizing various activities in various EU member states.
ETSI GR SAI 005[156] focuses on DL while investigating current mitigation countermeasures. It defines the machine learning model process, which comprises both the construction and deployment phases of the model life cycle.
The **ITU/WHO Focus Group on Artificial Intelligence for Health**[157] develops a uniform methodology for evaluating AI approaches in healthcare. Members of the FG come from numerous research

152 ITU-T, "Focus Group on Machine Learning for Future Networks including 5G." [Online]. Available: https://www.itu.int/en/ITU-T/focusgroups/ml5g/Pages/default.aspx

153 ITU-T, "Recommendation ITU-T Framework for evaluating intelligence levels of future networks including IMT-2020," Feb 2020. [Online].Available: https://www.itu.int/rec/T-REC-Y.3173/en

154 Tsbmail, "Framework for data handling to enable machine learning in future networks including IMT-2020," Feb 2020. [Online]. Available: https://www.itu.int/rec/T-REC-Y.3174/en

155 E.Commission. (2020) The European AI Landscape: The Workshop Report. [Online].Available: https://ec.europa.eu/jrc/communities/sites/jrccties/files/reportontheeuropean ailandscapeworkshop.pdf/

156 ETSI, "Securing Artificial Intelligence (SAI)," Aug 2021. [Online].Available: https://www.etsi.org/committee/sai

157 ITU-T,"Focus Group on Artificial ntelligence for Health." [Online].Available:https://www.itu.int/en/ITU-T/focusgroups/ai4h/Pages/default.aspx

institutions, governmental organizations, hospitals, and other institutions. FG A ITU and the World Health Organization cooperative project is called AI4H. (WHO).

The **ITU/WMO/UNEP Focus Group on Artificial Intelligence for Natural Disaster Management (NDM)**[158] develops a roadmap for the safe and efficient application of AI techniques to NDM. Data collection and handling, modeling advancements at various spatiotemporal scales, and effective communication are considered.

4.9 Open Challenges

There are many technical and commercial bottlenecks with the NS implementation. The main challenge is to manage standardization associated with the network slices in generating new businesses, where industrial giants come together. On the one hand, where NS brings flexibility and connectivity to various industrial verticals, it demands revolutionary changes in every aspect of operations (integrating automation and intelligence). Slicing provides MNOs, CSPs, and industries with the most needed value proposition to create new business models that depend on the service and applied configurations[159]. The telco giants control the end-to-end value chain in Business-to-Customer (B2C) and Business-to-Business (B2B) sectors.

Solution providers must implement software and virtualization technologies to adequately package aggregated services to reap the benefits of carrier aggregation and network slicing. Serviceability and quotation keep getting more complicated as there are more telecom suppliers. Utilizing pooled telecom services without adding a new burden on sales labor and resources requires automated software[160].

Developing new businesses need clarity in the requirements like service life-cycle, resource allocation (estimated and actual), and other varying parameters like leasing costs and SLAs. Some identified challenges associated with slicing and slices include mobility, dynamic slice creation/management, QoS, slice isolation, handovers, and latency. Apart from technical bottlenecks, we have regulatory challenges that include business ethics, political (geographical regions), and governmental laws.

[158] ITU, "Focus Group on Artificial Intelligence for Natural Disaster Management." [Online]. Available: https://www.itu.int/en/ITU-T/focusgroups/ai4ndm/Pages/default.aspx
[159] https://www.chalmers.se/en/departments/e2/news/Pages/Designing-the-6G-networks-of-the-future.aspx
[160] https://www.masterstreamerp.com/blog/what-is-carrier-aggregation-in-telecom

5 Conclusions and Future Research Directions

This last section of the thesis will conclude our proposed work with open research areas that can provide possible collaboration and new heights in terms of more market-ready solutions. We will give concluding remarks for each main section presented so far. The contributions toward future research directions and expected outcomes are illustrated in Figure 5-1.

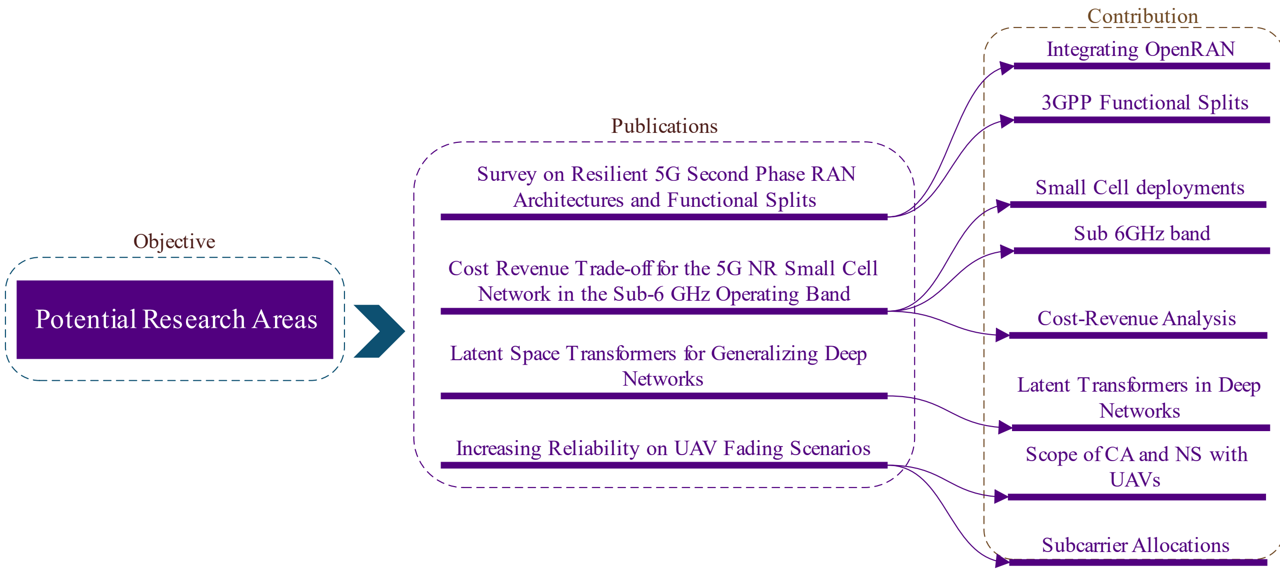

Figure 5-1 Objective Mapping to the Publications

5.1 Summary of Publications

Latent Space Transformers for Generalizing Deep Networks

Conference Paper: H. Farkhari et al., "Latent Space Transformers for Generalizing Deep Networks," 2021 IEEE Conference on Standards for Communications and Networking (CSCN), 2021, pp. 130-135, doi: 10.1109/CSCN53733.2021.9686099.

This work advances a concept for the generalization of deep networks employing latent transformers, controlling load balancing, preserving bandwidth, and reducing latency brought on by complex computations, in addition to the standardization concerning deep neural networks and AI.

Cost Revenue Trade-off for the 5G NR Small Cell Network in the Sub-6 GHz Operating Band

Conference Paper: (Submitted) Khan, B., Nidhi., Rui Paulo, A. Mihovska and Fernando J. Velez, " B Cost Revenue Trade-off for the 5G NR Small Cell Network in the Sub-6 GHz Operating Band" 25th International Symposium on Wireless Personal Multimedia Communications (WPMC) 2022.

This paper provided a study showing opportunities in industries incorporating 5G RAN dis-aggregation. We offered a cost-revenue-profit trade-off implementing small cells with splits 6 and 7 (7.2) of 3GPP in sub-6 GHz networks. We discussed in detail the revenue-profit model for deployments with and without splitting, assuming cost parameters and traffic costs.

Survey on Resilient 5G Second Phase RAN Architectures and Functional Splits

Journal Article: Khan, B., Nidhi., OdetAlla, H., Flizikowski, A., Mihovska, A. & Velez, F. J., 20 Nov 2021, (Submitted) In: IEEE Transactions on Network and Service Management. Special Issue, 18 p. Research output: Contribution to journal/Conference contribution in journal › Journal article › Research › peer-review

This paper thoroughly covers the principles of the evolution of the RAN architecture, its essential components, and implementation issues. We explained the classic RAN architectural development to OpenRAN and discussed the significance of centralized, distributed, and virtualized RAN architectures. We elaborated on the benefits and challenges of RAN centralization (energy efficiency, reduced power costs, and fronthaul costs) and data traffic management among various data processing units and distributed antennas.

Increasing Reliability on UAV Fading Scenarios

Journal Article: J. Viana et al., "Increasing Reliability on UAV Fading Scenarios," in IEEE Access, vol. 10, pp. 30959-30973, 2022, doi: 10.1109/ACCESS.2022.3149588.

This article aimed to examine the potential uses of NS and CA with UAVs while I was on secondment. We looked at the Constant Packet Combining (CPC) and Adaptive Packet Combining (APC) methods used for Unmanned Aerial Vehicle (UAV) communication in the presence of large-scale fading, where the channels are vulnerable to abrupt degradation over extended periods because of impediments. To handle command and control messages mapped for UAV use cases, we integrate Single Carrier (SC) Frequency Domain Equalization (FDE) with the Iterative Block Decision-Feedback Equalizer (IB-DFE). We include closed-form equations for the equalization design in addition to performance metrics like the bit error rate (BER), packet error rate (PER), throughput, number of retransmissions, goodput (the transmission rate without a large number of retransmissions), and outage probability.

5.2 Research Conclusions

The sub-sections in this section are organized as illustrated in Figure 5-2. We will hence provide a concluding remark on each sub-section of the thesis and eventually draw a conclusion with the open research questions.

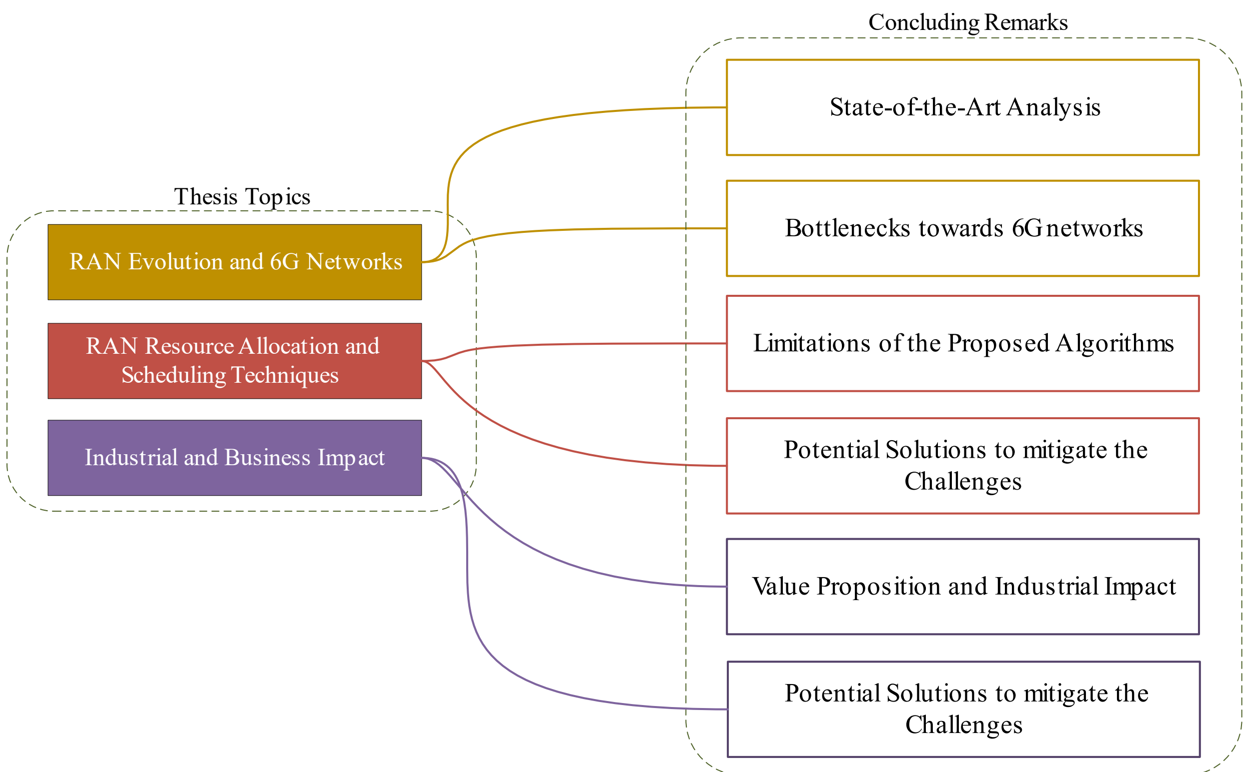

Figure 5-2 Structure of the Section with Concluding Remarks

5.3 5G and 6G Network Challenges

5.3.1 Network Slicing Challenges

- To identify the fundamental design challenges of RAN slicing.
- To formulate, develop and assess a selected case of RAN slice deployment.
- Intelligent service function chaining
- Mobility-aware slicing
- Dynamic spectrum slicing
- Algorithmic aspects of resource allocation
- Isolation among network slices

5.3.2 Carrier Aggregation Challenges

Downlink CA challenges include:

- ***Downlink sensitivity****:* For designing a duplexer for each CC, interference between uplink and downlink at the reception at downlink needs to be considered. With large frequency separations between two bands, either a separate duplexer/diplexer or multiplexers/hexiplexers can be used. However, a multiplexer is more challenging to develop as it increases PC board area while simplifying the RF front end.
- ***Harmonic generation****:* Non-linear components like transceiver output stages, power amplifiers (PAs), duplexers, etc., results in Harmonics. Design developments should consider device performance against the reduced harmonic generation.
- ***De-sense challenges*** *in CA radio design:* Limited filter attenuation causes Multiband radio signals to interfere, resulting in a higher probability of desense in CA applications if isolation or cross-isolation between the transmit and receive paths.

Uplink Challenges

To reduce maximum power, the Intra-band uplink CA signals use more bandwidth and have higher peak-to-average-power ratios (PAPRs) than standard LTE signals. 3GPP allows for different Maximum Power Reductions (MPRs) to be applied based on different configurations of RBs. Because of higher peaks, more signal bandwidth, and new RB configurations, a Power Amplifier design needs proper tuning for very high linearity.

Implementation Challenges

Hardware implementation and resource allocation are critical in CA [18]. There are crucial requirements like signal processing capabilities, Radio Frequency (RF) chains, oscillators, strong battery life, etc. From the RF context, CA-FDD implementation is more challenging. The mobile network operators (MNOs) have fragmented frequency resources, and with CA implementation, this will result in the coexistence of multi-operator networks placed closely [19]. The transmitter and receiver design considerations are critical to reducing the interference caused due to the undesired transmitter emissions and the cross-isolation issues as UEs communicate on multiple bands simultaneously.

5.3.3 RAN Evolution and 6G Networks

The 6G vision encompasses three worlds: the physical world of items and organisms, the digital world of information, communication, and computers, and the human world of our senses, bodies, intelligence, and values. Regulations and technological advancements are also crucial for developing and deploying future networks. Consequently, one of the significant issues facing society due to the development of 6G enabling technologies is the requirement that the associated services are available to everyone and anywhere they are required. This need for digital inclusion includes "easy-to-use technology" as well as "global coverage" (at an affordable cost for deployment and the customer as well).

Disruptive technologies, including AI, ML, deep analytics, software, sophisticated computer technologies, advanced sensing, 3D imaging, and AR/VR, are driving changes in the capabilities and design parameters of Future Wireless Networks (FWN) based on 6G encouraging the development of new applications with demanding performance standards.

From a technology perspective, 6G will provide a vast opportunity to the users and MNOs to explore different services and use cases. The new spectrum will have new challenges. New features of the 6G networks have been presented along with associated services and enabling technologies. After establishing newly evolved KPIs and requirements, various 6G standardization initiatives worldwide have also been addressed. We have learned that the scope of standards and technology development needs to be broadened to support future ecosystems. The product needs to comply with the standards to support the full capabilities of upcoming networks. Higher layers are made available for research, bringing new challenges and enormous opportunities. Different organizations are drafting the specifications and standardization requirements for 6G in different use case scenarios and consider 6G guidelines, 100x data throughput, and sub-millisecond latency compared to the 5G networks.

5.3.4 RAN Resource Allocation and Scheduling Techniques

We identified significant overhead to the proposed resource scheduling algorithm while extracting the CQI information from the base stations to feed the UEs. We discussed this challenge and potential solutions in the discussion section. The solution to mitigate the overhead issue is out of the scope of this work.

To mitigate this overhead while maintaining at the SO level an accurate view of UE channel quality, we propose in our second and third contributions, respectively:

- A machine learning approach to infer the stability of UE channel conditions and
- predictive schemes to reduce the CQI reporting intensity based on the implied channel status.

5.3.5 Industrial and Business Impact

There are many technical and commercial bottlenecks with the NS implementation. The main challenge is to manage standardization associated with the network slices in generating new businesses, where industrial giants come together. On the one hand, where NS brings flexibility and connectivity to various industrial verticals, it demands revolutionary changes in every aspect of operations (integrating automation and intelligence). Slicing provides MNOs, CSPs, and industries with the most needed value proposition to create new business models that depend on the service and applied configurations. The telco giants control the end-to-end value chain in Business-to-Customer (B2C) and Business-to-Business (B2B) sectors.

Solution providers must implement software and virtualization technologies to adequately package aggregated services to reap the benefits of carrier aggregation and network slicing. Serviceability and quotation keep getting more complicated as there are more telecom suppliers. Utilizing pooled telecom services without adding a new burden on sales labor and resources requires automated software.

Developing new businesses need clarity in the requirements like service life-cycle, resource allocation (estimated and actual), and other varying parameters like leasing costs and SLAs. Some identified challenges associated with slicing and slices include mobility, dynamic slice creation/management, QoS, slice isolation, handovers, and latency. Apart from technical bottlenecks, we have regulatory challenges that include business ethics, political (geographical regions), and governmental laws.

5.4 Open Research Directions

5.4.1 Secondment Collaborations

Recommended advancements have produced effective training methods for Deep Neural Networks (DNN) in Machine Learning (ML) algorithms, computational power, processing, preprocessing approaches, and computer hardware (DNNs). Moreover, deep feedforward networks have offered improved acoustic modeling[161]. As a result, there will be an exponential increase in the number of DNN application cases across various industries. Due to rising demands, processing speed and methods, parallel computing, and latency will become increasingly crucial to connected consumers. Deep-network application development is made possible by edge computing, cloud computing, and 5G Ultra-Reliable Low Latency Communications (URLLC), which offer high Quality of Services (QoS) for consumers with these

[161] A. R. Mohamed, G. E. Dahl, and G. Hinton, “Acoustic modeling using deep belief networks,” IEEE transactions on audio, speech, and language processing, vol. 20, no. 1, pp. 14–22, 2011.

requirements. Researchers use mixed deep networks more frequently to attain better performance and more accuracy. New developments in computing methods and training models will also lead to the evolution of neural networks.

Beyond 5G wireless communications networks and deep hybrid networks, certain unresolved obstacles exist in achieving seamless integration. Standards assist innovations and research institutions in developing new training models and network architecture enabling massive data and processing capabilities. It is hypothesized that standardizing latent space will encourage research into cutting-edge hybrid networks with little to no retraining. Latent spaces define the data representation in another domain space. For instance, the space led to modifying certain data properties, such as mathematical transformations. Deep networks, for instance, automatically select, extract, and transform new domains, and there are no restrictions on the number of layers or units per layer however, because these variables are based on performance and are hyper-parameters.

Thus we proposed splitting deep networks using the latent space to lessen the amount of retraining. The proposal also emphasizes the concept of combining data from multiple trained deep networks from various fields (e.g., text, speech, image processing, and others) to reduce latency and computation needs in deep network applications. Some concepts were introduced for lowering training processing costs; training techniques to create hybrid networks from pre-trained networks; and transfer learning techniques for combining pre-trained deep networks with other networks.

5.4.1.1 The Proposed Idea

The latent space is a separate domain space[162] where data can be reduced to represent new optimal features effectively. The additional features might be easier to differentiate for each class, making it easier to solve classification issues. Usually, when we alter data features, such as by a mathematical transformation, those features are transformed into a different domain called latent space. Deep neural networks automatically choose and extract features. After each layer, the characteristics are transformed into a brand-new latent space domain. The number of layers and the number of units per layer are unregulated.

The number of units and layers are both hyper-parameters that can be modified and varied from one researcher to the next, depending on the results' performance. Deep networks are conceptually divided into at least two sections to gain access to latent space specified by a particular standard. The number of network layers that come before it must give a certain quality, and this latent space should adhere to specific rules

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[162] A. Oring, Z. Yakhini, and Y. Hel-Or, "Autoencoder Image Interpolation by Shaping the Latent Space," in Proceedings of the 38th International Conference on Machine Learning, ser. Proceedings of Machine Learning Research, M. Meila and T. Zhang, Eds., vol. 139. PMLR, 18–24 Jul 2021, pp. 8281–8290. [Online]. Available: https://proceedings.mlr.press/v139/oring21a.html

and standards. The deep hybrid networks that use the encoder components of autoencoders to transfer features in the new latent space without standardization and then feed to another deep network are a practical illustration of this concept.

Figure 5-3 1 shows how to combine two deep networks with distinct functions (such as video and audio recognition) by merely training the latent transformer unit and employing the components of two deep networks with specific goals. Arrows indicate the procedure steps and the components drawn from each deep network. The source produces voice data in the first path, followed by pre-processing. It is converted to latent space1 after inputting into the DL1 portion of the deep network. Traditionally, the data would be put into the DL1's second layer after classification and regression, allowing us to observe the outcomes. The face-scanning data would approach deep network 2 using the same approach as input 2. The latent transformer block could transfer data from one latent space to another using standard latent spaces. This conversion enables the creation of two more paths using the first component from one network and the second from a different network.

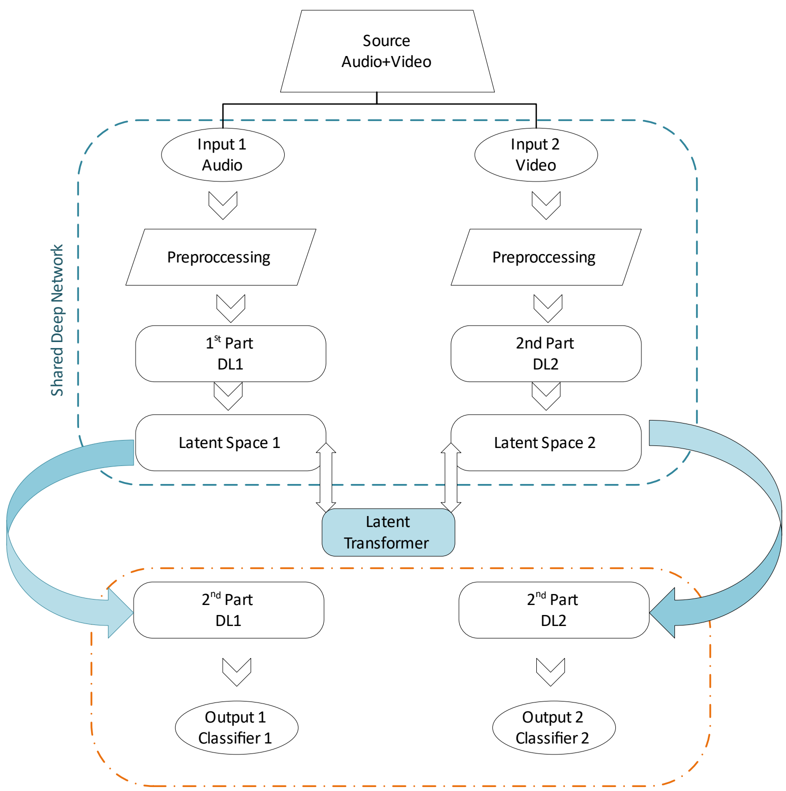

Figure 5-3 Proposed Methos to mix two Deep Networks using Latent Transformers

Deep Networks' generalization of standards in Research and Development (R&D) lowers the cost of processing training, increases security investment, offers a cutting-edge solution with a competitive edge over upcoming rivals in 5G markets, and facilitates experience sharing with key players in the standardization process. Therefore, standardization fosters innovation, widens commercial opportunities, and globalizes recent technology advancements. The growth of the IoT, new use cases for extended reality and advancements in deep learning techniques coincide with the development of the 5G telecommunication networks, which will eventually result in the creation of applications combining them to offer high-quality services (QoS). As a result, accessing high bandwidth with low latency will be more necessary than before, leading to the vast volume of data being moved from the edge to the cloud for processing. Developers may get a chance to build and enhance new cloud services based on the deep network standard latent domains by dividing deep network components between edge and cloud and transferring the represented latent data.

5.4.2 Future Research Directions

We lack enough literature to support the integration of CA and NS to cater high demands of heterogeneous traffic. Taking into account our contributions to slice creation and resource allocation followed by cross-carrier scheduling in CA, we proposed to have an integrated algorithm that can allocate the network instances resources employing aggregated frequencies.

From this, we can take forward the use of latent space transformers and see possibilities for integration in NS and CA environments. This can provide a solid base to transform the NS framework into an intelligent platform using AI/ML. Using latent transformers to share data among deep networks to generalize them could lower training expenses. The standardization process can use this generalization. Additionally, merging pre-trained deep networks to produce various hybrid networks for new uses, research, and development might open up a potential for creativity. Deep learning and artificial intelligence have several standards accessible. None of them, however, considers the potential for information sharing through latent transformer blocks. Unfortunately, the standards activities are private, making it difficult for scholars to access all advances easily and suggested frameworks.

As a result, we now offer the needs and associated recommendations to create our concept, assuming that standards do not cover the region we are covering. Additionally, we demonstrated several uses for this standard (e.g., processing images and sounds, mixing security and resource allocation algorithms in 5G networks and IoT devices, ensembling multiple deep networks, and extended reality scenarios).

Appendices

A Appendix A Publications

Trends in Standardization Towards 6G

Nidhi[1,*], Bahram Khan[2], Albena Mihovska[1], Ramjee Prasad[1]
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** Corresponding Author*

Received 02 August 2021; Accepted 07 November 2021;
Publication 16 December 2021

Abstract

Mobile networks have always been an indispensable part of a fully connected digital society. The industry and academia have joined hands to develop technologies for the anticipated future wireless communication. The predicted Key Performance Indicators (KPIs) and use cases for the 6G networks have raised the bar high. 6G networks are developing to provide the required infrastructure for many new devices and services. The 6G networks are conceptualized to partially inherit 5G technologies and standards but they will open the ground for innovations. This study provides the vision and requirements for beyond 5G (B5G) networks and emphasizes our vision on the required standards to reach a fully functional and interoperable 6G era in general. We highlight various KPIs and enabling technologies for the B5G networks. In addition, standardization activities and initiatives concerning challenges in the use of spectrum are discussed in detail.

Keywords: 6G networks, spectrum management, standardization development organization, spectrum sharing, terahertz.

Journal of ICT Standardization, Vol. 9_3, 327–348.
doi: 10.13052/jicts2245-800X.932

1 Introduction

Mobile communication technology has evolved since 1981 from the first generation of mobile communication (1G) to the upcoming fifth generation (5G) [1]. This evolution shows that a new generation of mobile communication exists every decade and offers new services to the users. Therefore, it is expected that 6G will emerge and come into action around 2030 [2]. Each generation offered enhancements in reliability, data speed, costs, available network functions, power efficacy, security, system performance, latency, network coverage, and services. As a result, disruptive technologies can be seen from each generation, like narrowband in 2G technology, broadband in 3G, 4G ultra-broadband, wireless world wide web currently in 5G, and expectedly, revolutionary terrestrial wideband in 6G. Besides, there will be enhancements in the bandwidth while data transmission is increased. The 1G began with an analog assembly, which turned to digital communication and circa 25 MHz bandwidth utilization for both 2G and 3G, while bandwidth increased up to 5 times, to 100 MHz in the case of 4G networks [3]. 5G use cases are deployed in the 30–300 GHz spectrum bands for wireless communications. On the other hand, 6G is estimated to demand higher frequency bands utilization, in the range above 300 GHz and up to several THz [4].

Fast growing data-centric intelligent systems, futuristic scenarios, networks, and applications have imposed challenges to the currently deploying 5G networks [5]. The crucial differentiating characteristic of 5G is low latency, particularly guaranteed latency, that desired deterministic networking to guarantee the end-to-end latency target, with the reliability, required by future use cases. However, 5G deployment is currently minimal in some typical scenarios, like access in remote areas, e.g, villages or motorways, whose coverage is not satisfactory. Terrestrial 5G New radio will not support some applications that contain actual driverless vehicles. Therefore, in such environments, satellite communication networks are needed, which can improve the coverage as compared to terrestrial networks. Besides, Unmanned Aerial Vehicles (UAVs) communication networks are essential for quick response in strict and challenging environments, and high-quality communication service can be provided to ships by Maritime communication network. Applications such as Virtual Reality (VR), the mix of VR, high-quality three-dimensional video, and VR and Augmented Reality (AR) will require Tbps, and terahertz or optical frequency bands can be candidate bands.

Although 5G New Radio (NR) is a tremendous evolution step, it will not fulfill all the future network requirements (2030) [6]. Next generation networks are likely to assist in several deployment scenarios for different applications, such as coverage from space-air to ground-sea, communications coverage, high-mobility, vehicle to everything, robotic machine, integrating communication, sensing, computing, and high touch VR. 6G is expected to provide nearly 100% geographical coverage, millisecond geolocation update rate, and sub-centimeter geo-location accuracy to fulfill use cases' requirements and support an enormous amount of data generated by heterogeneous networks, wide bandwidths, large numbers of antennas, and diverse communication scenarios [5, 6].

6G networks are expected to completely shift the existing communication network to new extreme network capabilities, which cater to the demands of the future data-driven society. The majority of the 5G Key Performance Indicator (KPIs) are valid for the 6G. It is expected that the evolution to 6Gwill require per link peak throughput that reaches Tbps. Some use cases, like factory automation, will exist, characterized by ultra-high reliability, ultralow latency and high accurate synchronicity, with maximum latency of almost around 1 μs. In 6G it is expected that in 1 billion bit there will be just one erroneous bit, whilst facilitating outstanding industrial control. Security and privacy are also essential KPIs of 6G. Hyper security high-end user and industrial control will be needed. At the radio interface, a wider bandwidth will be required under the sub- THz and THz bands. Therefore, it is essential to understand how the research community is investigating and focusing on the 6G wireless communication networks.

The use of the spectrum involves many challenges but, at the same, it is an opportunity for future networks. These high-frequency bands will provide a significant role in the overall network. Many exiting IoT scenarios still face cost and battery limitation challenges. However, in 6G, it is expected to provide battery support from the network in some context. On path loss,H_2O molecular absorption has a significant impact, particularly at a lengthier distance. Penetration through different materials and reflection from the surface are factors to study while classifying the radio spectrum. Although these KPIs must be investigated in more detail, a basic set of the KPIs is shown in Figure 1 [7].

The standards are the key to smoothening the timely journey towards 6G networks. Deciding whether they are open or not helps to have a unified approach throughout the pre-development and development phase. Additionally, it helps to join forces against obstacles en route and accelerate innovation. Many standardization bodies are working in similar directions, in similar or different areas. There are huge overlaps and intersections; thus,

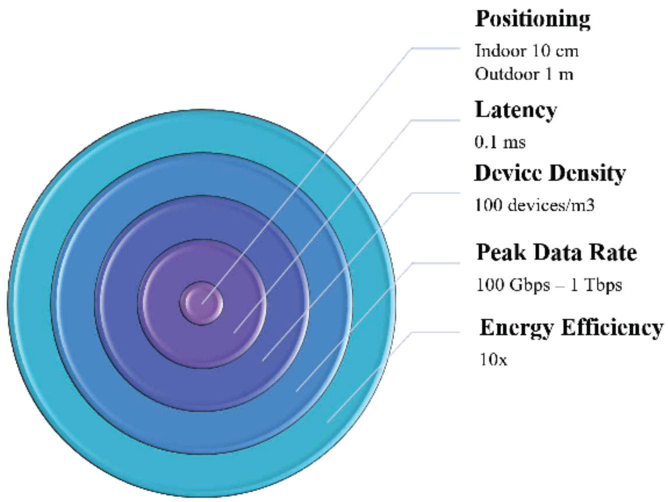

Figure 1 Key performance indicators for 6G.

it is essential to facilitate the idea of cross-research. Furthermore, these standard bodies work to identify the right time to initiate actions concerning pre-standards or full standards activities.

This paper aims to draw a complete picture of 6G Networks from a standardization perspective. First, we define the concept of a standardization body and how it operates at various levels. Then, the paper contributes to the 6G expectations, services, identified KPIs, and challenges. The remaining paper is outlined as follows: Section 2 addresses the Spectrum Management in 6G, Section 3 describes various 6G use cases, and Section 4 addresses 6G enabling technologies. Section 5 describes the role of standards and relevant standardization bodies. Sections 6 and 7 addresses the spectrum requirements in 6G and describes standardization activities in detail. Finally, conclusions are drawn in Section 8.

2 Spectrum Management

Spectrum management efficiently handles available frequency bands and has taken several arrangements and tactics in the history of mobile communication networks [8]. It comprises the spectrum allocation, which has been based on an administrative approach, common unlicensed mechanisms, and an allocation scheme, depending on the market. In the literature, the available details of 6G communication networks and their spectrum are limited, as research is still in its early stages. It is expected that 6G will be deployed in the Terahertz (THz) frequency bands range aimed at mobile communications [9]. Spectrum bands presently under 2G/3G/4G/5G in different countries need to be available for 6G [10]. The 6G spectrum bands will also be allocated in frequencies higher than before, leading to various spectrum management approaches that imply distinguishing the higher, mid, and lower bands.

Spectrum management of 6G frequency bands is challenging and will combine sensing with communications. The inclusion of Artificial Intelligence (AI) in spectrum access decisions will open the door for full dynamic operation. 6G networks will sense the environment of the radio and will adapt it in real scenarios [11, 12].

Figure 2 shows the 5G and 6G available frequency bands and presents their basic properties. It explains that the increase in free space loss is slight when going into the THz region, and from 30 GHz onward. With constant antenna area, the free space loss is compensated by the increase in the antenna gain. Relatively the free space loss, the downside of higher frequencies is the rise of the complexity and parallelism in RF hardware. The underlying reduced beam width creates signal acquisition and beam tracking problems in different mobile applications. Different IoT devices' costs, ranges, battery limitations will not quickly scale with the evolution to higher frequencies. The THz spectrum must be managed in terms of path loss and according to the sub-bands reflection properties to optimize resource reuse. In those scenarios that support multiple applications, the overlap of different sub-channels must be prevented by carefully performing frequency planning. Figure 2 shows that whil frequency bands up to 3 GHz support up to 10 km link distances, coverage ranges in upper-frequency bands will be significantly less [13].

3 6G Use Cases

The KPIs identified for the 2nd phase of 5G hold importance in 6G networks and are slightly modified based on new 6G network requirements. A rich blend of use cases that explore 6G features can be identified in [15]. The proposed 6G use cases are concentrated on positioning, latency, device density, peak data rate, and energy efficiency. It ranges from human twin to manufacturing units (smart factory plus). The human digital twin requires low latency and peak data rate, while the smart factory additionally needs security

FREQUENCY BAND	0.3-3 GHz	3-30 GHz	30-300 GHz	0.3-3 THz	3-30 THz
WAVELENGTH	100-10 cm	10-1 cm	10-1 mm	1000-100 μm	100-10 μm
DOMINANT PROPAGATION MECHANISM	LoS, Reflection, Diraction, Scattering, Penetration	LoS, Reflection, Diraction, Scattering	LoS, Reflection	LoS, Reflection	LoS, Reflection
DOMINANT ATTENUATION EFFECTS	Free Space Loss	Free Space Loss -Transmission Loss Through Materials High at Upper Band	Free Space Loss/ Molecular Absorption -O_2 @60 GHz -H_2O > 24 GHz	Free Space Loss/ Molecular Absorption -High H_2O Peaks	Free Space Loss/ Molecular Absorption -High H_2O Peaks
SUPPORTED LINK DISTANCES	10 km	1000 m	100 m	<10 m	<1 m
TX POWER LIMITING FACTOR	Regulation	Regulation	Technology	Technology	Technology
APPROXIMATE SYSTEM BANDWITH	up to 100 MHz	400 (or 800) MHz	Up to 30 GHz	Up to 300 GHz	> 100 GHz

Figure 2 Characteristics of the spectrum bands for 5G and 6G [14].

and low latency communication. 6G aims to transform the world into a global digital village, as follows:

Human Digital Twin – With a collaboration of interdisciplinary sciences and 6G technology digital twins, the human body can be designed to form a virtual human world that realizes the human health data, monitoring in real-time. 6G will accurately associate urine biochemistry, blood routines, color Doppler ultrasound, and many other examinations with delivering a person his/her accurate or statement of their health status with time.

High-Speed Internet Access in the Air – 6G will be using new network strategies to support air users and will consider satellite transmission to enable high quality service provision (but expectedly with higher cost).

New Smart City – 6G will enable unified network architecture while adding new business scenarios. In 6G systems, IA will be deeply integrated and considered at multiple levels. for efficient transmission, internal security, seamless networking, large-scale deployment, automatic maintenance, and alarming hazards. Moreover, many sensors will be mounted over the city and on the buildings. In these environments, AI will enable different required processes without human intervention.

Cyber Robots and Autonomous Systems – 6G will boost the proliferation of autonomous systems and robots. 6G will promote a very high-level self-driving cars and will make life easy for travelers; the possibility of the self-driving car needs many efficient 6G-enable sensors, like odometer, inertial measurement equipment, sonar light detection, and many other. Furthermore, 6G will communicate between the UAVs and ground controllers. High demand applications in agriculture, science, business, military, logistics, aerial photography, disaster relief, and entertainment will be supported by swarms of UAVs.

XR (Extended Reality) is based on Holographic Communication – With the high-speed increase in the advancement of technology, expected in 2030, the need for virtual interaction will advance the Augmented Reality (AR)/VR to extended reality (XR). The customers will be allowed to enjoy the upgrade conveyed about by holographic communication and holographic display anytime and anywhere. XR will enable hearing, smell, touch, taste, sight and emotions, concerts, sports, painting, and other fully immersive holographic experiences.

Global Emergency Communication Rescue – 6G networks will be able to provide coverage in all regions by supporting different applications in emergency communications. For example, when earthquakes happen, the destruction of the terrestrial communication network can be covered with deployed unmanned aerial networks and satellite communications.

Smart Factory Plus – 6G networks will not be limited to only work in the factory. Instead, they will assure full connection and stability, security to the entire production cycle. 6G networks will quickly and flexibly connect intelligent devices that require to be connected inside the factory, and will provide dynamic adjustment according to the requirement of the production line using AI. Through the 6G network, Smart Factory PLUS will add an end-to-end closed loop.

It is expected that the 6G ecosystem creates opportunities for new businesses by implementing their use cases in real-time. According to the Finnish 6G Flagship [13], these innovations can enhance usage in a very innovative way and will pave the way to:

- Co-creation, bringing researchers and companies together;
- Research to business process, presenting research outputs to companies;
- Promoting research findings in relevant verticals/application areas while different players become forerunners in digitalization.

4 Enabling Technologies

Technologies that enable 6G use cases contain, above 6 GHz, edge AI, communication with large, intelligent surfaces, integrated terrestrial, airborne and satellite networks, wireless transfer, and RF energy harvesting, terahertz communications, cell-free communication, artificial intelligence and carrier aggregation, by implementing multi-band scheduling, as follows:

Carrier Aggregation: Carrier aggregation (CA) can improve coverage, throughput, resource reuse, system capacity, fairness, service quality, and user experience. Telecommunication service providers provide high data rate application services, offering high service quality energy-efficient and cost-effective. Consequently, mobile applications will meet the customer requirements through advanced methods for carrier aggregation, one of the main contributors to fulfill these requirements. Whereas CA has been successfully in (up to) Release 10 LTE-Advanced macro-cellular networks with typical bandwidths for each carrier of 20 MHz (and up to 100 MHz, if available), and with up to five different non-contiguous carriers, bandwidths of hundreds of MHz for each carrier, up to 32 different carriers can be supported with Release 13 and beyond [16]. This enhanced framework brings augmented flexibility to aggregate a large number of carriers in different bands and will also be helpful for Licensed Authorized Access (LAA) operation in the unlicensed spectrum where large blocks of spectrum are available.

Communication with Large Intelligent Surfaces: For enabling better spectral and energy efficiency, Multiple-Input and Multiple-Output (MIMO) will be added to the 6G, MIMO, in the direction of large, intelligent surfaces and innovative environments, will support massive wireless communications surfaces [6, 17].

Wireless Power Transfer and Energy Harvesting: With the current trend of research on wireless energy, wireless energy transfer is getting mature. It is foreseen in 6G that base stations will provide essential power transfer for user devices. RF energy harvesting enables to get power from a nearby environment using RF communications, and provides an attractive solution for lifetime power-constrained users' batteries and their recharge. According to [18], the harvesting of energy from surrounding or specialized energy sources (low-power, energy-efficient wireless devices) can be self-sufficient and environment-friendly.

Communication in the Terahertz Band: The THz band will play a significant role in 6G. It ranges from 0.1 THz to 10 THz and will provide more bandwidth, higher capacity, secure transmission, high energy efficiency, miniature transceivers, terabit-per-second link capacities, and ultra-high data rates [15].

Cell-Free Communication: Before 6G, the use of UAVs in a place with no infrastructure was assumed while, in 6G, it is planned that they will be using it for the dead zone, also allowing cell-free communication. In 6G, user equipments will be connected to the cell and the whole network. As a consequence, handover and coverage issues will be sorted out in new efficient ways.

Artificial Intelligence (AI) and Machine Learning (ML): For automation purposes, the AI and ML will fully support 6G. It will take the responsibilities of network selection, resource allocation, and handover, particularly in delay sensitive applications and to aid positioning.

Integrated Terrestrial, Airborne, and Satellite Networks: Drones will overcome terrestrial networks by supporting the hotspots connectivity. Further terrestrial and drones base stations will be in contact with satellite connectivity for better coverage availability. This type of communication aims to enhance user throughput and improve the services, considering the combination of high-altitude platforms, terrestrial base stations, and satellite stations.

5 Standards and Standardization Bodies

The outcome of any research is based on the set standards for its operation. It is defined as the requirements and specifications for a product, process, or service [19]. It is also defined as the accepted pattern with considered quality assurance. Furthermore, it is a set of regulations that directs its usage. In literal terms, standards are the way to do things to provide many benefits to one and all.

The need for standards is growing in hand with development in technology. The need for global information and communication technology (ICT) standards are evolving every day with the advancements. It is a prime necessity to have a set of standards to guide the entire development process to maintain interoperability among its processors and successors. The ICT standardization process for telecommunication networks is itself vast and critical [20, 21]. The software and hardware companies are liable to comply with the interoperability standards within the multi-vendor ecosystem.

Products must be standardized before they get into the commercial market. Standards are developed by organizations, alliances, or forums, i.e., Standards Development Organizations (SDOs).

5.1 Standards Development Organizations (SDOs)

SDOs are organizations, alliances, or forums that develop standards and regulations and are formed by stakeholders from different verticals, like manufacturers, providers, consumers, and regulators. Academia and industries play a vital role in setting out requirements and providing convincing arguments to develop a standard [19–21]. They also led down a set of regulations to ensure a legitimate development process. They also led down a set of regulations to ensure a legitimate development process. There are different types of SDOs based on different classifications. Figure 3 illustrates the SDOs classification and types, according to the European Telecommunications Standards Institute (ETSI) [21].

International *SDOs* represent the members globally and are members from National or Regional standard bodies, like ISO (International Organization for Standardization), IEC (International Electrotechnical Commission), ITU (International Telecommunication Union), among other. *Regional SDOs* include industry, academia, and national SDOs from various countries, like the African Organization for Standardization, formerly ARSO. In addition, at a country level, there are *National SDOs* (NSDOs), which issue

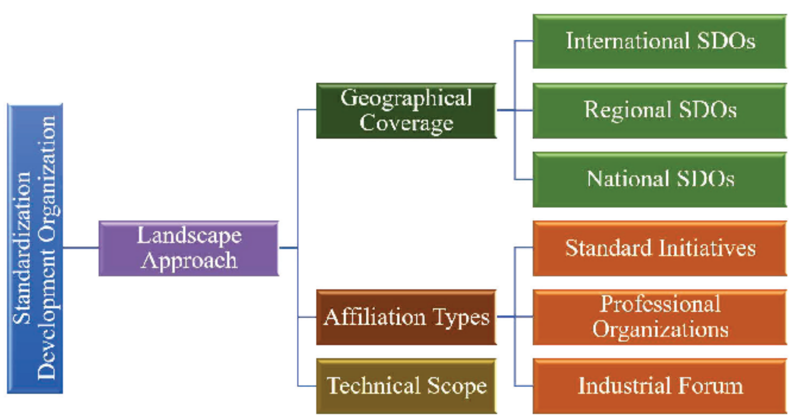

Figure 3 Types of standardization organizations.

country-specific standards and collaborate with International and Regional SDOs [20].

SDOs set up *Standard Initiatives* groups to collaborate and coordinate standardization efforts on different subjects, like the 3rd Generation Partnership Project (3GPP) and oneM2M. *Professional Organizations (POs)* connect independent professionals to promote best practices and innovation in routine activities. The Internet Engineering Task Force (IETF) and the Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) are examples of POs.

5.2 Standardization and Innovation

The introduction of standards and requirements at the early stage of Research and Development (R&D) activities is essential to avoid delays and identify the fallbacks. Standardization and research activities reside in a closely weaved structure and are developed in parallel. Depending on the landscape, standards play crucial parts in the entire development cycle. Innovation activities require that a pre-standard exists to guide the applied research. The ETSI Industry Standardization Groups (ISGs), for example, provide pre-standards to support research before achieving formal standards [20, 22]. Abided by the legal and regulatory obligations, standards define safety, safe practices, security and privacy procedures, among other.

6 Spectrum Requirements for 6G

In 2019, the Federal Communications Commission (FCC) [23] opened a new spectrum range to boost 6G research activities. It has allowed frequencies between 95 GHz and 3 THz for research purposes and labelled it “the far frontier of spectrum policy.” As 6G is going towards such high bands spectrum while operating in the ultra-high radio frequencies, enormous challenges arise in terms of propagation. Somehow, coexistence is of crucial importance for access to the frequency spectrum. Furthermore, some of the technologies as described below will be critical in 6G Networks.

6.1 Spectrum Associated with 5G Networks

The three megatrends established by ITU in IMT 2020 are Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC), and Ultra-Reliable and Low Latency Communications (URLLC). eMBB

Table 1 5G spectrum allocation

Frequency Bands	Range	Application
Low bands	$<$2 GHz	eMBB, URLLC & mMTC applications
Mid bands	2–8 GHz	
High bands	$>$24 GHz	eMBB and URLLC applications

describes the category for bandwidth-hungry applications such as high-definition telepresence, telemedicine, remote surgery, and similar. In addition, it covers technologies like Carrier Aggregation (CA), Massive Input massive output (MIMO) or Multi RAT. mMTC describes the fast-growing, high-volume, dense IoT nodes/applications, such as smart metering, smart cities or asset tracking. These are mainly applications with Low Power, Low Cost, and Low Complexity requirements. Finally, URLLC includes mission-critical services such as autonomous vehicles, healthcare, and industrial automation and these applications strike for Low Latency, String Security, and Ultra Reliability.

In 5G, the spectrum is allocated based on the applications described in Table 1 [12]. Since spectrum is a scarce resource, its availability is a challenge. Therefore, reusing the existing spectrum bands is essential in 6G to meet high bandwidth demands. The standardization initiatives to exploit the licensed and unlicensed spectrum will certainly be of fundamental importance in the coming years.

6.2 New Spectrum Beyond THz

New spectral bands need to be investigated in close collaboration with the terrestrial counterpart for propagation conditions and development of channel models encountered by the NTN (Non-Terrestrial Networks) elements both in inter-node communications and in non-terrestrial to terrestrial communications [20, 24]. In association with the 6G ecosystem for terrestrial applications, additional spectrum above 100 GHz and NTN, the frequency bands beyond 50 GHz, and even above THz are expected to be used. In addition to that, NTN systems building on free-space optical communication can use even higher frequency bands (i.e., 150–300 THz). The architecture for evolutionary NTN systems will provide a cost-efficient network configuration by supporting flexible topologies and reusable infrastructure between terrestrial and non-terrestrial networks. UAVs can act as flying nodes of the 6G network capable of processing, computing, and communication functionalities.

6.3 Associated Challenges

There is a vast difference between how devices operate in homogeneous and heterogeneous networks. The homogeneous networks support licensed bands wherein different technologies operating in unlicensed bands coexist. Some of the key challenges and design considerations are the following ones:

- Efficient spectrum sharing algorithm for complex network environments.
- Random motions of UEs and the frequent handovers in the dense environment influence spectrum sharing performance.
- 5G/6G support of reliable data transmission of varying sizes. Thus, the spectrum sharing strategy needs to support time-varying data requirements.
- Design collaboration algorithms among multiple Base Stations (BSs) and Access Points (APs) in heterogeneous networks.

7 6G Standardization

The world is moving towards the Beyond 5G communications ecosystem, supported by massive innovation and research activities. Different study groups are drafting an initial set of standards based on different use-cases and KPIs. 3GPP is expecting to publish 6G requirements beyond 2023 [7, 20]. Thus, fully-fledged 6G systems will mature in about a decade from now. Both academia and industry are working on a plethora of technologies like millimeter wavebands (mmW), terahertz (THz) communications, RISs, incorporation of Artificial Intelligence (AI) at core design, ML at the radio interface, or holographic communications. In May 2019, ITU introduced IMT 2030 concept to define B5G as a hybrid network.

Industry giants, like AT&T Inc., Facebook Inc., and QUALCOMM Inc., are working together in both R&D and deployment sectors towards 6G standards. On the other hand, the Next G Alliance [20, 24], formed in 2020, is working towards a 6G rollout from a different perspective, including deployment, R&D, and manufacturing standardization. In the east, China formed alliances to initiate 6G early research [22].

In Europe, the European Commission Radio Spectrum Policy Group (RSPG) [25] recommends supporting, 6G initiatives by the European Commission (EC) and the Member States. It opens up for the usage of the European Union (EU) harmonized spectrum, as well as the flexible usage of new THz harmonized spectrum to support fixed wireless access and wireless backhauling [22, 25]. The 6G Flagship project, centered at the University of Oulu of Finland, works on 6G technologies [13]. According to [26], 6G development should facilitate open collaboration and standardization between different stakeholders in a multi-disciplinary manner, ultimately creating true partnerships for all benefits. While pushing many technological boundaries on the journey to 6G, the UN Sustainable Development Goals (UN SDGs) are an essential lens to help prioritize development. Technology standards that support those use cases that hold the highest promise for improving human lives and protecting the environment need to be advanced first (by helping policymakers and involving communities). Vodafone Germany [27] announced a 6G research and development facility in Dresden. The EU-funded "Hexa-X" project, led by Nokia, is investigating future technologies for 6G.

Japan [22] NTT Docomo is investing considerable funds to build a 6G research infrastructure, and they target to have the 6G specifications ready by 2025. In South-Korea, Samsung has demonstrated an end-to-end 140 GHz wireless link using a fully digital beamforming solution in the THz spectrum [28] to mark its presence in 6G initiatives [15]. The R&D institute NIIR [29] agreed to test 5G technology with Ericsson while collaborating with the Skolkovo Institute of Science and Technology [22] for 6G R&D.

It is anticipated that 3GPP Release 18 will bring new features and capabilities to 5G. Release 18 is expected to be approved by 2023. The following releases are expected to focus on B5G and 6G specifications. The roadmap for 5G NR NTNs is expected to have products available with the finalization of 3GPP Rel. 17, and by 2023, 5G NR NTN systems will be operational. By 2025, new frequency bands, i.e., >50 GHz and beyond THz, will be applicable for NTN systems. Figure 4 illustrates the overall roadmap for 6G development [20].

Figure 4 European union 6G development roadmap.

8 Conclusions

This study has presented an overview of the standardization process and emphasized 6G standardization requirements while considering the challenges of spectrum usage in upper frequency bands. From a technology perspective, 6G will provide a vast opportunity to the users and MNOs to explore different services and use cases. New features of the 6G networks have been presented along with associated services and enabling technologies. After establishing newly evolved KPIs and requirements, various 6G standardization initiatives across the world have also been addressed. We have learned that the scope of standards and technology development needs to be broadened to support future ecosystems. Products need to comply with the standards to support the full capabilities of upcoming networks. Higher layers are made available for research which has brought new challenges along with enormous opportunities. Different organizations draft the specifications and standardization requirements for 6G in different use case scenarios and consider 6G guidelines, 100x data throughput, and sub-millisecond latency, compared to the 5G networks.

Consequently, the path towards the development of future wireless standards and technologies will be compelling. Critical considerations for the development of the next generation of standards and technologies are as follows. First, the SDOs need to increase their scope to bring new horizons to the communication ecosystem. Second, there is a need for the New Standards Evolution Paradigm to support reusability and scalability. Third, to overcome shortcomings in the SDOs, there is a need for Universal global standards to prevent their duplication. Finally, industry and markets should encourage the healthy and competitive development of the new and existing solution providers while ensuring a stable and sustainable global supply chain, without significant disruptions.

Acknowledgment

This work was supported by FCT/MCTES through national funds and when applicable cofounded EU funds under the project UIDB/50008/2020, ORCIP (22141-01/SAICT/2016) and TeamUp5G. TeamUp5G has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

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Biographies

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1

Introduction

Nidhi[1], Albena Mihovska[1], Anand R. Prasad[2] and Ramjee Prasad[1]

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The best way to predict the future is to create it. Technology innovation connects societies and becomes a part of everyday life.

The sixth generation of wireless communication (6G), succeeding the 5G cellular technology, opens up several possibilities in terms of technology and offered services. 6G is expected to allow usage of available higher frequency spectrums to cater to increased capacity, throughput, and low latency ($< 1\,\mu$s). 6G will witness the unification of various technologies like Artificial Intelligence (AI), Machine Learning (ML), Augmented/Virtual Reality (AR/VR), etc., to provide an immersive user experience. It is foreseen as the accelerator of transformation and innovation globally. These developments challenge the current capabilities of the enabling wireless communication systems from various aspects, such as delay, data rate, degree of intelligence, coverage, reliability, and capacity. Thus the research should seek breakthroughs from the current network architecture and communication theory to provide novel concepts that can be key for designing a new system such as 6G. At the same time, it is crucial to enable such technology developments to stay ‘green’ and take into account major environmental concerns, such as climate change, which can be achieved by novel, ‘green’ digitalized business models and other requirements for sustainability and beyond.

The fifth generation of wireless communication (5G) is in its deployment phase and has set new parameters to speed up the initiatives towards 6G.

The commercial deployment has exposed the shortcomings in the present communication techniques. Thus, it laid out the well-defined expectations from the 6G systems to support enhanced user experience applications ranging from autonomous systems to Extended Reality (XR) [1]. 6G has been defined with numerous use cases and applications [2], but it lacks its fundamental network architecture and design. It will exploit high-frequency bands and new access techniques to evolve the wireless communication era. Various enabling technologies are identified to have the potential to cater requirements of a new set of services.

1.1 Evolution of Mobile Communication

Communication has been an essential part of our lives since the beginning. The Evolution of Communication is an ongoing process aided by advancing technologies. The journey from the wired telephone to AI-aided real-time communication [3] has marked importance for a better, well-connected and progressing society. The wireless communication sector is considered a “Living” industry as it continues to grow. The growth is directly proportional to demands in society. So far, we have witnessed five generations of mobile communication and are on our way to more upcoming generations. In the First Generation (1G), Second Generation (2G), Third Generation (3G), Fourth Generation (4G) mobile communication, the “G” represents the “Generation”. Every decade a generation of mobile communication is succeeded by a new one offering distinct features and services to meet user and network demand. The critical characteristic differences in mobile generations are data traffic, data rate, throughput, latency, coverage, device density, reliability, and security [4].

1.1.1 1G – First Generation of Mobile Communication (Analogue Systems)

1G was launched in 1979, and it marked the first generation of cellular telephony. It was based on analogue technology and was dedicated to voice calling. It uses narrowband frequency channels to transmit voice signals. With 1G, several standards were developed regionally simultaneously [5, 6], such as Nordic Mobile Telephone (NMT), Advanced Mobile Phone System (AMPS) and Total Access Communications System (TACS). The maximum achieved speed for 1G systems was 2.4 Kbps with poor battery life, less security and voice quality.

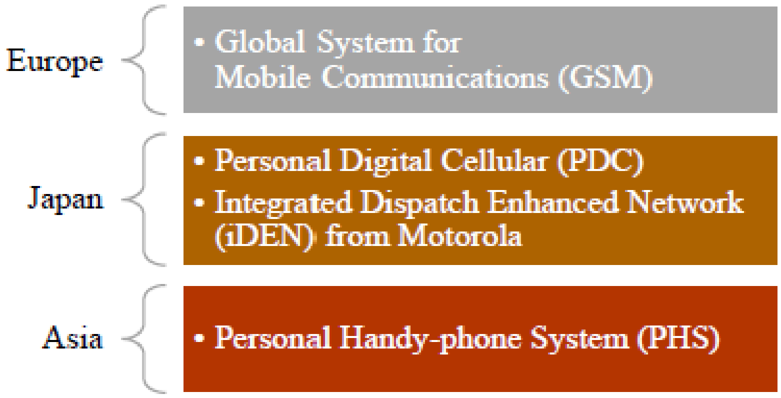

Figure 1.1 Worldwide Initiatives for 2G Mobile Systems

1.1.2 2G – Second Generation (Digital Systems)

The second generation of mobile communication was launched in the early 1990s, and these mobile systems use digital radio signals. The driving force behind 2G was to add security and reliability to the communication channel [4]. 2G standard systems witnessed several independent initiatives regionally. Figure 1.1 illustrates the country-wise initiatives.

GSM was introduced by European Telecommunications Standards Institute (ETSI) in 1987 [7]. It implemented Time Division Multiple Access (TDMA) and Frequency Division Duplex (FDD) schemes. Alternatively, Code Division Multiple Access (CDMA) was introduced by Qualcomm [8]. These multiplexing schemes allowed 2G systems to incorporate multiple users on a single channel. In addition to the voice calls, 2G systems offered data services, Short Messaging Systems (SMS) and enhanced features of conventional calling like call hold, conferencing, etc. With the General Packet Radio Service (GPRS), 2G systems achieved a speed of 50 Kbps, and with Enhanced Data Rates for GSM Evolution (EDGE), the rate was up to 1 Mbps.

1.1.3 3G – Third Generation

2001 witnessed the rising of 3G Mobile Systems. The International Telecommunication Union (ITU) defined the International Mobile Telecommunications 2000 (IMT-2000) framework [9] for the 3G cellular networks. 3G systems marked the revolutionary changes in mobile communications by offering services like web browsing, email, video downloading, picture sharing and fast internet speed at a rate of 200Kbps. It marked the switch from multimedia phones to Smartphones. It offered a cost-efficient increased data rate along with enhanced voice quality. Universal Mobile Telecommunications System (UMTS) was introduced with 3G systems. It used wideband CDMA (WCDMA) with achieved data rates up to 2 Mbps (stationary) and 384kbps (mobility). The theoretical maximum data rate for HSPA+ is 21.6 Mbps. High-speed internet made data streaming one of the killing applications of 3G.

1.1.4 4G – Fourth Generation

4G mobile systems were based on the IMT-Advanced requirements [10]. 4G systems' approach was practical to offer users high speed, high quality and high capacity. It promised to achieve 100 Mbps (Mobility) and 1 Gbps (Stationary) with a reduced latency of 300ms to <100ms. 4G systems reduced the network congestion significantly. It improved in-built security and introduced the concept of multimedia and the internet over IP. The key enabling technologies include Multiple Input Multiple Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM). It also defined Heterogeneous Networks (HetNets), Small Cells (SC) [12] and additional features like Carrier Aggregation (CA) [11], Coordinated Multipoint (CoMP) and advanced Multiple-Input Multiple-Output (MIMO) transmissions.

4G systems also introduced the following positioning methods and enhancements [13];

- *Network-Based Positioning* (Release 10 [14, 15])
- *Radio Frequency Pattern Matching* (Release 9 [16]- Release 12 [16])
- *Positioning Enhancements* (Release 9 [17]- Release 12 [18])

1.1.5 5G – Fifth Generation

5G systems are currently in the commercial deployment phase and intended to improve their predecessor-4G through data rates, connection density, latency, and other enhancements. These systems exploited the 30 GHz – 300 GHz spectrum of millimetre waves (mmWave) to achieve a maximum of 35.46 Gbps. It utilized the concepts of Small Cells to increase coverage and reduce latency [12]. 5G systems also exploited advanced access technologies such as Beam Division Multiple Access (BDMA), Non-Orthogonal Multiple Access (NOMA), Quasi-Orthogonal Sequences, Filter Bank Multi-Carrier (FBMC),

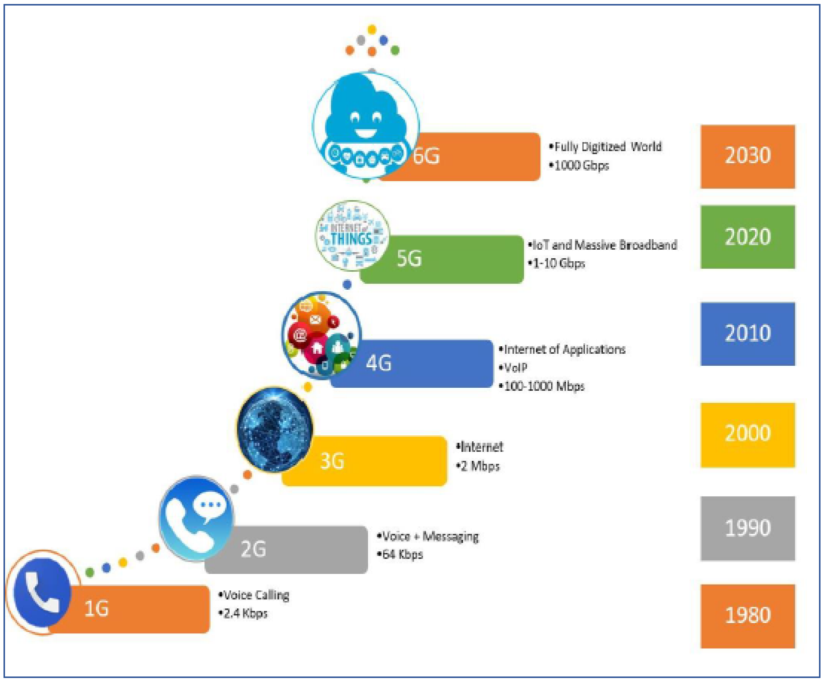

Figure 1.2 Evolution of Mobile Communication

[19, 20] etc. The BDMA technique provides base stations multiple access by facilitating the antenna beam divided based on the base station location. The scalable Orthogonal Frequency-Division Multiplexing (OFDM) is dominant in 5G networks to achieve ultra-low latency. It also incorporated Network Slicing (NS) [21] to cater customized services from Mobile Network Operator (MNO) side based on the Service Level Agreement (SLA). On the user experience side, implementing AI, AR/VR, and XR opened new use cases, applications, and services. Figure 1.2 illustrates the distinctions between 2G, 3G, 4G, 5G, and 6G.

1.2 6G KPIs and Use Cases

Different studies and research bodies, including the 3rd Generation Partnership Project (3GPP), have specified standards based on bandwidth, data rate, latency, access technologies, energy and spectrum efficiency, connection

1.4 6G System Architecture

6G networks are foreseen as massive IoT use cases and a magnificent amount of data. As discussed earlier, it is crucial to design the network components such that they autonomously work in parallel to provide ubiquitous connectivity and coverage. AI and ML are eminent in 6G system architecture, making it intelligent, self-evolving/configuring, self-organizing, and self-healing. The main identified pillars to building 6G infrastructure are as follows;

- Air Interface
- New Spectrum
- Application of AI and ML algorithms
- Interoperability
- Coexisting Radio Access Technologies (RAT)

1.5 6G Standardization

Worldwide activities and alliances from industry and academia are taking initiatives towards 6G standards. The Next G Alliance is focused on 6G deployment, research and manufacturing standardization [32]. The European Commission Radio Spectrum Policy Group (RSPG) [33] has specified various requirements for the 6G initiatives in Europe. To add to the list, The 6G Flagship project (University of Oulu of Finland) [34], Vodafone Germany [35], NTT Docomo, Japan [36], Samsung-South Korea [37], NIIR [38] and many more are working on 6G standardization activities from various perspectives. 3GPP [22] is expected to release 6G specifications in its Release 18 by 2023 [39].

1.6 Challenges in 6G

The key challenges foreseen in 6G networks are illustrated in Figure 1.7. These challenges are covered gradually in the following chapters.

1.7 Book Overview

"*6G Enabling Technologies: New Dimensions to Wireless Communication*" intends to highlight the critical aspects of future wireless technologies. The motivation of this book is to bring a comprehensive view of research activities towards future mobile networks - 6G. In this book, we present contributions

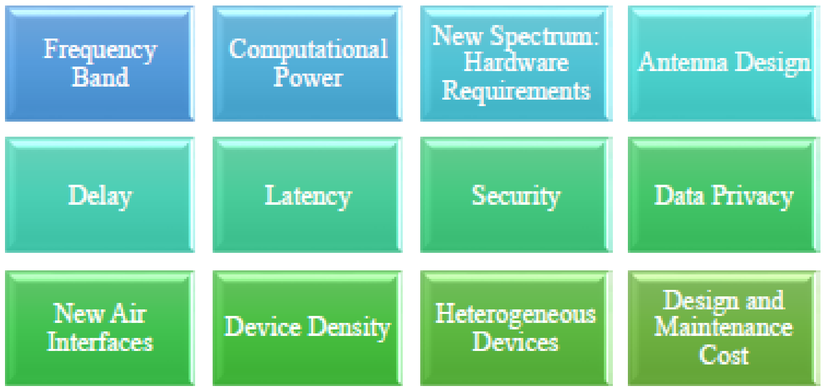

Figure 1.7 6G Challenges

from pioneers across the globe to bring forward the research trends in 6G Wireless Networks. The book introduces critical technologies behind 6G wireless communication and mobile networking. It drafts the fundamental system requirements, enabling technologies, eminent drivers, evolved use cases, research requirements, challenges, and open issues expected to drive 6G research. It explains a general vision of 6G technology, including the motivation for conducting 6G research and recent progress in 6G research, followed by chapters on architectural evolution and enabling technologies, including the advancements in infrastructure. It targets students and young researchers involved in telecommunications and provides them with cutting-edge wireless networking technologies and market analysis. The motivation is to understand the research activities for future networks fully.

This book not only discusses the potential 6G use cases, requirements, metrics, and enabling technologies but also discusses the emerging technologies and topics such as 6G Physical Layer (PHY) technologies, Reconfigurable Intelligent Surface (RIS), Millimetre-Wave (mmWave), and Terahertz (THz) communications, Visible Light Communications (VLC), transport layer for Tbit/s communications, high-capacity backhaul connectivity, cloud-native approach, Machine-Type Communications (MTC), edge intelligence, and pervasive Artificial Intelligence (AI), network security and blockchain, and the role of the open-source platform in 6G. The book is divided into sections, as illustrated in Figure 1.8.

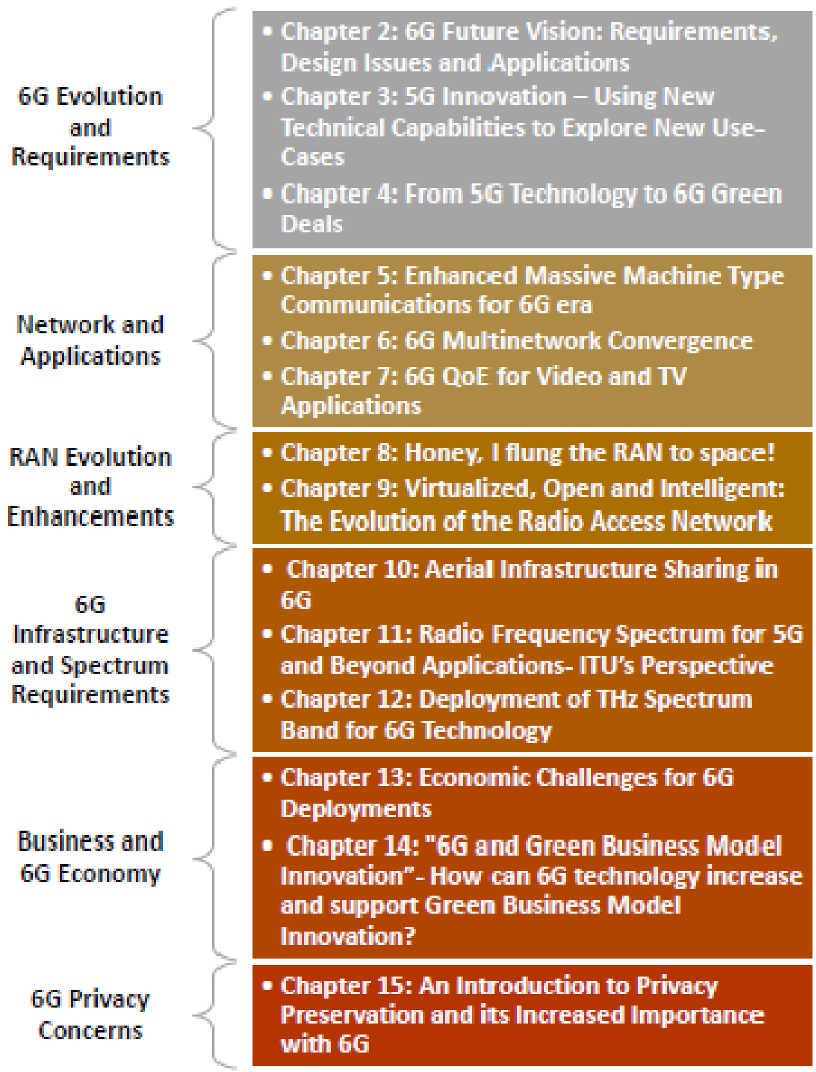

Figure 1.8 Book Structure

- 6G Evolution and Requirements
- New Use-Cases

- Network and Applications
- RAN Evolution and Enhancements
- 6G Infrastructure and Spectrum Requirements
- Business and 6G Economy
- 6G Privacy Concerns

1.8 Conclusions

This book presented the international research effort towards 6G communication systems. In particular, the book focused on the various technology enablers of 6G.

The capabilities and design dimensions of Future wireless networks (FWN) based on 6G are being driven by disruptive technologies such as AI, ML, deep analytics, software and, advanced computer technologies; advanced sensing, 3D imaging, AR/VR. This, in turn, drives the emergence of new applications that are manifested by stringent performance requirements.

The book comprises valuable discussions highlighting the need to efficiently and flexibly provide diversified services such as Enhanced Mobile Broadband (eMBB) access, Ultra-Reliable Low-Latency Communications (URLLC), and massive Machine-Type Communications (mMTC). The representative scenarios and services evolving from 5G (described in Chapters 2–4) are Further-Enhanced Mobile Broadband (FeMBB), Ultra-Massive Machine-Type Communications (umMTC), Extremely Ultra-Reliable and Low-Latency Communications (eURLLC), and Extremely Low Power Communications (ELPC). These scenarios demand peak data rates >1 Tbps, the latency of 10-100μs, and user experienced data rate >1 Gbps; such performance requirements are pretty beyond current 5G capabilities.

However, satisfying these requirements is essential for delivering the envisioned FWN applications that are emerging due to advances in technologies, such as sensing, imaging, displaying, and AI, with application scenarios that more and more will be based on AR/VR content. Related issues were discussed in Chapters 10–12. Enabling the use cases for FWN is an essential driver for the user demand and the value proposition, the basis of business model innovation, which is a topic discussed in Chapters 13, 14. Recently, many standardisation bodies have started establishing a 6G initiative focusing on 6G use cases and requirements.

With advances in AI, machines can transform data into reasoning and decisions that have the potential to enable the envisioned applications over 6G networks, as described in Chapters 5–7. At the same time, such advances introduce machines as a new type of user, in addition to humans, that make the demands on the performance requirements even more stringent. As today's domestic and industrial machines transform into swarms of multi-purpose robots and drones, new approaches based on human-machine haptic and thought interfaces to control them from anywhere should become an integral part of the future wireless networks. Network operators face considerable challenges in extending the network coverage and meeting the increased capacity demands while using a limited pool of capital and resources. Manual configuration of networks for Management and Orchestration (MANO) will make things even more complicated, time-consuming, susceptible to error, and expensive. AI can provide unprecedented opportunities to the MANO framework, unleash vast performance potentials of wireless networks, identify correlations and anomalies that cannot be observed by inspection, suggest novel ways to optimise network deployment and operation and facilitate making decisions with minimal human intervention. AI and Data Analytics (DA) will help solve traffic management issues and influence new antenna design, dynamic sharing of spectrum, and self-organised network architectures to improve the design and deployment of 6G. The deployment of AI and data analytics has already been proposed in various standards, including the 3rd Generation Partnership Project (3GPP) Network Data Analytics (NWDA) and the European Telecommunications Standards Institute (ETSI) Experimental Network Intelligence (ENI) NWDA utilises the approach of slice and traffic steering and splitting. At the same time, ENI uses a cognitive network management architecture and context aware-based approach.

Chapters 8, 9 presented research towards the opening of the radio access network (RAN) to enable interoperability of vendor solutions; for the efficient implementation of intelligence in the network and novel access solutions. The Open-RAN concept allows for the separation of the digital and radio components of the RAN infrastructure and, thus, enriches the resource management, control, and other functions within the RAN with AI.

The design of 6G networks needs to consider the QoE for the user into strong consideration. The general principle of QoE-awareness in network design should be implicitly supported in all layers of the functional architecture and take into account the subjective nature of the perceived experience. Therefore, it is crucial for QoE management to completely integrate precise QoE monitoring mechanisms focused on transparent real-time data collection and storage, effective big data and ML algorithms for data evaluation and functions that will ensure the adjustment and reshaping of collected data across the network components (Chapters 6, 7).

Biographies

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He is also an advisor to several organizations such as CTIF Global Capsule, GuardRails and German Entrepreneurship Asia. Anand is an innovator with 50+ patents, a recognized keynote speaker (RSA, MWC etc.) and a prolific writer with six books and 50+ publications. He is a Fellow of IET and IETE.

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Ramjee Prasad is a member of the Steering, Advisory, and Technical Program committees of many renowned annual international conferences, e.g., Wireless Personal Multimedia Communications Symposium (WPMC); Wireless VITAE, etc.

Overview of 5G New Radio and Carrier Aggregation: 5G and beyond Networks

Overview of 5G New Radio and Carrier Aggregation: 5G and Beyond Networks

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***Abstract*—Recent pandemic has affected the telecom industries with the need for connectivity more than before. It has accelerated the research and innovation activities towards 5G and beyond networks. The purpose of the presented work is to provide the urgency of the situation and state the development with the 5G NR (New Radio). 3GPP launched the standardization activity for 5G system in Release 15, 5G New Radio (NR). This paper presents a comprehensive overview of the development of NR, including deployment scenarios, numerologies, frame structure, new waveform and enhanced carrier aggregation (CA). Since coverage and capacity are the key elements of an optimal 5G user experience. Carrier aggregation is visualized as critical for 5G and upcoming networks. It enhances data capacity by aggregating carriers from same/different spectrum bands. Release 10 introduced carrier aggregation and in LTE-Advance, up to five component carriers can be aggregated but commercial solutions use up to three component carriers providing a maximum downlink speed of up to 450Mbps. This paper provides an overview of carrier aggregation, its needs and set of potential solutions and research scope to mitigate the foreseen challenges with CA.**

Keywords— 5G NR, Carrier Aggregation, LTE-Advance

I. Introduction

A. Societal Impact on Telecom Industry

The year 2020 has affected every genre of lives. Drastic transitions have been observed at the personal and professional levels. The demand for ubiquitous connectivity has witnessed a quantitative transition, as people tend to be online more than before. There is a shift of mobile data traffic from commercial areas, offices, etc. to residential areas by virtue of lockdowns. New pandemic lifestyle has triggered work-from-home culture in the majority of sectors including education, trading, software industries, conferences, webinars, etc. resulting in intensified demand for connectivity in both fixed and mobile networks.

The intensified data usage is directly proportional to the rise in services like work-based applications, virtual networks, video conferencing, entertainment apps, social media uptime, etc. These services also demand a high quality of service with minimum latency. Ericsson's Mobility Report 2020 [2] suggested that the mobile data traffic displayed an uneven distribution pattern and an increase ranging from 20-70 per cent in the voice calls activities during the initial lockdown phase. The fixed residential networks are experiencing high mobile data traffic while the usual hotspots have shown decreased or negative mobile traffic records.

This extensive transition worldwide has created a huge growth in mobile network traffic. Measures are taken to support the unusual growth and it has accelerated the need for 5G and beyond network deployment. Ensuring connectivity while maintaining QoS are the main aim of the telecom industries. To have a control of the situation, it has become utmost priority to connect health cares, hospitals, running businesses, education, etc. As per the survey made by [2], 83% asserted the Information and Communication Technologies (ICT) have been essential to cope up with daily activities.

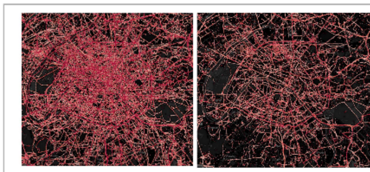

Figure 1 Transition in Mobile Network Traffic in central Paris two weeks before (a) and after (b) lockdown [2]

Most of the consumers have raised concerns in the degraded service and performance. Many telecom giants have already responded to the new societal standards like Vodafone, Proximus, Telenor, Telefonica, Orange, etc. [3].

Therefore, telecom giants have escalated the initiatives to bridge the gaps in connectivity. The research and innovation activities are getting intense towards 5G deployment and technologies to support beyond 5G era.

B. 5G Network Expectations

The need for 5G Network is more now than before to match up the demand to maintain the new lifestyles. [2] Suggests that consumers rely on the upcoming solutions for better network coverage, reduced latency and higher speeds compared to current 4G networks. New use cases evolved where 5G enabled robots can serve as medical assistants. The constructive consequence of this pandemic is demand for 5G to replace the legacy broadband infrastructure.

5G system was designed to meet IMT-2020 requirements set by the ITU-R [5]. 5G will provide more advanced and enhanced capabilities compared to 4G LTE (IMT-Advanced). Table 1, summarizes the 5G requirements. 5G targets a 20x peak data rate, 10x lower latency and 3x spectral efficiency than existing 4G LTE systems. The full-fledged 5G network rollout is awaited to exploit undisrupted services. Some of the 5G expectations are [2]; Autonomous Vehicles (such as AR/VR assistance, Infotainment, AR Dashboards), Resilient Networks, Remote healthcare (such as Ambulance Drones,

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Smart Equipment), Enhanced Augmented and virtual reality (AR/VR) applications (Technical Assistants), Green and Cost-Efficient Network [4], Financial Services, Agricultural Innovations (such as Predictive Maintenance, Autonomous Harvesting), Media and Entertainment (such as High-quality streaming, 3D broadcast), Manufacturing (such as Cloud Robotics, Goods Tracking), etc.

To have a mature 5G connectivity, we are still lagging on the technology and the required 5G hardware. In this paper, we are presenting an overview of Carrier Aggregation as one of the prominent technologies to achieve high network throughput and spectral efficiency. This paper is organized into the following sections; Section I is the introduction, which comprehensively explains the current scenario and 5G requirements. Section II defines the 5G New Radio and Spectrum. Section III describes briefly Carrier Aggregation and its benefits. It also describes LTE-CA. Section IV drafts the scope of CA for 5G and beyond networks and Open challenges.

Table 1: Key performance requirements of IMT-2020

Requirement		Value
Data Rate	Peak	DL: 20Gbps UL: 10Gbps
	User Experienced	DL: 100Mbps UL: 50Mbps
Spectral Efficiency	Peak	DL: 30bit/s/Hz UL: 15bit/s/Hz
	Average	DL: 3.3 ~ 9 bit/s/Hz UL: 1.6 ~ 6.75 bit/s/Hz
Area Traffic Capacity		10 Mbps/m^2
Latency	User Plane	1 -4ms
	Control Plane	20ms
Connection Density		1,000,000 device/km^2
Reliability		1-10^{-5} success probability
Mobility		0km/hr ~ 500 km/hr
Mobility Interruption Time		0ms
Bandwidth		100 MHz

II. 5G New Radio and Spectrum

3GPP is responsible for defining a new 5G core network (5GC) and a new radio access technology (5G "New Radio"). 3GPP Release 15 [6] introduced 5G New Radio (NR) in 2018 as the global standard for the air interface. 5G NR has following deployment modes [7];

- Standalone Mode: In this deployment, User Equipment (UE) operated by 5G Radio Access Technology without any requirement 4G LTE RAT. NR gNB acts as the master node and offers service in both control and user planes.
- Non-Standalone Mode: It combines multiple RAT. In this mode, both LTE and 5G cell connections are required. LTE/LTE-A eNB will be the master node and act as the anchor carrier i.e. all the control plane will be with eNB and gNB will serve the user plane.

3GPP Releases 16 [8] and 17 [9] demonstrated new enhancements of 5G NR which includes existing features and new deployment verticals. The carrier frequencies are increased to achieve higher data rates and to accommodate more spectrum needs. [10] For 5G NR deployment with existing LTE/LTE-Advance networks with same or different coverage, it is important to consider backward compatibility. The feasible deployment scenarios are considered based on the Master Node selection.

A. 5G NR Design Specifications

5G NR is designed specifically to co-exist with the LTE to utilize existing cellular structure and enhances overall network performance by reduced interference, low latency, usage of beamforming and multiple antennae.

The significant enhancements in 5G NR features are [8] as follows:

- Multiple-Input, Multiple-Output (MIMO) and Beamforming Enhancements
- Dynamic Spectrum Sharing (DSS)
- Dual Connectivity (DC) and Carrier Aggregation (CA)
- User Equipment (UE) Power Saving

The new verticals and deployment scenarios from Release 16 are mostly as follows:

- Integrated Access and Backhaul (IAB)
- NR in Unlicensed Spectrum
- Industrial Internet of Things (IIoT)
- Ultra-Reliable Low Latency Communication (URLLC)
- Intelligent Transportation Systems (ITS)
- Vehicle-to-Anything Communications Positioning. (V2X)

3GPP releases [7][8][9] eventually introduced the new features called, enhanced mobile broadband (eMBB), URLLC and massive machine-type communications (mMTC). These new services offer urgent data delivery with ultra-low latency and massive packet transmissions are of crucial importance for NR. eMBB decribes the category for bandwidth-keen applications. such as high-definition telepresence, telemedicine and remote surgery and supports high capacity and high mobility radio access. URLCC describes mission-critical services such as autonomous vehicles, healthcare, and industrial automation. These applications strikes for Low-Latency, String-Security and Ultra-Reliability. mMTC describes the fast-growing, high-volume, dense IoT nodes/applications. Smart Metering, Smart Buildings, Smart Cities and Asset Tracking are some of them. These are mainly applications with Low-Power, Low-Cost, and Low-Complexity.

Integration of the above mentioned features and to optimize network performance, an efficient Resource Management algorithm is required [10]. This also requires a ready model with concrete deployment scenario, frame structure, access technologies and enhanced Carrier Aggregation schemes (discussed in following sections).

B. 5G NR Frequency Bands

5G NR frequency bands are categorized into two different ranges, namely Frequency Range 1 (FR1) and Frequency Range 2 (FR2). The 5G frequency bands are mainly sub 6GHz and mmWave bands. Sub 6 GHz is used for long-range while mmWave bands are suitable for short-range. 3GPP TS 38.101 [8] provides a list of frequencies of the 5G NR standard. FR1 includes sub-6GHz frequency bands has been extended to cover potential new spectrum offerings from 410 MHz to 7125 MHz. FR2 includes frequency bands from 24.25 GHz to 52.6 GHz.

Since we know, the spectrum is the scarce resource so have available spectrum, unlicensed frequency bands are being exploited [8]. The NR operations in unlicensed spectrum target the 5GHz and 6GHz unlicensed bands. It supports both standalone operation and licensed-assisted operation in NR Standalone.

C. NR Numerology, Waveforms and Frame Structure

In comparison with LTE subcarrier spacing, 15kHz, NR supports multiple subcarrier spacing summarized in table 2 [11]. This support to multiple types of sub-carrier spacing in NR distinguishes it from LTE.

In 5G NR, each numerology is labelled as a μ and $\mu = 0$ represents 15 kHz similar to that in LTE. And in the second column, the subcarrier spacing of other μ is derived from ($\mu =$ 0 and scales up to the power of 2.

Table 2 Types of NR Numerology

μ	$\Delta f = 2^{\mu}.15[kHz]$	Cyclic Prefix (CP)
0	15	Normal
1	30	Normal
2	60	Normal, Extended
3	120	Normal
4	240	Normal

The slot length inversely proportional to the numerology, wider the subcarrier spacing- shorter the slot length as explained in Table 3[11] [12].

Table 3 NR Slot Lengths

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

According to TR 38.802 [12] and TR 38.804 [13], the maximum channel bandwidth per NR carrier is 400 Mhz in Release 15 [7]. In NR, transmitters and receivers have a wider bandwidth at high-frequency bands. The high carrier frequencies and a large subcarrier spacing are exposed to the Doppler Effect and inter-carrier interference (ICI) respectively.

The sub-frame length of NT is 1ms, which consist of 14 OFDM symbols, each15kHz subcarrier spacing and normal Cyclic Prefix (CP). Each slot can carry control signals at the start and/or end OFDM symbol and enable gNB to allocate resources for emergency services under URLLC applications. The TDD scheme in NR is more flexible than that in LTE. NR adopts mini-slots to support small size packet transmissions with similar features.

The frame length is composed of 12 subcarriers in frequency domain capable of basic scheduling supporting same subcarrier spacing and prefix.

For considering waveforms for NR, many schemes were investigated like filterbank multicarrier (FBMC), generalized frequency-division multiplexing (GFDM), etc. over key characteristics like enhanced bandwidth, increased efficiency in terms of power and spectrum, reduced interference, etc. OFDM based new waveform makes one of the potentials for NR because of its easy and flexible design.

III. CARRIER AGGREGATION AND 5G NR

Carrier Aggregation is the technology to enhance the data capacity, throughput, data rates and improved network performance in the uplink, downlink, or both. It allows efficient spectrum utilization by combining two or more carriers in the same or different frequency bands, into a single aggregated channel [13][15]. It enables aggregation of FDD and TDD and licensed and unlicensed carrier spectrums. Carriers can be aggregated in three ways as illustrated in Figure 2:

- Intra Band Contiguous CA: It is a rare scenario with given frequency allocations today but can be possible with new spectrum bands like 3.5 GHz and so. This aggregation is the simplest in terms of hardware implementation. The contiguous channels are of the same size and in the same spectrum band.
- Intra Band Non- Contiguous CA: It is expected in countries where spectrum allocation is noncontiguous within a single band, when the middle carriers are loaded with other users, or when network sharing is

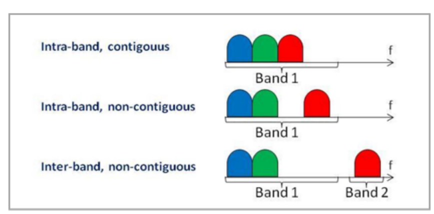

Figure 2 Carrier Aggregation

considered. The non-contiguous channels are of different sizes within the same spectrum bands.

- Inter Band Non- Contiguous CA: It is the most realistic scenario since there is no contiguous wide spectrum to achieve the IMT-Advanced peak data rate. The channels are of the same size in different spectrum bands.

Carrier aggregation was introduced in Release 10 as a new feature to combine different component carriers to increase overall bandwidth and throughput. It played an important role to provide operators flexibility for making the best use of available spectrum. 44 frequency bands are available providing 700 MHz -2.7 GHz theoretically that can be aggregated, but commercial solutions can use up to three component carriers with an achieved downlink speed of up to 450Mbps.

Carrier aggregation technology is critical to allow coexistence of 4G and 5G by allowing operators to combine different 4G carriers with 4G carriers or with 5G carriers. The LTE-A standard specifies that each of the component carriers (CCs) is limited to 20 MHz of bandwidth and aggregation of up to five allows a maximum of 100 MHz of total signal bandwidth which gives a fivefold increase in channel capacity and data speed [14].

A. Cross Carrier Scheduling

Cross-carrier scheduling is an important feature in HetNets to mitigate the issues of inter-cell interference at cell-edge. It can be used to balance the traffic loads and scheduling across different component carriers [15][16][17].

B. Dynamic Spectrum Sharing

DSS provides a cost-effective and efficient solution for enabling a smooth transition from 4G to 5G by allowing LTE and NR to share the same carrier. In release 16, the number of rate-matching patterns available in NR has been increased to allow spectrum sharing when CA is used for LTE [15].

C. Dual Connectivity and Carrier Aggregation

Release 16 reduces latency for setup and activation of CA/DC, thereby leading to improved system capacity and the ability to achieve higher data rates. Unlike release 15, where measurement configuration and reporting does not take place until the UE enters the fully connected state, in release 16 the connection can be resumed after periods of inactivity without the need for extensive signalling for configuration and reporting [1][7]. According to TR 38.802 [12], the following points are the highlights:

- Maximum number of Carrier Aggregation / Dual Carrier is 16
- Maximum aggregated bandwidth in phase 1 is around 1 GHz (contiguous or non-contiguous)
- Cross-carrier scheduling and joint UCI feedback is supported
- Per-carrier TB mapping is supported

D. Benefits of Carrier Aggregation

- Efficient use of available spectrum and leveraging of the underutilized spectrum.
- It allows MNOs to efficiently utilize the fragmented frequency resource.
- Network carrier load balancing: Enables intelligent and dynamic load balancing with real-time network load data.
- CA helps in the aggregation of frequencies irrespective of spectrum regulations. It can aggregate licensed, unlicensed as well as perform aggregation in shared spectrum scenario.
- Increased uplink and downlink data rates with better network performance and higher throughput.
- The expanded coverage allows carriers to scale the networks resulting in enhanced scalability.

IV. Challenges

A. Downlink CA challenges include:

- *Downlink sensitivity:* For designing a duplexer for each CC, interference between uplink and downlink at the reception at downlink needs to be considered. With large frequency separations between two bands, either a separate duplexer/diplexer or a multiplexers/hexiplexers can be used. However, a multiplexer is more challenging to develop as increases PC board area while simplifying the RF frontend.
- *Harmonic generation:* Non-linear components like transceiver output stages, power amplifiers (PAs), duplexers, etc. results in Harmonics. Design developments should consider device performance against the reduced harmonic generation.
- *De-sense challenges in CA radio design:* Limited filter attenuation causes Multiband radio signals to interfere with each other resulting into a higher probability of desense in CA applications if isolation or cross-isolation between the transmit and receive paths.

B. Uplink Challenges

To reduce maximum power as the Intra-band uplink CA signals uses more bandwidth and have higher peak-to-average-power ratios (PAPRs) than standard LTE signals. 3GPP allows for different Maximum Power Reductions (MPRs) to be applied based on different configurations of RBs. Because of higher peaks, more signal bandwidth, and new RB configurations, a Power Amplifier design needs proper tuning for very high linearity.

C. Implementation Challenges

The hardware implementation along with resource allocation is critical in CA [18]. There are crucial requirements like signal processing capabilities, Radio Frequency (RF) chains, oscillators, strong battery life, etc. From the RF context, CA-FDD implementation is more challenging.

The mobile network operators (MNOs) have fragmented frequency resource and with CA implementation this will result in coexistence of multi-operator networks placed closely [19]. The transmitter and receiver design considerations are critical to reducing the interference caused due to the undesired transmitter emissions and the cross-isolation issues as UEs communicate on multiple bands simultaneously.

V. Potential Solutions and Open Research Areas

A. Receiver and Transmitter Design Considerations

Multiplexers and RF Filters: To provide faster data rates using available spectrum chunks, the number of aggregated carriers will increase and so the simultaneous transmission within UEs. The consequences with the increased transmission in UEs leads to critical issues concerning the number of antennae, RF filtering techniques, multiplexers, quadplexers, etc. [18] [19] Multiplexers provide isolation to the aggregated carriers, simultaneous with low insertion loss and low current consumption. It also provides in-band and cross-isolation. RF filter design consideration needs to be mapped accordingly to meet the required quality of performance. The bulk acoustic wave (BAW) and temperature compensated-surface acoustic wave (TC-SAW) filters [18] needs proper matching.

Guard Band Setting: Even though in non-contiguous CA, sufficient amount of frequencies are used as a guard band to avoid interference but it still remain open to interference caused by adjacent carriers of other systems. In the case of high mobility, orthogonality of adjacent carriers will be affected by a large Doppler shift [20]. Therefore, the guard band setting for a component carrier is critical for CA irrespective of the type to have high spectral efficiency.

B. Resource Allocation and Scheduling Techniques

Sleep Time: Sleep Control is elementary in HetNets in terms of having reduced power consumption and high QoS. It has been investigated as a mean for QoS provision but limited research is done so far for CA operations [23]. Sleep awareness management for CA Operations can benefit from developing energy-efficient networks with improved performance.

Power Allocation: Optimization through joint resource allocation and relay-based component carrier selection can boost system performance and interference mitigation [20] [23]. For Uplink (UL) communication, the main constraint is the transmission power. Bandwidth enhancement is not effective if the user device reaches its maximum transmission power. Increase in peak-to-average power ratio (PAPR) is critical with multiple simultaneous transmissions as it reduces UE transmission power. This makes it challenging for users to allocate multiple component carriers with a power limitation, especially in unfavourable channel conditions. Adequate component carrier selection schemes in uplink can enhance system performance.

Cross Carrier Scheduling: Cross carrier scheduling techniques are effective in handling intercell interference (ICI). ICI is a major issue with users at cell-edge [22]. Physical Downlink Carrier Channel (PDCCH) requires more transmit power than the traffic channel. With this scheduling technique, the component carriers are divided into primary and secondary to offer service to the primary cell and the secondary cell respectively.

Packet Scheduling: Packet scheduling and component carrier assignment are significant CA functionality for downlink transmission. A large amount of overhead is caused because of uplink signalling transmissions which make packet scheduling and channel awareness characteristics important. This scheduling prioritises user with good channel state for allocating resources. It uses the multiuser frequency domain scheduling diversity. The prominent requirement for packet scheduler design is to handle multiple component carrier environments.

VI. Conclusions

CA is significantly used to achieve high spectral efficiency by utilizing the fragmented frequency resources by MNOs. The enhancements in the 3GPP's releases 16 and 17, CA is an eminent technology for upcoming networks. It contributes to a wide range of applications and use-cases. With recent enhancements, CA can aggregate up to sixteen component carriers can be aggregated to achieve a bandwidth up to 1GHz because of the latest enhancement in 5G NR specifications. CA comes as a solution scarcity of available spectrum, it has its critical implementation challenges. The complex filter designs, the importance of Multiplexers to different crucial considerations from RRM perspective like power allocation and resource block scheduling will open a new research area and the market for future networks.

Acknowledgement

This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

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BIOGRAPHIES

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Survey on Resilient 5G Second Phase RAN Architectures and Functional Splits

Survey on 5G Second Phase RAN Architectures and Functional Splits

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***Abstract*—The Radio Access Network (RAN) architecture evolves with different generations of mobile communication technologies and forms an indispensable component of the mobile network architecture. The main component of the RAN infrastructure is the Base Station, which includes a Radio Frequency unit and a Baseband unit. The RAN is a collection of base stations connected to the core network to provide coverage through one or more radio access technologies. The advancement towards cloud-native networks has led to centralizing the baseband processing of radio signals. There is a trade-off between the advantages of RAN centralization (energy efficiency, power cost reduction, and the cost of the fronthaul), and the complexity of carrying traffic between the data processing unit and distributed antennas. 5G networks hold high potential for adopting the centralized architecture to reduce maintenance costs while reducing deployment costs and improving resilience, reliability and coordination. Incorporating the concept of virtualization, and centralized RAN architecture enables to meet the overall requirements for both the customer and Mobile Network Operator. Functional splitting is one of the key enablers for 5G networks. It supports Centralized RAN, virtualized Radio Access Network, and the recent Open Radio Access Networks. This survey provides a comprehensive tutorial on the paradigms of the RAN architecture evolution, its key features, and implementations challenges. It provides a thorough review of the 3rd Generation Partnership Project functional splitting complemented by associated challenges and potential solutions. The survey also presents an overview of the fronthaul and its requirements and possible solutions for implementation, algorithms, and required tools whilst providing a vision on the evaluation beyond 5G second phase.**

***Index Terms*—eCPRI, Functional Splitting, Open RAN, Centralized RAN, Virtualized RAN, BBU, CU, DU, 5G Second Phase.**

I. Introduction

This work was supported by FCT/MCTES through national funds and when applicable co-funded EU funds under the project UIDB/50008/2020, ORCIP (22141-01/SAICT/2016), COST CA 20120 INTERACT, SNF Scientific Exchange-AISpectrum (project 205842) and TeamUp5G. TeamUp5G has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

Each generation of mobile communication technologies (1G, 2G, 3G, 4G and 5G first phase) has enabled the telecommunications operators to upgrade their network and renew its infrastructure to fulfil their customer's demands. However, decreasing costs, reducing energy consumption and improving the service have been limiting network operation. A shift towards novel radio access technologies is thus in order. Fifth Generation (5G) contributions are gradually going through the commercialization phases. With the 3rd Generation Partnership Project (3GPP) Release 16 [1], the second phase of 5G is introduced to define the transformative and evolutionary features and capabilities of Radio Access Network (RAN). The second phase of 5G intends to enhance the battery life, performance and support multitude of applications and services. The first phase of 5G Networks is already commercialized globally. There are still few customers with 5G User Equipments (UEs). Operators have not yet solved many outstanding issues, for example, adopting a cost-effective architecture that effectively addresses the current ultra densification issue that hinders every Mobile Network Operator (MNO) [2].

With the evolution of 5G applications and services, new RAN architectures and protocols are emerging. Network densification is among the potential contenders for increasing the network capacity [3], [4]. The introduction of virtualization is transforming the communication networks and the RAN architectures including the Radio Units (RU) and the Base Band Units (BBUs) which were usually at the cellular Base Stations (BSs). The 3GPP [5] has defined the idea behind virtualization of network functions and functional splitting in order to promote RAN centralization by while reducing the total cost of densification. The idea is to support flexible, cheap, energy efficient and straight forward Remote Radio Heads (RRHs) that provide extensive benefits, such as joint processing of radio signals, load balancing, network extensions, and power reduction. 3GPP has defined the new RAN architecture where the functionalities of 5G BBU are split into several functional blocks, such as the Centralized Unit

(CU), the Distributed Unit (DU) and the RU, forming the key building blocks of the Next Generation RAN (NG-RAN). Figure 1 presents the NG-RAN concept. The splitting up of the functionalities at BBU significantly reduces the transport rate requirements. Enhanced Common Public Radio Interface (eCPRI) protocol in the fronthaul transport should provide a cost-efficient enhancement of the performance [3].

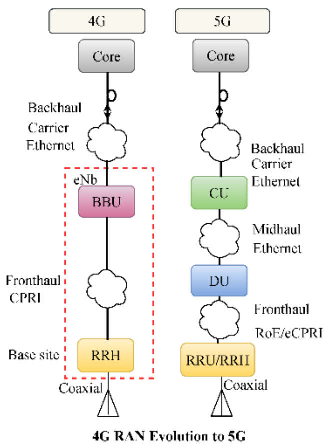

Fig. 1: The evolution of 4G RAN to 5G.

Since the beginning of 4G deployments, there are many works describing and analyzing the various functional split options. In 2018, Larsen et al. [6] gave "*an overview of where the most effort has been directed in terms of functional splits, and where there is room for further studies*". This contribution aimed to provide an update while being self-contained. The contribution exposes recent tools, emulators, simulators, and analysis of the impact of functional splitting. Furthermore, some detailed comparisons of these splits are reported together with the discussion of and their pros and cons with within different use cases are reported.

In this work, we address tools that make it possible for researchers and practitioners to analyze and choose the best functional split options according to their own requirements. We provide comparative graphs, and show how many researchers are using these tools. The published real-time implementations of the functional splits are also identified. We include our analysis and vision on the RAN fronthaul, midhaul and backhaul evolution.

The remaining of the survey is organized as shown in Figure 2. Section II-A2 starts with several definitions and then presents our current overview of the RAN terminology from 3GPP, Open RAN and other sources. Section III describes the current research status on the functional splitting, and explains each split, in detail while summarizing the essential aspects, from theory to implementation, algorithms, and tools (simulators or emulators) requirements. Section IV addresses ongoing research on front/mid/backhaul and explains the move from Common Public Radio Interface (CPRI) to the enhanced CPRI (eCPRI). Section V presents a detailed overview of recent advancements in RAN architectures. We discuss virtualized RAN (vRAN) and Open Radio Access Network (OpenRAN) conceptual architectures in detail and how they evolved, and address the main implementation challenges and opportunities in Section VI. Finally, conclusions are drawn in Section VII.

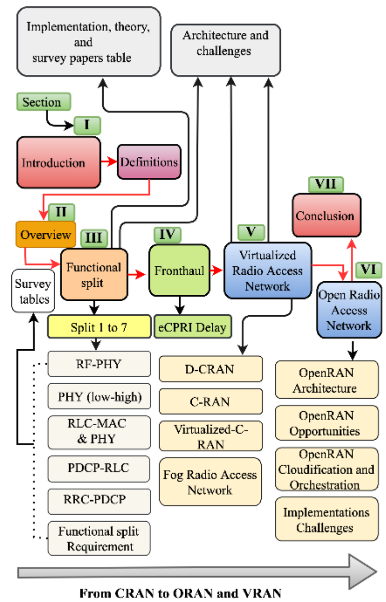

Fig. 2: Overall structure of the survey, with details of sub sections of the paper.

II. Overview

A. Overview of O-RAN Fronthaul

Fronthaul indicates the connection between the multiple RRHs and the centralized BBUs, facilitating a more expansive coverage range and faster data transmissions. As defined by the O-RAN Fronthaul specification [7], the fronthaul interface is defined as Open Fronthaul when it acts as an interface between the multi-vendor DU and RU by the defined signaling and control formats [8]. The open fronthaul architecture defines the Open RAN Distribution Unit (O-DU) and the Open RAN Radio Unit (O-RU) entities as logical nodes for accommodating RLC/MAC/High-PHY layers and Low-PHY with RF processing based on lower layer functional splits respectively.

1) Operational Planes: The O-RAN Fronthaul defines four different operational planes as shown in Figure 3(a) [7]–[9].

- **Control Plane (C-Plane):** It establishes the control between the DU and RU in real-time and transmits messages defining the scheduling information, data transfer coordination requirements, FFT size, length of the cyclic prefix, subcarrier spacing, beamforming and downlink precoding configurations, etc.

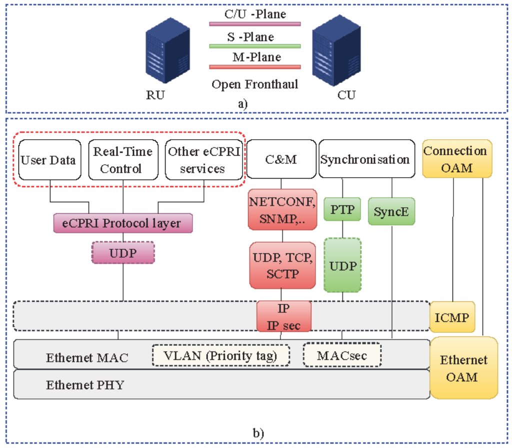

Fig. 3: Typical fronthaul protocol stack considered by the O-RAN ALLIANCE and eCPRI to support: user and control planes, other eCPRI services, Control and Management (C&M), synchronization (PTP or SyncE over UDP or directly over Ethernet) and Operation and Maintenance [10]. This survey focus on the user and control planes.

- **User Plane (U-Plane):** characterizes the frequency domain's In-band and Quadrature (IQ) sample data transfer between the DU and RU in the frequency domain. The U-Plane transmits messages containing DL/UL user data (PDSCH/ PUSCH), DL/UL control channel data (PDCCH/ PUCCH), and UL PRACH (connection request purpose) data, among other to the RU before the transmission initiates. Additionally, The U-Plane also supports data compression and DL data precoding.
- **Synchronization Plane (S-Plane):** is responsible for synchronizing and aligning the time, frequency, and phase clocks between the DU and the RU. S-Plane uses different sync profiles like the IEEE 1588 PTP packets, Synchronous Ethernet (SyncE), Physical Layer Frequency Signals (PLFS), among other to control the timing and synchronization aspects.
- **Management Plane (M-Plane):** manages the RU, and facilitates functionalities for FCAPS (Fault, Configuration, Accounting, Performance, and Security) required by the other operational planes, and supports C/U Plane IP and Delay management. M-Plane eliminates dependency on the vendor's RU to support a multi-vendor OpenRAN infrastructure.

2) Protocol Stack: The O-RAN Fronthaul specifications [7] enlist guidelines and blueprint for implementing the four operational planes: Control, User, Synchronization, and Management planes. Figure 3(a) and (b) illustrates the O-RAN fronthaul protocol stack for the 4 different operational planes. The functions of the operational planes are explained in the above section. The O-RAN Fronthaul Interface (FHI) library [8] supports IQ sample transmissions, O-RAN packets generation, appending IQ samples in the packet payload, and extracting IQ samples from O-RAN packets for split 7.2x based O-RAN architecture [8] [9]. The O-RAN FHI library constitutes of (i) O-RAN specific packet handling functionality (src), (ii) Ethernet and supporting functionality (ethernet) and (iii) Set of header files to support external functions and structures. The C/U-Plane transmits eCPRI or Radio over Ethernet (RoE) essential data over the Ethernet or the UDP/IP protocol stack. The S-Plane transmits PTP and SyncE essential data over the Ethernet. The Management-Plane (M-Plane) transmits NETCONF signals over Ethernet with TCP/IP with Secure SHell (SSH).

B. Definitions

Essential definitions of the RAN architecture and functional splitting are as follows:

- **Backhaul:** is the connection to the internet or the core [11].
- **BBU:** Baseband unit transports a baseband frequency or a unit that processes baseband [12].
- **Core network:** offers different services to the customers who are interconnected by the access network, or it is the site among the external networks and radio network [13].
- **CPRI:** Common Public Radio Interface is the interface specification for the fronthaul, i.e., between the radio equipment and radio equipment control of radio base stations, considers for wireless cellular networks.
- **CU and DU:** The 5G gNodeB (gNB) is divided into two physical entities CU and DU, generally CU provide support to higher layers and DU provides support for the lower layers [14].
- **eCPRI:** enhanced CPRI for th is the interface specification be radio equipment and radio equipment control of radio base stations, considered for wireless cellular networks.

While the eCPRI is the enhanced version of CPRI and its connecting enhanced radio equipment and enhanced radio equipment control through fronthaul transport network and is used for 5G systems [15], [16].

- **Functional split:** It is the set of techniques proposed by 3GPP, that divide the network functions to different part to improve overall system performance [17].
- **Fronthaul:** is commonly the link among the the controller and the radio head or small cell. Also, it is the link between the radio head and UE device. It is considered as the end link [11].
- **Midhaul:** is the link between the controller the radio head that provides information to the next link [18].
- **Network Function Virtualization (NFV):** facilitates the virtualization of the network services, such as routers, firewalls, and load balancers, packaged as VMs to enable that allow the mobile service providers may run their network on standard servers instead of proprietary hardware solutions [19].
- **RAN:** is the mobile network part connecting the end-user devices by sending information via radio waves over the Internet. It performs complex processing and handle the increasing demand based on the user-specific services [20].
- **• Virtualized RAN (vRAN):** Virtualized RAN virtualizes the RAN functions to promote agility in RAN deployment and management offered by the service providers. vRAN eliminates the dependency on proprietary solutions and enhances flexibility in hardware, software and system integration [21].
- **Remote radio head:** is the remote radio transceiver which maintain the connection to radio base station unit via electrical or wireless interface [22].
- **Software-defined network:** facilitates network service management and faster configuration based on the software. It separates the CU and DU and centralizes the network control and configurations [23].
- **Virtual Machines:** are the computing-enabled resource virtualization of a physical systems to execute and deploy programs and applications [24].
- **OpenRAN:** defines interoperability of open hardware, software, and interfaces for the wireless cellular networks. OpenRAN disaggregates the RAN to facilitate an open user and control plane with incorporated synchronization and management plane [25].

C. Introduction to RAN functional splits

Among many organisations contributing to the xG cellular mobile telecommunication standards, the ITU and 3GPP are instrumental. The increasing complexity of the RAN and its management, the virtualization of network functions, the hope to deploy AI-powered distributed networks, the benefits of open interfaces, and the potential to propose innovative connectivity-based services led many organisations and companies to push toward open RAN standard, including, maybe unsurprisingly to some readers, Facebook and Google.

Late 2020, the 2018-founded O-RAN ALLIANCE and the 2006-founded Next Generation Mobile Networks (NGMN) Alliance signed a cooperation agreement to *decompose* the RAN. As explained in the next paragraphs, RAN decomposition, radio network dis-aggregation, base station dis-aggregation and RAN functional splits are somewhat similar terms used when addressing the challenges of 4G and beyond RANs.

The NGMN Alliance is formed by service providers and has defined and developed many RAN topologies to model demand-service-cost-performance statistics. Distributed RAN (D-RAN) and Centralized RAN (C-RAN) are dominant examples of the newly defined topologies based on the requirements. D-RANs demonstrate the lowest latency using Baseband Unit (BBU) at the cell site while requiring usually acceptable transport capacity. The C-RAN solutions propose centralized BBUs and thus require a high-performance transport layer. The C-RAN eliminates the requirement of configuring the individual cell site based on BBU's capacity [26], [27]. The C-RAN architecture is shown in Figure 4. The C-RAN consists of the Remote Radio Heads (RRHs) at cell sites connected via a fronthaul (FH) network to BBUs in a BBU Pool (Farm or Hotel depending on the authors). The BBU Pools are connected to the Core Network via the backhaul (BH) network. The C-RAN topology eases the load balancing among the BBU computing resources [27].

Each RRH carries out radio functions, mainly at the physical layer, and is located at the cell site defining the mobile service coverage area. The BBUs are remotely located in BBU Pools and are responsible for processing the radio signal [28].A BBU is executing and processing radio functions, for example, modulation, channel estimation, Fourier transforms, and error correction. The fronthaul network should provide a low-latency high bandwidth transport for user and control data and synchronization, unless satellite-based synchronization at each cell site is preferred. The fronthaul network should also provide control and management of the radio equipment.

The CPRI and eCPRI standards specify the fronthaul connecting the BBU and RRHs (Figure 4).

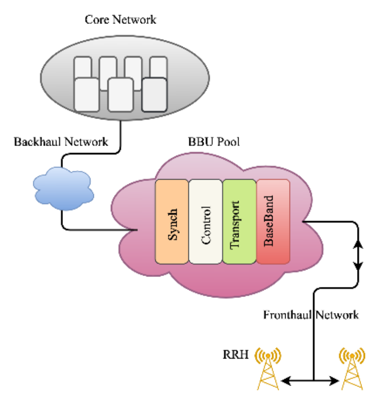

Fig. 4: C-RAN architecture: the BBU and RRH are connected through the fronthaul while BBU and core network are connected through backhaul.

Most 2G and 3G cellular sites were deployed with a base station hosting both the BBUs and the Radio Units (RU), also called Radio Heads (RH) near the cell site mast and with coaxial cables to link the RUs and the antennas on the mast. The concept of separating the BBUs and RRHs with a point-to-point radio transmission or an optical fiber was first introduced in 3G. The BBU-RRH links are called the fronthaul (FH) links. In 2003, several equipment manufacturers defined the open CPRI specifications to transport, over the fronthaul, I/Q user data, synchronization data and Control & Management data. The CPRI v7.0 was specified in 2015 [29]. The CPRI signals can be transported over an electrical cable but are usually transported over an optical fiber less than 2km although the link could be as long as 20km [30], [31]. The CPRI line bit rate ranges from 1.288 Gbps to 24.3302 Gbps supporting one to twenty four (20MHz 4G LTE signal). CPRI is a constant bit rate Time Division Multiplex (TDM) stream. Synchronization and accurate timing can be insured using global navigation satellite system (GPS, Galileo, QZSS, NavIC, BeiDou, etc.), or via the CPRI link using the synchronous property of TDM signal, or PTP (IEEE 1588v2) or SyncE (ITU-T G.826x). All details can be found in the CPRI specifications [29]. Note that eCPRI, presented next, is replacing CPRI for 4G and 5G fronthauls.

In 2017, the enhanced CPRI (eCPRI) [32], [33] specifications started to be designed to enable 5G fronthauls to be carried using a continous bit rate over dark fiber, WDM, and even Ethernet. In 2019, Ericsson, Huawei Technologies, NEC and Nokia updated the eCPRI specification enabling flexible deployments of fronthauls. The eCPRI allows splitting the physical layer to allow data fronthaul bit rate raises from the CPRI maximum bit rate of 25Gbps to any available bit rate, e.g. 100Gbps [34]. The eCPRI also enables to analyze and prioritize traffic. The eCPRI splits are denoted A to E and the mapping to 3GPP splits is given in Figure 5 [33].

Despite the efficiency of the eCPRI, massive MIMO will impose high line rates requiring the use of Dense Wavelength Multiplex (DWDM) if the processing for each MIMO antenna is kept at the BBU. In an experimental setup in 2020, Le et al. [35] demonstrated that *"an aggregated [5G] radio bandwidth of 25.6 GHz was transmitted on a single optical wavelength over 40 km without fiber chromatic dispersion compensation"*. Note that the 40km distance leads to a latency (133μs) below the maximum latency of 250μs on the eCPRI fronthaul [36].

The C-RAN architecture was introduced for 4G. C-RAN places the BBUs in a centralized BBU pool (hotel or farm) [6]. Some advantages of centralized radio signal processing of C-RAN are:

- To share the BBUs resources on-demand depending on the traffic load on the attached RRH in the served cells: in the simplest scheme, BBUs can be launched or turned off as needed and, more complex schemes could optimize the resources; allocated to BBUs while reducing energy consumption using AI techniques;
- To simplify or enable radio processing features requiring cooperation between cell sites such as advanced interference management, fast handover, Coordinated Multipoint (CoMP) transmission and reception;
- To virtualize some or all functions required from the BBUs;
- To ease upgrades.

The C-RAN architecture with its BBUs and RRHs shown in Figure 4 is identified as one of the 5G enablers. Nevertheless, it is challenging to reach the high-capacity requirement of the fronthaul network when centralizing the base band units for multiple antennas, especially for MU-MIMO. Some challenges have been addressed by the CPRI discussed in the next subsection. To reduce the load over the fronthaul, researchers are investigating techniques to maintain the benefits of the C-RAN and further reduce the burden on the fronthaul link. Heterogenous Cloud RAN (HCRAN) and Fog RAN (FRAN) have been described to mitigate some C-RAN challenges [37]–[39]. Some details will be provided in the following sections. It is recalled that in 5G and beyond, the baseband units (BBUs) functionalities are splitted between Control Units (CUs) and Distributed Units(DUs) as shown schematically in Figure 1.

1) 3GPP, CPRI and eCPRI Functional Splits: 3GPP has defined eight functional split options. They include further sub-splitting possibilities in the lower and higher physical layer [40]. DU's functions are highly near to the user and will be placed at the antenna side. The functions in the CU will benefit from the centralization processes as well as from the high processing powers within a data center. The functional splits proposed by 3GPP and eCPRI, Small Cell Forum and NGMN are presented in Figure 5 [33]. To improve the CPRI requirements, several higher-layer functional splits are proposed in the literature [41]. The proposal from [40] shifts the radio processing responsibility from the BBU to the RRH while reducing the burden of the fronthaul. According to our research, the most beneficial and popular split is the option seven Physical (PHY) layer, and its underlying intra splits. Besides, split seven has further sub-splits that involve moving Inverse Fast Fourier Transform (IFFT), resource mapping, precoding, and cyclic prefix addition, functionalities to RRH, which efficiently reduce the load over the fronthaul.

Split six is the Media Access Control (MAC) split, known as MAC-PHY split. It moves the RF and PHY and other functionalities to the RRH. Split option two is the split between the Packet Data Convergence Protocol (PDCP) and Radio Link Control (RLC). In this split, the network layer/PDCP functionality is kept in the BBU while all the other processing functionalities (RLC, MAC, PHY, and RF) shift to the RRH. Option 1 to Option 6 are well-thought-out to comprise the higher layer splits [2].

Different splits have been defined in the eCPRI specification [43]. eCPRI has introduced splits named A, B, C, D, I_D, II_D and I_U, and E [42].

When presenting the split, the downlink is usually considered first and the split is said to be between higher layer functions at the CU and lower layer at the DU. A single split defines: (1) a Backhaul (BH) bewteen the Core and combined CU/DUs, and (2) a Fronthaul (FH) between each CU/DU and RUs. Double split introduces a Midhaul (MH) between each CU and the DUs. A very good overview from Huber&Suhner show the detailed architecture and the complicated terminologies related to functional splits [44].

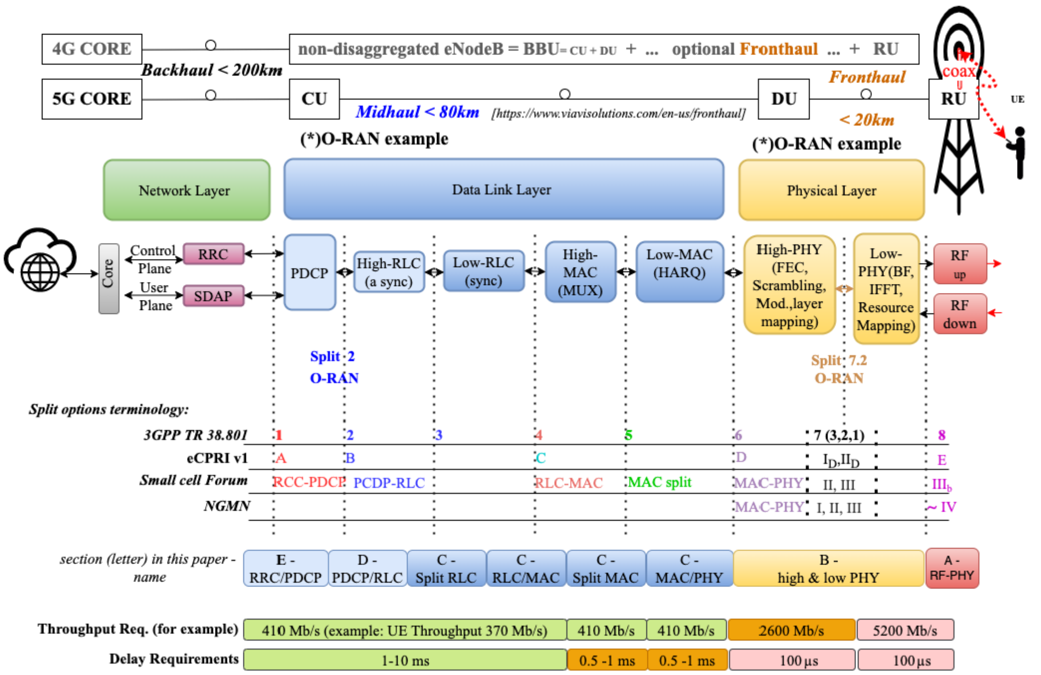

Fig. 5: Different functional splits proposed by 3GPP [33], eCPRI, Small Cell Forum and NGMN [42] with different names.

The mapping between eCPRI and (3GGP) splits are:

- eCPRI A (3GPP 1) between user Data (IP in 4G) or control RRC (Radio Resource Control) and PDCP (Packet Data Convergence Protocol),
- eCPRI B (3GPP 2), between PDCP and RLC (Radio Link Control),
- no eCPRI split for the 3GPP split 3 separating the RLC high and low (segmentation),
- eCPRI C (3GPP 4), between the RLC and MAC (Medium Access Control), i.e., the multiplexing controlled by a scheduler,
- no eCPRI split for the 3GPP split 5 separating the MAC multiplexing and the MAC HARQ (in 5G NR , HARQ is asynchronous in downlink and uplink but in 4G/LTE, HARQ is asynchronous in downlink and synchronous in the uplink),
- eCPRI D (3GPP 6), between the MAC (HARQ) and MAC-PHY (Forward Error Correction, Rate Matching and Scrambling, all bit processing before/after modulation/demodulation),
- eCPRI I_D (3GPP 7.3) for the downlink only (subscript D) between Scrambling and Modulation/Layer Mapping/Precoding,
- eCPRI II_D (3GPP 7.2) for the downlink only between the Precoding (N symbols per antenna) and the Resource Element Mapping to each sub-carrier and Beamforming Port Expansion (if any); for the uplink: the corresponding eCPRI split is called I_U between the Resource Element Demapping and the channel estimation and other received signal processing steps before demodulation,
- no eCPRI split for the 3GPP split 7.1 between the signal and the iFTT (for OFDM processing) and addition of the Cyclic Prefix (to mitigate the multipath effects), in the downlink.
- eCPRI E (3GPP 8) between the Cyclic Prefix insertion or removal and the RF (Radio Frequency) transmission on the downlink or uplink, respectively.

More details are provided in the next section.

As discussed in [45], data link layer splits (3GPP 1 to 6) offer gains in performance concerning CoMP, interference mitigation, scheduling and Radio Resource Management (RRM), and resources sharing, as more functionalities are centralized in the CU. Moreover, the CU can be connected to many DUs, controlling various cells in a reasonably large area.This change in the classical architecture improves and advances RRM and scheduling algorithms. However, this solution increases the complexity of the fronthaul interface and implies a potentially considerable increase in the latency and throughput. As a consequence, OpenRAN provides split option 7.2 (precoding/RE Mapper) only while avoiding split option 8 (digital/analog IQ symbols). For example, tens of Gbps at mmWaves transmission transported for, say, 64 antennas

TABLE I: Number of split options proposed by 3GPP.

Split Number	Split Name	Covered in section III
8	RF-PHY	A
7	High-Low PHY Split	B
6	RLC-MAC, and PHY Split	C
5		
4		
3	PDCP-RLC	D
2		
1	RRC-PDCP	E

would be very challenging to be carried on the fronthaul as tera bit per second might be required. But a macrocell site with some microcells could be served using centralized BBUs.

According to 3GPP, there is market demand for two somewhat different split option opportunities. The first one consists of options 6, 7, and 8 (low level), and it targets the operators with sufficient fiber fronthaul transport. On the other hand, options 1, 2, 3, and 5 (high level) splits may be deployed by operators that do not have fiber fronthaul transport yet or need to postpone investment in fiber transport.

2) Open Radio Access Functional Splits: The introduction in 2016 of the open standards for RAN formed the basis for implementing functional splits [46], [47]. The split options rely on the available transport links and network services. Hence, using open standards makes the implementation and assignment of network functions flexible. Open Radio Access Network (OpenRAN) has been proposed to transform traditional communication systems towards an open, intelligent, virtualized and fully interoperable RAN [48]. The OpenRAN Alliance (O-RAN), created in 2018, is a group aiming at enabling RAN key solutions based on general-purpose hardware and software-defined technology that can be open from different perspectives [49]. The main aim of the O-RAN openness is to break the vendor lock-in, proprietary execution of the software, underlying hardware, by launching open standard RF interfaces that increase operational savings using vRAN and C-RAN. The RAN openness will provide flexible deployment and access of BBUs, CUs, DUs and RRHs from different vendors to shape adaptable and scalable RAN networks. OpenRAN made network architecture flexible by adding fronthaul and midhaul transport by offering alternatives to service providers.

Open RAN concepts intend to enable any split to create flexible RAN architecture. In 2021, the O-RAN ALLIANCE defined a low-level split option 7.2x, between 7.2 and 7.1, i.e., between the 1-subcarrier by 1-symbol resource element de-mapper and the beamforming port reduction-expansion. Split 7.2x include fronthaul de-compression techniques of IQ signals.

III. 3GPP Functional Splits

A. Naming Conventions

This section provides a detailed overview of the conceptual aspects of the 3GPP functional splits by analyzing and explaining the algorithms associated with each split. For ease of understanding and cross-reference, we have provided a naming convention for the 3GPP-defined splits in Table I. Detailed charts and tables are added for comparison among different simulators. Moreover, simulators/emulators that are frequently considered for functional splitting implementation are discussed. The tables shown below show specific simulator.

B. RF-PHY Split (option 8)

Split eight was initially considered based on traditional C-RAN designs: the CPRI or another standard is used to link the BBU and Remote Radio Head or Unit (RRH/RRU) support [50]. Currently, the deployment of split option 8 is indeed still advantageous in some use cases.

Split option 8 is based on the CPRI industry-standard interface. CPRI provides the complete split-up of the Radio Frequency (RF) from the PHY layer to all-out virtualization gains. All the protocol layers from the PHY layer and above are centralized, resulting in a very compactly synchronized RAN, as shown in Figure 6. The placement of only the RF sampler and up-converter in the DU gives a precise and simple DU. This method enables the existence of several functions such as mobility and efficient management of the resources [51]. BAhram khan

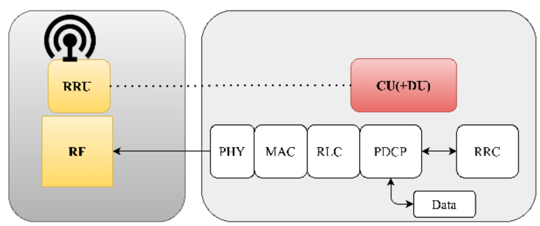

Fig. 6: RF-PHY split architecture.

Bitstream over the fronthaul link is continuously using split eight, and depends on the scales for the count of antennas [51]. This architecture moves New Radio (NR) functions from central to distributed structure. Its advantages are as follows [50]:

- It provides a flexible hardware implementation that supports scalable cost-efficient solutions;
- The split between central and distributed units allows feature coordination, real-time performance optimization, and load management.

Moreover, the DU can assist multiple radio units in handling the digital signal processing and optimize the network traffic.

FPGA is claimed one of the cheapest and possible selections for the implementation of split 8 [52], [53]. FPGAs consider the digital processing assignments in DU but they can correspondingly integrate analog sub-systems. gNodeB [54] from IS-Wireless (ISW) [55] is a software solution that can be deployed on either physical or virtual resources. ISW-gNodeB is a 3GPP-compliant implementation of the 5G-NR base station and enables any protocol stack cutting option. An ISW-gNodeB consists of independent Network Functions, which implement 3GPP-compliant NR RAN protocols namely: PHY, MAC, RLC, PDCP, SDAP, RRC, NRAP. The ISW-gNodeB

TABLE II: Literature review on RF-PHY split.

Concepts/Algorithm/Consideration	Simulator/Emulator /Analysis
Encapsulating CPRI over Ethernet (CoE), stringent CPRI desires like delay & jitter to make CoE a certainty, considered PHY & RF split option 8 [52]	FPGA-based Verilog MATLAB Simulink
Latency is mathematically analyzed using queuing theory, and closed-form formulas [56]	Mathematical analysis
Development of virtual network architecture while considering flexibility to choose the suitable functional split for small cell [57]	MATLAB
Virtualized multi-layer cellular network [58]	Numerical model analysis
Real-time implementation of functional split among RRH and BBU, to balance the transmission throughput among RRHs and BBUs [53]	FPGA, MATLAB and Simulink
Software solutions offering 5G NR protocols to implement the 3GPP Split 8 [54]	IS-Wireless gNodeB
Theoretical & mathematical concepts on split 8 [59], [60], [61], [62], [51], [63], [64], [65], [66], [67], [68]	Analysis

Network Functions can run together or independently and can be deployed on either physical (e.g. a small cell chipset) or virtual resources (e.g. dedicated COTS server or shared cloud resources).

Table II shows a set of characteristics for the RF-PHY split and indicates whether simulations, emulations, or analytical approaches have been conducted by researchers from the indicated reference.

The PHY layer is shown in 7,

C. *High-Low PHY Split (option 7)*

As shown in Figure 7, the physical layer is split in two parts: (1) the High-PHY and (2) the Low-PH.

The High-PHY handles the Forward Error Correction (FEC), etc.

The 3GPP option 7 split has centralization benefits through MIMO, Carrier Aggregation (CA), and Coordinated Multi-Point (CoMP) [69]. CoMP is seen as a significant candidate for 5G in terms of system performance improvement, and is separated into two classes: MAC sub-layer coordination and PHY layer coordination. CoMP include joint transmission and joint reception.

Figure 7 presents the functions of the PHY layer in the downlink direction, and presents the data information that is exchanged between the different blocks. The transport block is the input to the PHY layer from the MAC sub-layer on the top. As we can observe, the PHY layer's overall procedures transform the transport block received from the MAC sub-layer into In-phase and Quadrature (IQ) symbols, as shown on the top of Figure 7. The transport blocks are encoded and segmented into block segments and then passed through the rate matching block. Next, the rate-matched codewords are scrambled. The scrambled codewords are then passed through the modulation mapper, where the bits are converted into symbols, according to the modulation order. Then, the layer mapping block takes the modulated symbols into account and maps them into one or various transmission layers [70]. The precoding block then precodes the symbols on each layer before transmission through the desired antenna ports occurs. The resource element (RE) mapper is responsible of mapping the antenna symbols into resource elements, converting them into subcarriers. These subcarriers pass through the IFFT block [71], which produces the IQ symbols in the time domain. Finally, the Cyclic Prefix is attached. This split is detailed in Table III.

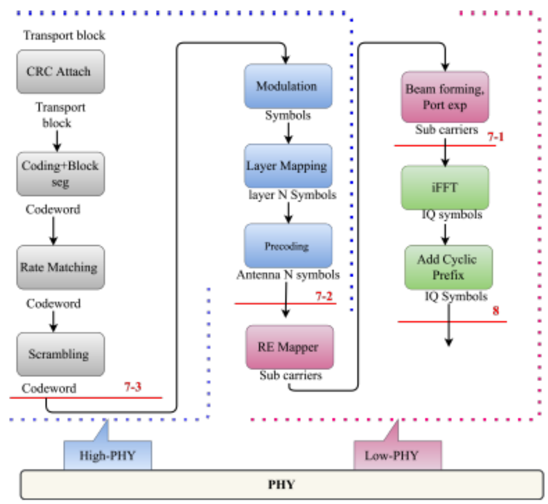

Fig. 7: 3GPP split 7: detailed splits 7.3, 7.2, 7.1 and 8 in this (conventional although strange) order considering the downlink and the 4G/LTE protocol stack (5G NR is the same at this level of details).

In split option 7, the PHY layer functions are defined between the DU and CU [36]. The PHY split has further sub-splits, namely 7.1, 7.2 and 7.3. These splits are enhanced in [72] [73]. Split seven's UL and DL bandwidth mathematical expression is presented in [36], [74]. Figure 7 shows the PHY layer procedures/blocks according to the Long Term Evolution (LTE) protocol stack. Figure 7 presents the functional split proposed in [6]. All the three sub-options of the PHY layer keep the Fast Fourier Transform (FFT)/IFFT in the DU to reduce the fronthaul bit rate [70], [57].

In the splits 7 of the PHY layer, the IFFT transformations and the Cyclic Prefix insertion are computed in the DU [75]. Compare to Split 7.1, the split 7.2 further reduces the bit rate over the fronthaul by keeping two more functionalities at the DU: resource elements mapping and beamforming. Option 7.3 keeps even more PHY functionality at the DU, resulting in a complex DU and lower achievable bit rates: grey and blue functions in Figure 7. Each split has its benefits and drawbacks, as shown in Figure 8. The splits 7 are considered as the best compromises for fronthaul bit rate requirements versus advantages due to centralization. Hence, Splits 7 are the strongest candidates to achieve high capacity in ultra-dense networks [76] and the fronthaul bit rate is dropped to values comparable to eCPRI.

Spliting options 7.2, 7.3, 6 or below should be used to avoid considerable bit rates on the fronthaul between the RU and DU.

Table V contains additional details on the 7.x splits.

The PHY latency requirements are stringent due to the need for coordination from the upper layers. As elaborated in [77], the round-trip latency of 5 ms is required for Hybrid Automatic Repeat Request (HARQ), located in the MAC sub-layer. The comparison of PHY latency with the latency of splits from other layers is defined in [78]. These latency requirements limit the distance between CU and DU to 40 km of optical fiber [78], and from 15 to 20km of dark fiber connectivity [79]. Note that splits 7.x requires the shortest CU-DU distances. Much longer CU-DU distances (¡200km) can be achieved using for example split 2 as discussed later and shown in 5. More details are out of the scope of this introductory survey.

The one-way latency is defined in [41] by considering the PHY layer's ideal or near-ideal characteristics. Timing and other frame and subframe requirements are explained in [80]. Because of the automatic repeat request placement within CU, the PHY split options are reliable even with non-ideal transmission conditions. It is possible to relax the fronthaul requirements in terms of latency and bandwidth, by considering the PHY and RF splits as the baseline. For example, to keep a processing FFT/IFFT block and subcarrier mapping/demapping at the DU reduces the fronthaul bandwidth requirements by a factor of 2.5 [57]. By performing the IFFT/FFT function at DU, the cyclic prefix is removed from the Baseband signal, and only the received signals of the allocated Physical Resource Blocks (PRBs) are forwarded to the CU pool.

TABLE III: Literature review on the PHY (High-Low) split.

Concepts/Algorithm/Consideration	Simulator/Emulator /Analysis
Exploited functional split at PHY & utilize it to serve RAN in capacity-limited scenarios [81], [82]	MATLAB
Implementation of split 7 by using Open Air Interface (OIA) & considering NR [83]	Open Air Interface (OAI)
Prototyping & validation of a DU Lower PHY transmission chain, for 5G and NR [84]	FPGA, MATLAB and Simulink
Design of an adaptive RAN that switches between two different centralization options at runtime, switch from MAC-PHY to PDCP-RLC without service interruption [85]	srsLTE, USRP B200 1 Gb/s Ethernet link
Spliting for efficient fronthaul, to enable the consumed bandwidth with cooperative radio, intra-PHY functional split C-RAN architecture and 7.1, 7.2 and 7.3 splits [76]	OAI
MAC-PHY split generation to find an amount of overhead traffic on the downlink [86]	srsLTE
5G-NR DU & CU, UL receivers implementation [87]	FPGA, MATLAB and Simulink
Complexity of the RRU with 5G NR considering functional split option 7.2 [88]	FPGA
The software solution to implement stack cutting option defined by 3GPP at split option 7, between RU and DU, [54].	gNB (ISW)
Survey papers, theoretical & mathematical concepts [76], [86], [87], [88], [89], [90], [91], [92], [57], [93], [94]	Mathematical & theoretical analysis

D. RLC-MAC, and PHY Split (option 6, 5 and 4)

The MAC Layer, green box, in Figure 9 is an interface to the RLC layer: blue box. The MAC layer sends or receives the data from layer 1 using transport channels [95], while logical channel services provide the data transfer to or from the RLC sub-Low layer. There are 2 logical channels classified as traffic and control channels [96]. Data on a transport channel is organized into dynamic-sized transport blocks, whereas transport formats determine the configuration of the transport block.

Based on the Protocol Data Units (PDUs) delivered from the RLC sub-layer towards the MAC, MAC Service Data Units (SDUs) are configured and later converted to MAC PDUs, which are provided later on in a form of transport blocks to the PHY layer. Each transport block is transmitted in a single transmission time interval in the MAC sub-layer. The MAC sub-layer details for multiple underlying UE MAC entities, are explained in [95]. The MAC sub-layer has a set of functionalities defined in [97]. The 3GPP sets rules for mapping the logical channel traffic to transport block are addressed in [97].

The MAC Layer handles the resource scheduling. The MAC Layer plays a fundamental role in the implementation of Carrier Aggregation (CA) techniques. The MAC Layer generates one transport block per transmission time interval (TTI) per component carrier. The MAC Layer shares the MAC packet data units and control elements over different component carriers. Each component carrier within the MAC sub-layer has its own HARQ entity. All the cells involved in CA within the cell group are under a single MAC entity. Authors in [98] and in [99], [100], [101] addressed the aspects of CA and Dual Connectivity (DC) with respect to the MAC sub-layer. Due to the execution per TTI, the MAC scheduler requires very low latency and low jitter [102]. The NGNM Alliance [103] warns that placing the MAC functions in a CU-pool (Split 5 or 4) can limit the CoMP functions performance.

The functional split options 1 to 5 have relaxed latency requirements on fronthaul, as the HARQ processing and other time-critical functions are placed in the DU close to the antennas. According to [63], setting the MAC in the CU pool will ease the use of LTE-Advanced in unlicensed bands.

With Split 5, low and high RLC, PDCP and RRC will be in CU, and the low MAC (HARQ, multiplexing/scheduling) will be in DU. Functions like scheduling decisions can be performed at CU, for example, inter-cell interference coordination, CoMP. With Split 5, the HARQ, a MAC time-critical processing tasks are computed at DU [73]. The split 5, with the High MAC containing multiplexing and scheduling decision at the CU could ease the MAC management by the mobile network operator [104].

The Split 6 or MAC-PHY split and its resulting reduced fronthaul bit rate requirements are addressed by 3GPP in

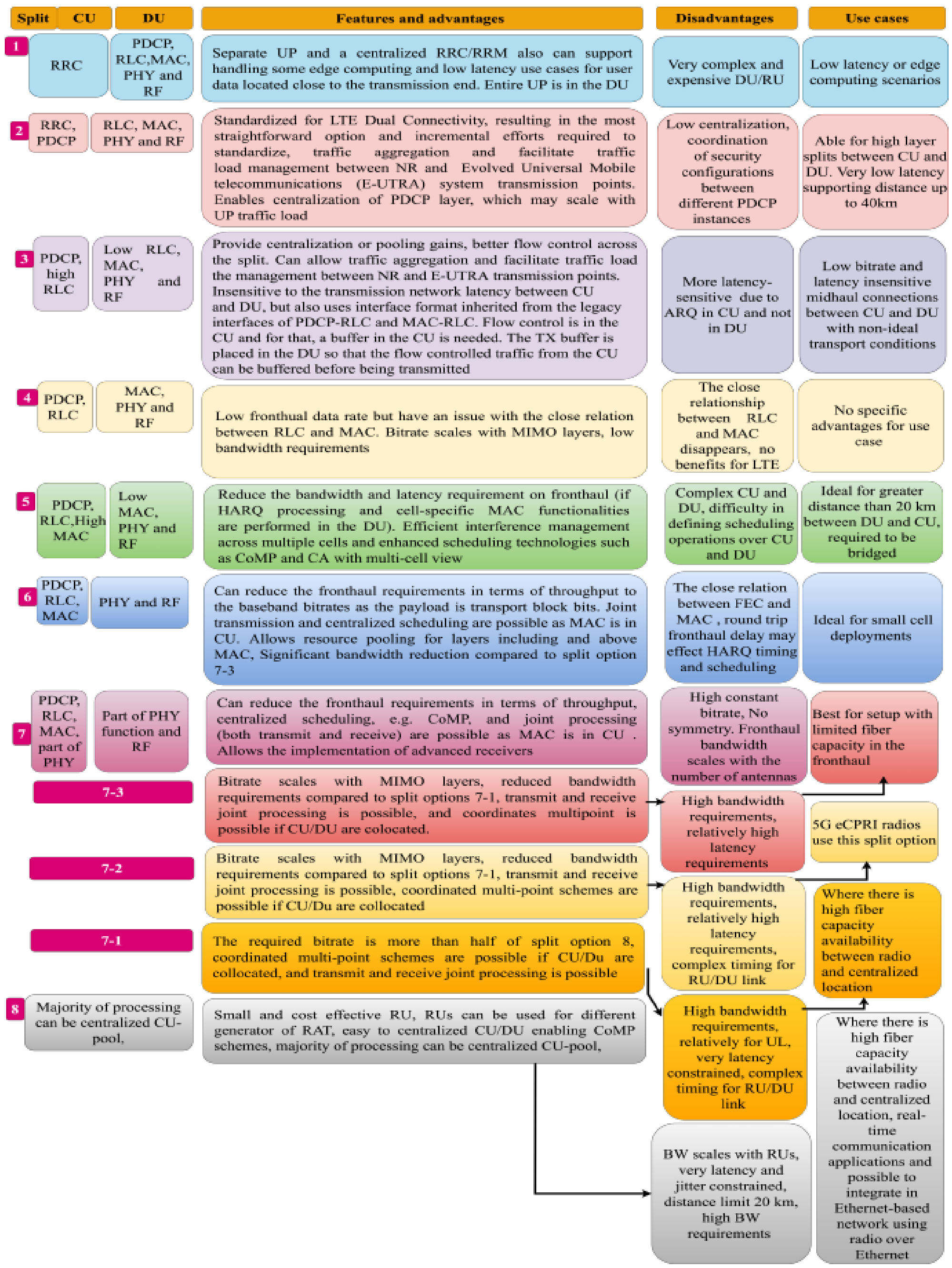

Fig. 8: Advantages and disadvantages in the perspective of this survey.

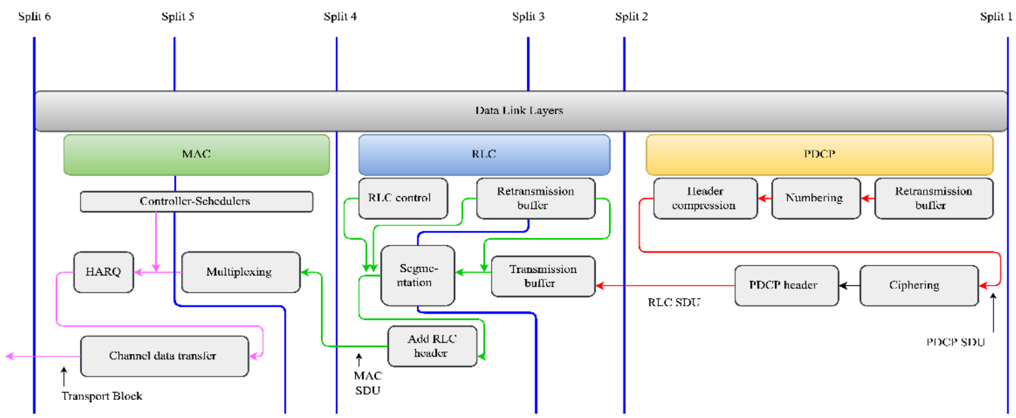

Fig. 9: Architecture of Split 1 to Split 6 of the data link layer: from PDCP to RLC to MAC in the downlink.

[105], [106]. The Split 6 (MAC-PHY) specifies the transport of MAC PDUs instead of IQ-data blocks. The Split 6 is advantageous compared to CPRI as it decreases the fronthaul capacity requirement: for example, [105] reported a fronthaul bit rate of about 137Mbps for the Split 6 while Split 8 requires over a 100 times more: 14'700Mbps for 4G. For 5G: 7Gbps (Split 6) is required instead of 157Gbps (split 8).

The Small Cell Forum favors the Split 6 to reduce costs of 4G and 5G small cell deployments. The Small Cell Forum publishes the so-called 5G network functional application platform interface (5G nFAPI). The 5G nFAPI extends for 5G the functional split between the MAC and PHY functions to enable virtualization of the MAC function. The nFAPI support communication between the Virtual Network Function (VNF) handling the MAC layer in the DU and the Physical Network Function (PNF) in the RU. Note that the Small Cell Forum refers to S-DU and S-RU instead of DU and RU.

Table IV provides a glimpse on several papers discussing the split 6 to 4, i.e., the MAC (High-Low) and PHY splits.

TABLE IV: Literature review on split between MAC (High-Low) and PHY split

Concepts/Algorithm/Consideration	**Simulator/Emulator /Analysis**
To minimize the intercell interference & the fronthaul bandwidth utilization by dynamically selecting the appropriate functional split considering PHY-MAC split [107]	MATLAB
Trade-off between bandwidth and RRU complexity for different splits [88]	FPGA
Optimization of processing & bandwidth resource usage, minimizing the overall energy consumption compared to i) cell-centric, ii) distributed and iii) centralized Cloud-RAN approaches [108]	Open Air Interface (OIA)
Examine Ethernet as FH work in C-RAN, with focusing on the MAC and PHY split [109]	Open Air Interface
Theoretical & mathematical concepts [80], [110], [111], [112], [113], [114], [115], [104], [116], [117], [118], [119]	Analysis

E. PDCP-RLC split (3GPP option 3 and 2)

The 3GPP defines the Split 2 as the split between the Radio Link Control (RLC) in the DU and Packet Data Convergence Protocol (PDCP) in the CU [120]. The 3GPP Split 3 separates the RLC by keeping the segmentation (Low RLC) at the DU and the other RLC functions (High RLC) at the CU [120]. Split option 3 is further studied in [120].

The PDCP maintains the real-time operation using a buffer at the RLC level. Every incoming packet from the user plane, i.e., the Internet Protocol (IP)+SDAP packet is processed by the PDCP. The PDCP handles packet buffering and retransmission, layer 2 numbering, header compression, ciphering, and integrity protection before the RLC in the downlink. The RLC handles bufferization, segmentation, and ARQ retransmissions.

According to [63], the PDCP centralization in the CUs, i.e., the 3GPP Split 2, is a 5G enabler. The delay sensitive processing of ARQ retransmissions is kept at the DU which can be close to the RU.

According to [121], one PDCP traffic flow is considered per radio bearer. The traffic Split 2 is organized into several flows. Each flow can be directed to various access nodes and support multiple types of connectivity. According to [41], Split 2 keeps real-time support in the DUs, resulting in a relaxed CU-DU link requirement.

Figure 11 compares the bit rate among different functional spitting options in uplink and downlink.

Table V contains additional details on the PDCP-RLC split (Split 2).

The PDCP handles both the NAS/RRC messages for the Control Plane. (CP), and the IP/SDAP for the 5G User Plane (UP). Thus, the CU is composed of two logical components, one for the CP and one for the UP as defined in the context of Software Defined Network (SDN). Some authors uses the term: CU/CP split but this should not be confused with the functional splits discussed here. Based on the functional split requirements, all the network functions at the CU are

TABLE V: Literature review on PDCP-RLC split.

Concepts/Algorithm/Consideration	**Simulator/Emulator /Analysis**
Different functional splits implementation in the cloud-RAN [121]	Open Air Interface (OIA)
The CU/DU CP split at the RRC/RLC [122]	Open Air Interface (OIA)/SDR
Split buffering between the RLC & PDCP layers. PDCP buffer with per-flow queues, and applied to the RLC buffer a new dynamic sizing mechanism that enforces the lowest queuing delay that is compatible with the existing configuration of the RLC connection [123]	Open Air Interface (OIA)
C-RAN based architecture allows the selection & dynamic switching of different hetnets in the RAN [124]	Open Air Interface (OIA)
Software solution to offer NR RAN protocols such as PHY, MAC, RLC, PDCP, SDAP, RRC, NRAP in Option 2, between DU and CU, [54]	gNB (ISW)
Surveys, theoretical & mathematical concepts [125], [126], [127], [128], [125], [129], [130], [131], [132], [133], [134], [135], [136], [137], [138]	Analysis

organized as either part of the CP or UP [9].

In the RRC-PDCP (3GPP option 1) split, the whole processing for the control and user planes is placed in the DU. Split 1 is thus not very different from the usual Core-BBU-RRH. As the processing of the user data is now near the transmitter there is an advantage for caching. However, features like intercell coordination are not supported in this split 1 option. Consequently, Split 1 is not advantageous if many cells are connected to a CU pool [6], [139].

The control and user plane splitting are designed and implemented in [62]. The RRC in the DU handles the control plane functions in this split 1 while the user plane functions are handled by the new 5G Service Data Adaptation Protocol (SDAP) to handle new services beyond IP for 4G. Authors from [140] show that the split option 1 (also called PDCP/RRC) requires low control plane overhead, which benefits load balancing and mobility management using virtualization.

In [141], complete and partial scheduling processes are performed at the RRC.

F. Functional Splits Requirements

The maximum latency requirement of each split option is shown in Figure 10.The splits 8 to 5 require a latency less than ms because more processing at DU . Split 3 and 2 requires a latency of 5ms or less which is higher as compared to split 8 to 4 because of less functions at CU . Split 1 has the less tight requirement, 10ms.

The downlink(DL) and uplink(UL) data rate of different splits. Figure 11 compares data rates according to the Small Cell Forum. One can see that all the given references are giving higher fronthaul bit rate between split option 5 to 8. High and low mm wave performs best for split option 7.1 and 7.2 and respectively the 5G (less than 6 GHz band) . overall the split options 8, 7.1 and 7.2 provide higher bit rate over fronthaul.

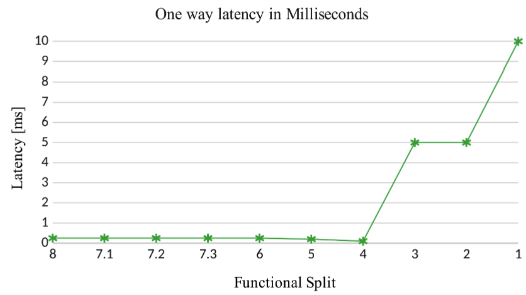

Fig. 10: Latency for different functional splits [41], [142].

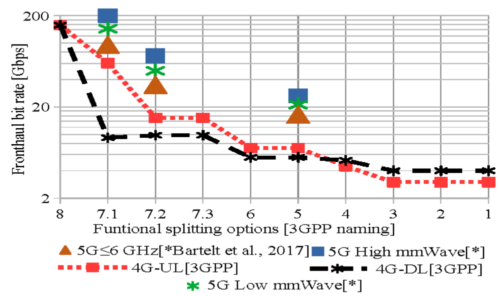

Fig. 11: Fronthaul bit rate (log scale) for different split options according to 3GPP [142], [143], Small Cell Forum [41] and Larsen et al. [6] for 4G (lines), and according to [*]Bartelt et al. for 5G sub 6GHz (triangles) and near mmWave (squares) [144].

Figure 12 presents a comparison of different simulators/emulators considered for the implementation of the splits by other researchers.

Mainly the Physical (PHY) layer split implementation is analyzed, and authors considered Field Programmable Gate Array (FPGAs) (62%, i.e., 31 out of the 50 papers considered here) and MATLAB (60%) For overall split implementation and testing in different scenarios, Software Radio Systems (30%),(srsLTE) and (20%) Open Air Interface (OAI) have been considered, among others (what other ... interesting).

This analysis is based on the research papers listed in the tables from this survey.

IV. Fronthaul

As shown in Figures 1 and 4, the fronthaul (FH) network link, usually via optical fibers or wireless connections, the BBUs or DUs to the radio equipment: RRHs, RRUs or RUs linked via coaxial cables to the antennas, e.g., [69]. The fronthaul carries the data, control, synchronization and operation & maintenance signals. 5G developments challenges current FH transport and next-generation FH interface, radio-over-fiber, and xHaul are being investigated [32], [145]–[147]. Some more details are mentioned in the next sub-sections.

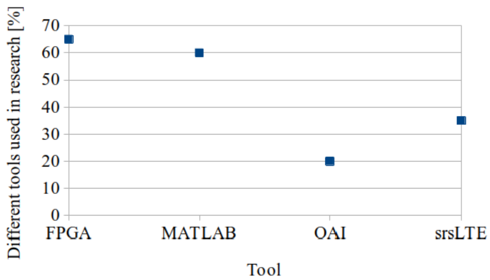

Fig. 12: Different simulators used for implementing functional splits.

A. Requirements and Standardization Bodies

The fronthaul requires high data rate, low latency, low jitter, and low packet loss. The data rate for CPRI is 2.46 Gbps in LTE Networks while the eCPRI capacity is more than 10 Gbps [69], [148], [149].

The traditional approach for the transport layer is not expected to continue within 5G and beyond. Instead, the next-generation network requires integrated BH and FH technologies, which can minimize Operational Expenditure (OPEX) and Capital Expenditure (CAPEX). The architecture integrating FH and BH in a shared packet-based network defined as Xhaul is presented in [146]. In fact, research has shown that operators are getting more interest in the FH. In a survey of global operator 2020 [150], it is reported that 46% of FH support will be needed for functional split implementation.

Realistic functional split implementation require standards and virtualization. The European Telecommunications Standards Institute (ETSI) is very active in standards related to virtualization and centralized RAN concepts. According to ETSI, base stations are held in cloud computing centers. With virtualization, the BBU, usually located at the base station sites can be moved to data centers, providing the opportunity for easier load balancing. With the virtualization of RAN functions, the functions can be flexibly distributed and moved across data centers, providing enhanced load balancing and advanced cooperation between antenna sites.

B. Delay

The FH architecture must satisfy specific 5G end-to-end delay to offer time-critical 5G services, such as URLCC. Some envisioned 5G applications could require delays as low as 1 ms. The fronthaul transport within the PHY layer corresponds to options D and E in eCPRI I [151], i.e., 3GPP split 6,7,8. In this context, the HARQ protocol limits the maximum delay between the BBU (or DU) and RRH. For example, after transmitting three 1ms-subframes, the UE sends a positive or negative acknowledgement in the fourth subframe. All the processing at the BBU or DU must be finalized and the frame is created before 3 subframe, i.e., 3 ms [152].

In [153], the suggested processing time of the BBU is 2754 μs. The 3ms HARQ limit leaves then a fronthaul path round-trip time of 246 μs. Thus, the maximum FH one-way latency is 123 μs, or about 24km assuming, as usual, a propagation speed of 200 m/μ.

Other sources such as [152], [154], [155] and IEEE 802.1CM consider a slightly stricter requirements for the delay, i.e., 100 μs for one way communications. This 100 μs maximum delay results from a breakdown of the HARQ processing which ensures the best performance for fronthaul. Delay longer than this target would degrade the performance of the radio network [152]. In the transmission path using optical fiber, the delay is close to 5 μs/km. Consequently, the maximum distance must be less than 20 km to accomplish the 100 μs highest end-to-end one-way delay.

C. eCPRI

In LTE-Advanced, fronthaul connections could use the CPRI protocols, while for 5G NR, eCPRI has been introduced [32]. Going toward the 2nd phase of 5G and beyond, more and more operators might consider the C-RAN architecture. With 4G, 5G NR and dual connectivity, the fronthaul network will carry an amount of traffic which is challenging the CPRI interface.

Currently, for 4G, several Telcos use the CPRI interface for their fronthaul connections. CPRI is a point-to-point interface. CPRI considers that operators will use the same vendors at each end of the fronthaul. The eCPRI will work as an open interface. The eCPRI also supports virtualization options, like software-defined network and network functions virtualization. eCPRI is claimed to provide more flexibility to operators to complement networks with shared equipment, improve bandwidth efficiency, and simplify deployments. However, unlike the CPRI, eCPRI neither supports end-to-end synchronization. eCPRI supports and recommends the PHY splitting. To reduce cost, eCPRI allows deployments using Ethernet transport technology.

In [156], the CPRI to eCPRI replacement have been implemented and, based on the specification of eCPRI, has encapsulated data in eCPRI format to create eCPRI packets. The system in [156] supports the raw Ethernet header, in which the payload contains one eCPRI message.

1) eCPRI Protocol Planes: The eCPRI specification defines three protocol planes between the eCPRI Radio Equipment (eRE): RU, RRU or RRH and eCPRI Radio Equipment Control (eREC): DU. The first is the user plane, the second is the control and management plane, and the third is synchronization plane (—JFW 2022 Jul 30: see *** above—). Some details are provided as follows:

- The user plane data protocol deals with user data. The real-time control information and related eCPRI services depend on the functional split implementation for the user data;
- The control and management involve non-time-based data flows within eCPRI nodes;
- The synchronization plane carries time-critical information essential for frame and time alignment, utilizing protocols such as precision time protocol (PTP) and SyncE

2) eCPRI Frame: eCPRI framing is supported by an Ethernet frame whose sections are transported by using separate layers of the Ethernet frames. The message (header) of eCPRI contains four sections, while the reserve portion keeps the payload. Details are as follows:

- The eCPRI protocol revision contains 4 bits.
- C is one bit and shows the eCPRI concatenated message. If it is 0, it indicates that the alternative frame of the same group follows. Otherwise, if it is one, it shows the last frame of the concatenated group.
- The message type section contains 8 bits and the payload size contains 16 bits that follows the eCPRI (message) header. There are eight different payload types carried in the eCPRI frame payload, that includes IQ data transfer, bit sequence transfer, real-time control data, generic data transfer, remote memory access, one-way delay management, remote reset, and event indication. These message types are defined below [157]:
  - **eCPRI Message Type 0- IQ Data Transfer** specifies the time/ frequency domain - IQ sample transfers between eREC (BBU) and eRE (RU), with the vendor-defined structure for the payload.
  - **eCPRI Message Type 1- Bit Sequence Transfer** specifies the transfer of user data between eREC and eRE.
  - **eCPRI Message Type 2- Real Time Control Data** specifies the vendor-specific real-time control messages associated with user data (IQ samples, bit sequence) between eCPRI nodes (eREC and eRE).
  - **eCPRI Message Type 3- Generic Data Transfer** specifies the transfer of the user plane and control messages for generic data transfer and data synchronization.
  - **eCPRI Message Type 4- Remote Memory Access** allows read/write action from/to opposite eCPRI nodes at a specific memory address using remote units. This service facilitates different read/write accesses depending on the driver routines and hardware implementation.
  - **eCPRI Message Type 5- One-Way Delay Measurement** estimates the one-way delay between two eCPRI-ports, unidirectional. The local time is sampled by the sender, including a Compensation Value (CV), while the receiver, time stamps the message on arrival and reverts with an internal CV to the sender.
  - **eCPRI Message Type 6- Remote Reset** is used when one eCPRI node requests a reset of another node. eREC sends the request to initiate an eRE reset.
  - **eCPRI Message Type 7- Event Indication** is used to inform the end of a link fault.

V. Virtualized Radio Access Network

This section recall first some basics related to virtualization and discuss then virtualized RAN.

A. Network Functions Virtualization and Software-Defined Networking

Network Functions Virtualization (NFV) and Software-Defined Networking (SDN) are considered as key pillars of 5G. SDN and a key protocol called OpenFlow is promoted by the 2011-founded Open Networking Foundation (ONF). The operator driven SDN & OpenFlow proposal led to the creation within the European Telecommunications Standards Institute (ETSI) of the Network Functions Virtualization (NFV) Industry Specification Group (ISG).

The 3GPP 5G architecture defines several core Network Functions (NFs) such as the Session Management Function (SMF) controlling the User Plan Function (UPF) via the N4 interface. By separating the SMF/controller from the UPF/packet forwarding element, the 3GPP 5G architectures follow the SDN concept of separating the control from the user traffic switching; a concept appropriately short named by 3GPP: CUPS for Control/User Plane Separation. CUPS was introduces by 3GPP for 4G and 5G.

To satisfy mobility requirements in the core network, the controlling protocol running over the N4 interface between the control plane (SMF) and the user plane (UPF) function is not OpenFlow but the Packet Forwarding Control Protocol (PFCP).

For the RAN, the Access and Mobility Management Function (AMF) is linked to the 5G base station (gNBs) forming the RAN via the N2 interface, and the gNBs are interconnected via the Xn interface. Mainly for access and handovers, the protocols over N2 and Xn are NGAP and XnAP, respectively, for the control plane and GTP-U for the user plane. More RAN controls and the virtualization of the controllers are not standardized and led to initiatives from operators and vendors to improve the RAN.

Virtualization techniques can be adapted to perform RAN enhancements. Virtualization technology separates the software from the hardware, i.e., the network and computing resources from the physical resources. The primary purpose of virtualization is to incorporate scalable and flexible solutions like efficient resource and cost management, load balancing, automatic scaling, operation and control procedures, and, it is often claimed to enable the introduction of Artificial Intelligence and Machine Learning based control. Virtualization allows MNOs to engineer the network by centralizing the network equipment to high-volume industrial servers, switches, and storage, among others, so called COTS (commercial off-the-shelf) equipment such as x86 physical machines or P4-devices. The centralized units, BBU, CU or even DU in the context of RAN, may reside at the data centers, and/or at so-called Point-of-Presence (PoP) or at or near the users premises, e.g., in the case of Private 5G. [158].

B. Distributed RAN and Centralized RAN

The Distributed-RAN (D-RAN) concept is presented to understand a basic virtualization. In a D-RAN architecture, each cell site is composed of isolated RRU and BBU subsystems. The RRU unit is connected to the assigned BBU through the Fronthaul connection using CPRI. Cells are equipped with radio functions and connected to the core network via the backhaul. Figure 13 presents the basic D-RAN architecture. Depending on the network requirements, network resources are allocated dynamically by the BBU [159]. The BBU or, more realistically, some parts of the BBU could run on virtual machines (VMs). The use of VMs and co-locating the BBUs led to the C-RAN architecture presented below.

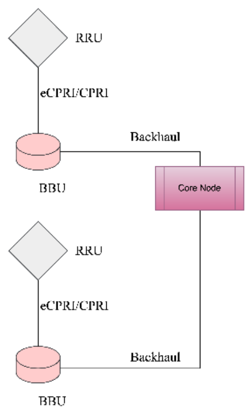

Fig. 13: D-RAN architecture: the classical setup with the antennas, RRU and BBU at each base station site. The short RRU-BBU fronthaul link remains proprietary although CPRI is used. The backhaul, usually over optical fiber or point-to-point microwave link is connected to a core node.

The fundamental of C-RAN architecture is to separate all BBUs from their RRU subsystems and move the BBUs to a centralized, shared, possibly virtual pool. The BBU subsystem is centralized in C-RAN. Each C-RAN cell site is composed of the antennas and the RRU subsystems. Figure 4 shows the basic C-RAN architecture. In C-RAN, network-related resources are kept at the edge, at the RRUs, and the core functionalities reside in the BBUs in the cloud. As a result, C-RAN networks are more flexible and, in some case, easier to deploy and maintain than the classic D-RAN if the fronthaul bit rate is supported.

C-RAN implementations are based in generic terms on Cloud Computing. Cloud Computing is the services provided by clusters of networked elements which may or may not be user-administered. In the context of cellular networks Cloud Computing allows Mobile Network Operators to store vast volumes of data generated by the devices and network and to insure cost effective sharing of required computing resources. In fewer words, C-RAN, like Cloud Computing, could ease on-demand availability of the networked data for RAN optimization. Sharing the COTS computing power and storage between BBU and end users seems obvious at first but might to very challenging to implement practically and securely.

C-RAN like Cloud Computing techniques present some challenges: increased latency, potential traffic congestion, increased data processing time if the computing resource in not available, and communication costs. To mitigate some challenges of Cloud Computing: Virtualization, Edge-Computing and Fog Computing could be presented as solutions.

C. Virtualized or Virtual RAN

To achieve high performance at the user-end while supporting many devices, MNOs migrate the data center to Mobile Edge Computing (MEC). MEC reduces latency issues and offers high data capacity. Incorporating NFV and SDN technologies with C-RAN help to virtualize the RAN functions and resources and are thus called "Virtualized-C-RAN" or "vC-RAN". vC-RAN implementation is related to some specific characteristics of the wireless access network like time varying channel conditions, interference, UE distribution, and mobility. Appropriate resource allocation, optimized interference management, etc., are challenging from the MNOs' perspective. The author from [160] proposed the concept of the virtualized base station to facilitate the virtualization of the computing resources of a BS in vC-RAN. The virtualized BS executes multiple protocol stacks of a BS in software while sharing the radio equipment at the hardware end. MNOs have been implementing techniques to achieve enhanced energy efficiency and decreased OPEX, as discussed in [160].

The virtual RAN (vRAN) isolates the software from the hardware by implementing the network virtualization functions. vRAN separates the RRU from BBU on a General-Purpose Processing (GPP) unit and implements functionalities in software. vRANs are composed of centralized pools of BBUs, virtualized RAN control functions and optimized service delivery protocols. vRAN could offers several advantages over conventional RAN deployments: scalability, flexibility, faster upgrade cycles, resource pooling gains, and centralized scheduling.

D. Fog Radio Access Networks (FRAN)

Centralizing the BBUs potentially far away from the base stations site might bring some concerns about optimizing local RAN problems such as handovers, local interferences, and services to static users.

Edge Computing and Fog Computing solutions have probably inspired the terms Mobile Edge Computing (MEC) mentioned earlier and Fog-RAN (FRan) presented next very briefly. Fog Computing forms a distributed computing environment that enables storage and data processing at the network edge [161]. The RAN architecture that enables fog computing is known as Fog-RAN, F-RAN or FRAN [162], [163]. FRAN aims to facilitate processing of the generated raw data at the computing units at the user end or closest proximity. Hence, FRAN forwards processed data instead of raw data, resulting in a decreased requirement for high bandwidth and QoS enhancement [164]. Thus, FRAN, CRAN, HCRAN (Heterogenous Cloud RAN) [38], [39], [165], and other cloud based RAN will certainly be re-visited and further improved. In the evolution of the RANs, the Open RAN has gained a particular attention. Open RAN is discussed in the following section.

VI. Open Radio Access Networks

The terms: Open RAN, OpenRAN, O-RAN, ORAN can all be found in the litterature. This survey cannot claim to present a unique definitions for each of these terms. The industry-focused Telecom Infra Project (TIP) initiated an Open RAN MoU Group in 2020 to "supports the development of disaggregated and interoperable 2G/3G/4G/5G NR Radio Access Network (RAN) solutions based on service provider requirements", quoted from telecominfraproject.com. The O-RAN ALLIANCE "has been founded in February 2018 by AT & T, China Mobile, Deutsche Telekom, NTT DOCOMO and Orange. It has been established as a German entity in August 2018. Since then, O-RAN ALLIANCE has become a world-wide community of mobile network operators, vendors, and research & academic institutions operating in the Radio Access Network (RAN) industry.", quoted from o-ran.org. The TIP OpenRAN and O-RAN ALLIANCE are joining forces to promote open RAN (ORAN as found on Cisco web sites).

A. Working Alliances and Groups

The O-RAN ALLIANCE [48] specifies open industrial standards for RAN interfaces that support interoperability. The preeminent intention for supporting new OpenRAN and vRAN architectures is to detach individual base station components and facilitate independent interactions. Open RAN assures interoperable RAN elements, both hardware, and software, from different vendors. Open RAN promotes 3GPP based vRAN architectures and provides MNOs with capabilities to overcome the challenges with proprietary hardware and software. The vRAN technologies aims to foster the development of OpenRAN standards by specifing open interfaces between the DU and CU and BBU. The DU/CU/BBU separation is based on the concept of the functional splits [166] and is claimed to enhance security, flexibility, and reduce CAPEX and OPEX costs. The DU/CU/BBU separation should provides MNOs with opportunities in the allocation of the functional blocks to maximize performance. OpenRAN will empower smaller MNOs and vendors to introduce their services and network customization based on requirements and needs [48].

Different working alliances towards OpenRAN are mentioned in Figure 14 [167]–[172]. The main purpose of these individual alliances and collaborations is to drive openness and interoperability in the RANs from 2G to 5G systems. The OpenRAN initiatives provide software and hardware solutions to support implementing an open and intelligent RAN. The O-RAN ALLIANCE specifications allows to build an open and modular RAN architecture based on 3GPP and dis-aggregated base station software. The O-RAN ALLIANCE has its own defined working groups to achieve the mission and vision of the alliance. The different OpenRAN working groups [173] are summarized in Figure 15.

B. OpenRAN Architecture

According to [174], [175]: OpenRAN focuses on three specific areas, namely: (a) separating the CU RAN from UP, (b) creating a modular or disaggregated base station software

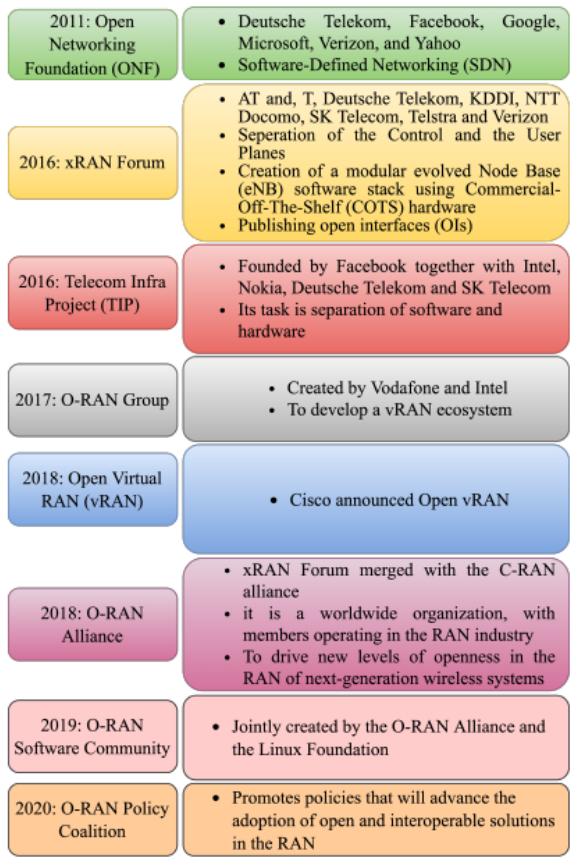

Fig. 14: Summary of initiatives and organization working towards OpenRAN architecture and infrastructure.

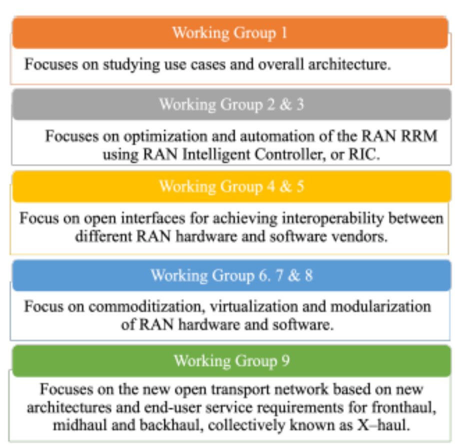

Fig. 15: Different OpenRAN working groups and associated tasks for developing new RAN architecture.

stack using Commercial-Off-The-Shelf (COTS) hardware and (c) Open Interfaces. OpenRAN mainly defines the concept of open architecture, enabled by well-defined interfaces between the different elements of the RAN. OpenRAN also defines the integration of machine learning and artificial intelligence techniques in the RAN [176]. All OpenRAN components must support the same Application Programmable Interface (API), allowing OpenRAN-based 5G deployments to integrate elements from multiple vendors and make it possible to utilize COTS hardware.

In March 2019, the O-RAN ALLIANCE defined the functional splits between the BBU and RRU to embed fronthaul functional requirements.

The O-RAN ALLIANCE defined a reference architecture [48] in order to support next-generation open virtual RAN infrastructures with intelligent radio. The reference architecture describes well-defined interfaces to facilitate an open, interoperable supply chain ecosystem with respect to the 3GPP and other industry standards organizations. Figure 16 shows the reference OpenRAN architecture.

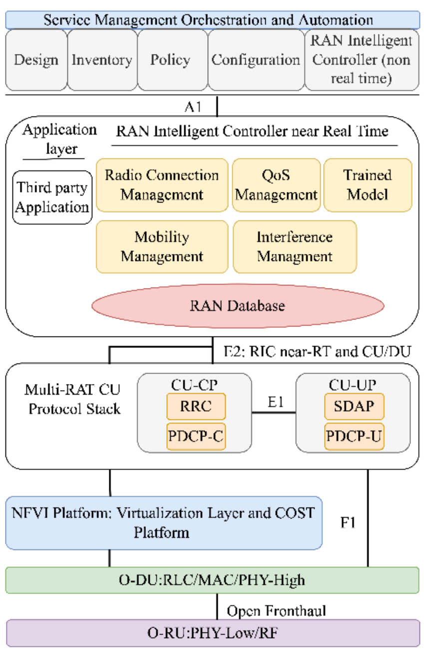

Fig. 16: OpenRAN architecture as defined by the O-RAN ALLIANCE to achieve an OpenRAN infrastructure.

The O-RAN architecture is basically based on (1) for the fronthaul: the 3GPP split 7.2 or Low Layer Split between the so-called O-RU and O-DU (O for O-RAN) and (2) for the midhaul: the 3GPP split 2 or PDCP/split between the O-DU and O-CU. Note that the CU-CP (Control Plane) and the CU-UP (User Plane) are explicitly mentionned in the O-RAN architecture. Similarly in essence to an SDN architecture, the forwarding elements (O-DU, O-CU-CP and O-CU-UP) are controlled by two so-called RAN Intelligent Controllers (RIC). Two RICs are needed to take into account two time scales required for efficient RAN functions: (a) a near-Real Time (near-RT) RIC to handle control from 0.1 to 1 second, and (b) a non-Real Time (non-RT) RIC to handle control above 1 second.

O-RAN ALLIANCE advocates the use of virtualization and so specifies a so-called Service Management and Orchestration Framework which contains the non-RT-RIC function. The non-RT-RIC communicate with the near-RT RIC with an interface called A1 and with the O-DU and O-CUs via O1. The near-RT control and optimization of OpenRAN elements and resources is performed through compact data collection and control over a new E2 interface (not specified by 3GPP for the DUs and CUs). The non-Real Time RIC implements control and optimization of RAN elements and resources. The non-Real Time RIC is anticipated to incorporate specific AI/ML workflow, which involves training modules and provides policy-based guidance for applications in the non-RT-RIC [176].

The O-CU element handles the RRC for the control plane and the Service Data Adaption Protocol (SDAP) for the user plane and the PDCP. The O-CU-CP hosts the RRC and the control-plane part of the PDCP protocol, while the O-CU-UP hosts the SDAP protocol and the user-plane part of the PDCP protocol. The PDCP streams are exchanged to the O-DU via the midhaul which could be physically or virtually almost anywhere in the Open Cloud. Midhaul distances up to 80km have been reported earlier in this survey, but it remains to be seen how vendors and operators uses O-RAN for their use cases.

The O-DU contains the RLC/MAC/High-PHY layers. The O-RU contains the Low-PHY layer and RF processing based on a lower layer functional split. The fronthaul link (RU-DU link specified by the so-called LLS-C/U/S interface) should be less than about 20km as reported in the first figure of this survey.

The virtualization platform, or Open Cloud, hosting the O-DU, O-CU and RICs, should handle the multi-RAT CU protocol stack and support many protocol processing for 4G or 5G. The virtualization platform isolates the blocks and performs virtual resource allocation [48].

Obviously, a lot of work remains for the operators and vendors to implement and exploit the O-RAN ideas. Major operators and vendors are working hard to make intelligent RAN a reality.

C. Open RAN Opportunities

OpenRAN benefits from the advancing RAN architectures toward interoperability and intelligence. OpenRAN holds enormous opportunities for both the user and the operators. OpenRAN defines new technical solutions and business models to tackle in- creasing costs, complex deployments, and many more by incorporating software and hardware disaggregation through open interfaces. [177]. In the whitepaper published by O-RAN ALLIANCE on use cases and deployment scenarios [178], an initial set of OpenRAN use cases is introduced, which benefits from the advances in open architectures and show high business value. OpenRAN ecosystem utilizes AI and ML capabilities at the back-end blocks of the architecture to facilitate an open and intelligent multi-vendor network.

ML and AI algorithms are applied within the deployment scenarios to manage and control RAN performance, configurations, and optimization, in real-time, for the envisaged use cases. The use cases are categorized based on the application area and requirements [178].

Each use case has its focus area, well-defined purposes, and requirements [178]. The concept of white-box hardware as the base site will motivate an economical 5G deployment. The so-called white-box Base Stations focus on uplink and downlink processing, RF conversions, and gateways. Most of the use cases are defined based on the incorporated AI techniques, and cover a comprehensive range of applications, from traffic steering, Service Level Agreements (SLA), dynamic handover management for Vehicle-to-Everything (V2X) to enhanced user services and experiences through optimized resources. Within various Unmanned Aerial Vehicles (UAVs)-based use cases, applications are introduced envisaginging OpenRAN and open interfaces. The context-based dynamic handover management for V2X use case focuses on supporting frequent handover requests in high-speed heterogeneous environments. A summary of the categorized use cases is presented in Figure 17. The O-RAN ALLIANCE web site hosts many impressive demonstrations of current and future OpenRAN capabilities [www.virtualexhibition.o-ran.org].

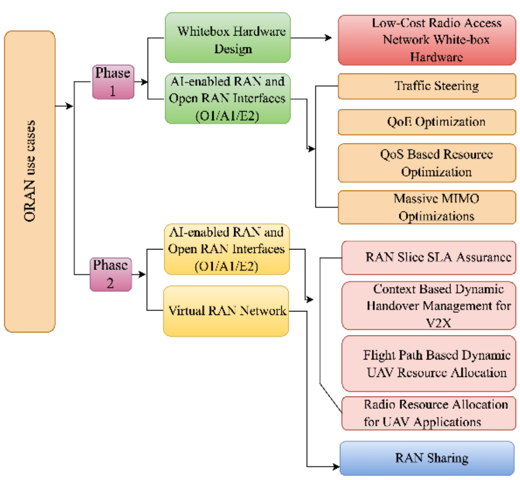

Fig. 17: Summarized OpenRAN use cases criterion as defined by the ORAN alliance to validate OpenRAN development.

D. Open RAN Cloudification and Orchestration Platform

The O-RAN ALLIANCE has defined and sketched requirements for open cloud architecture and various deployment scenarios, as discussed in [178]. The so-called Open-Cloud (OCloud) is an O-RAN cloudification and orchestration platform that classifies deployment options to expedite the cloudification of OpenRAN virtualized network elements. The OCloud provides a cloud computing platform encompassing physical nodes to execute applicable functionalities related to management and orchestration. The orchestration facilitates BBU resource pooling and cloudification, which should help in maximizing the operational improvement/cost ratio.

1) OCloud Architecture: OpenRAN cloudification architecture is based on the reference architecture provided by ETSI NFV Architectural Framework [179], which includes adequate COTS hardware to allow abstraction through virtualization. The ETSI NFV Architectural Framework implements virtual machines (VM) on the servers that facilitate Virtual Network Functions (VNFs) in the cloud. The Virtual Infrastructure Manager (VIM) acts as the control plane in OCloud and manages different servers as a single distributed system [178]. The VNFs mainly constitute the interfaces, virtualized open planes (O-DU, O-CU, NRT-RIC) along with the MEC applications and the 5G User Plane Function (UPF).

2) OCloud Deployment: OCloud defines a hierarchical deployment model comprising different modules like regional cloud and edge cloud hosted at independent or dependent levels. Figure 18 presents a hierarchical cloud deployment where each Edge Cloud, monitoring individual cell sites, is connected to the Regional Cloud. The VNFs are either implemented in the proprietary network element or on the OCloud component. Based on the different deployment scenarios in [178], the functionalities and hosting of O-DU and O-CU vary.

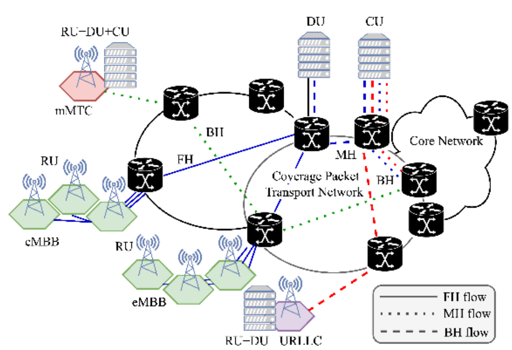

Fig. 18: A typical layout of a RAN infrastructure, e.g. [6], [180].

E. Implementation Challenges

One of the main challenges in O-RAN is to integrate the multi-vendor model and seamless interoperability between the services and equipment they provide. The RAN virtualization can bring concerns about the capacity of the fronthaul link in order to host several virtual BSs while maintaining the latency requirements between the RRH and BBUs. Implementing the functional splits can be challenging as it affects the fronthaul network's bitrate and latency.

Additionally, the open architecture imposes several challenges on security ground at various levels. The OpenRAN standards and 3GPP specifications have evolved in hand to facilitate RAN-functional splits resulting in RAN virtualization. On the deployment and implementation side, clear definitions for vRAN are stil lacking on how the software and hardware parts are deployed [45].

The challenges related to RAN virtualization to support 5G and beyond requirements for high data rate, low latency and high availability are very motivating for research and practicing engineers.

VII. Conclusion

This survey comprehends an extensive literature review on different functional splits proposed by 3GPP and the O-RAN alliance. A practical approach to the functional split requirements and implementation was provided. As a result of RAN splitting and virtualization, network deployments are more flexible and facilitate the creation of a multi-vendor marketplace for different radio and network components that are different from the traditional business models. By creating various interfaces between layers through splitting, new hardware and software products can be designed and fabricated while guaranteeing interoperability between elements produced by different manufacturers. The main advantages, disadvantages, and challenges are discussed. Each functional split is described in detail, and the underlying challenges are identified. Broadband access will be enhanced, and ultra-reliable low latency communications (URLLC) and massive Machine Type Communications will be supported. URLLC will enable applications like self-driving cars or coordinated autonomous UAVs, e.g., in a disaster-resilient swarm of co-ordinated drones participating in rescue missions. Expected 5G and beyond reliability and resilience are commonly cited to enable remote surgeries with physicians commanding high precision robots from remote hospitals in real-time and to support high-speed nano-robot communications for in-body healthcare applications. More realistically, 5G and beyond will serve the needs of the industry 4.0 and beyond.

Moving the processing functionalities from the RRHs to the DUs and CUs may be advantageous as the RAN architecture evolve and leads to an economy of scale. Many functional splits, serving various use cases, have been devised but have limitations. For example, the 3GPP split option 8 requires a data rate much higher than the total user data rate and a distance between CU and DU lower than 20 km. The split option 7.2 has been preferred by the O-RAN ALLIANCE. Different splitting implies different data rate and latency requirements.

For example, to implement split option 6, the PHY and RF are in the DU while the MAC is in the CU. The MAC layer performs functionalities like the computation/calculations and operations in CU considering software, whereas the RF (DU) takes care of the rest of the functionalities, resulting in high hardware costs.

Various standardization bodies are actively working to provide energy-efficient, reliable, and economic solutions by allowing BBUs to support multi-RF units.

The final part of the survey discussed the RAN evolution from C-RAN to OpenRAN. The virtualization functions were examined. The O-RAN ALLIANCE architecture was discussed while addressing how it might serve future stakeholders for 5G and beyond RAN. The O-RAN ALLIANCE intends to support diversified 4G to 5G and beyond use cases by developing the specifications and architectures with new open interfaces to control the DU and CU with the so-called RAN Intelligent Controller. State-of-the-art technologies for incorporating various split options were discussed. Some relevant solutions allow splitting, such as the split eight implementations using FPGA (hardware) [52], [53], gNodeB from ISW (software) [55] were presented. The ISW-gNodeB consists of independent network functions to implement PHY, MAC, RLC, PDCP, SDAP, RRC, and NRAP protocols.

The survey aimed to shed light on the various RAN architecture and deployment scenarios, providing a clear view of the functional splits, opportunities, and challenges. We provided detailed literature to justify the emergence of functional splits as an enabler for beyond 5G networks. In addition to the overview of functional splits, we also summarized the concept of virtualization and O-RAN ALLIANCE architecture. Although, we did not address Massive MIMO, CoMP, and mmWave, concerning functional splits in the scope of this survey.

Academia, industries, and research organizations are working toward an open RAN infrastructure to support RAN disaggregation. The O-RAN ALLIANCE implements different intelligent processing algorithms to deploy flexible and economic networks. Integrated Access Backhauling (IAB), edge processing with cloud, and virtualized (also Fog) RAN are open research areas that have the potential to incorporate intelligence into the network to support 5G second phase and 6G deployments.

VIII. Acronyms

3GPP	3rd Generation Partnership Project
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AI	Artificial Intelligence
ARQ	Automatic Repeat Request
BB	Base Band
BBU	Base Band Unit
BS	Base Station
BH	Backhaul
CA	Carrier Aggregation
CAPEX	Capital Expenditure
CoMP	Coordinated Multi-point
COTS	Commercial-Off-The-Shelf
CP	Control Plane
CPRI	Common Public Radio Interface
C-RAN	Centralized Radio Access Network
CU	Centralized Unit
CV	Compensation Value
DC	Dual Connectivity

DL	Downlink
D-RAN	Distributed RAN
DU	Distributed unit
eCPRI	Enhanced Common Public Radio Interface
eRE	eCPRI Radio Equipment
eREC	eCPRI Radio Equipment Control
E-UTRA	Evolved Universal Mobile telecommunications
FFT	Fast Fourier Transform
FH	Fronthaul
FPGAs	Field Programmable Gate Array
F-RAN	Fog RAN
GPP	General Purpose Processing
gNB	gNodeB
GTP-U	General Packet Radio Service Tunnelling Protocol
HARQ	Hybrid Automatic Repeat Request
IFFT	Fast Fourier Transform
IP	Internet Protocol
IQ	In-phase and Quadrature
ISW	IS-Wireless
LTE	Long Term Evolution
MAC	Media Access Control
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MNO	Mobile Network Operator
NF	Network Functions
NFV	Network Functions Virtualization
NGMN	Next Generation Mobile Networks
NG-RAN	Next Generation RAN
NR	New Radio
NRT	Near-Real-Time
nRT	non-Real-Time
OAI	Open Air Interface
O-CU-CP	OpenRAN Central Unit Control Plane
O-CU-UP	OpenRAN Central Unit User Plane
OpenRAN	Open Radio Access Network
OPEX	Operational Expenditure
O-RAN	OpenRAN Alliance
O-RU	Open Radio Unit
PDCP	Packet Data Convergence Protocol
PDUs	Protocol Data Units
PHY	Physical
PRBs	Physical Resource Blocks
QoS	Quality of Service
RAN	Radio Access Network
RAT	Radio Access Technology
RF	Radio Frequency
RIC	RAN Intelligent Controller
RLC	Radio Link Control
RRC	Radio Resource Control
RRM	Radio Resource Management
RRH	Remote Radio Head
RRU	Remote Radio Unit
RTT	Round Trip Time
RU	Radio Unit
SDAP	Service Data Adaption Protocol
SDN	Software- Defined Networking
SDU	Service Data Unit
SLA	Service Level Agreements
SON	Self-Organizing Networks
SR	Sample Rate
srsLTE	Software Radio Systems LTE
TTI	Transmission Time Interval
TTM	Time-to-Market
UAV	Unmanned Aerial Vehicle
UE	User Equipment
UL	Uplink
UP	User Plane
URLLC	Ultra-Reliable and Low Latency Communications
V2X	Vehicle-to-Everything
vBBU	Virtual BBU
vC-RAN	Virtualized-C-RAN
VM	Virtual Machine
vRAN	Virtualized Radio Access Network

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Spectrum Sharing and Dynamic Spectrum Management Techniques in 5G and Beyond Networks: A Survey

Spectrum Sharing and Dynamic Spectrum Management Techniques in 5G and Beyond Networks: A Survey

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Received 09 October 2020; Accepted 30 November 2020;
Publication 26 January 2021

Abstract

Advancing technologies and bandwidth hungry applications have increased the mobile data traffic in the radio spectrum. Utilizing spectrum is one of the indispensable performance metric seconded by techniques to increase the bandwidth. Spectrum efficient techniques have always been a part in all the generations of wireless communication. It has considered to be of utmost criticality with 5G networks. The spectrum sharing and management demands contributions from technical research groups as well as regulatory bodies. Recently, many technologies proved their potentials to invoke efficient spectrum utilization. Different approaches have been considered including cognitive radio, machine learning for dynamic spectrum management, spectrum sharing, spectrum harmonization, spectrum identification strategies, etc. An efficient technology is very important in order to have high spectral as well as energy efficiency. It is also important from cost-efficiency perspective. Therefore, this paper presents an overview of the various spectrum sharing and management aspects. This comparative study is motivated to provide a clear picture to design spectrum efficient system for 5G and beyond network.

Journal of Mobile Multimedia, Vol. 17_1–3, 65–78.
doi: 10.13052/jmm1550-4646.17133

Keywords: Spectrum, dynamic spectrum management (DSM), spectrum sharing, machine learning, spectral efficiency, spectrum allocation.

1 Introduction

Over the decades, wireless communications has emerged as the most agile and economical measure to connect people. From analogue telephony systems to high-speed data services with voice, it has gradually enhanced itself. With ongoing 5G rollouts and trials, the expectations are on the peak for data connectivity. Data-starved applications like multiplayer gaming, 4D video streaming, Ubiquitous connectivity, and many more has increased the mobile data traffic multifold. From the facts cited in Ericsson Mobility Report 2019 [1], the mobile data traffic will reach percent by 2024 and in [2], amid Covid-19 pandemic, uneven mobile data traffic distributions in residential and commercial landscapes. It also highlighted sharp increase in the voice calls. To meet the dynamic and expediting demands with new generation of wireless solutions, both Industry and Academia are struggling with one of the preeminent challenge of spectrum scarcity. Spectrum is the "OIL" in wireless systems as it restricts mobile network operators (MNOs) to provide services in terms of speed and coverage. Industries today needs more spectrum to address their beyond 5G use cases. An effective and concrete spectrum management and sharing techniques are the need to outweigh the challenge without exceeding the cost-constraints. The concept exploiting of millimetre wave (mmWave) frequencies was introduced by the Third Generation Partnership Project (3GPP) [3] as a measure to cancel out the scarcity of free spectrum below 6 GHz band in 5G standardization process. The mmWave spectrum offer high data rates but has challenges like high path loss and sensitivity to antennae, etc. In the present deployment scenario of spectrum, a huge amount is wasted or is under-utilized. Spectrum allotted to a particular MNO is not utilized if it is not providing any services in a particular region and thus, blocks the valuable resource. Therefore, measures to have techniques to increase spectrum is still critical.

In this survey paper, we will describe important parameters to achieve high spectral efficiency. Overall challenges in context of spectrum management and spectrum sharing technologies. In this paper, we will highlight

- Spectrum;
- 5G Spectrum Requirements
- Techniques for Spectrum Management

2 Why Spectrum is Critical?

Spectrum, in wireless community comprehends to the radio frequencies (RF) used for communication over the air interfaces. It carries information over number of applications ranging from broadcast systems, mobile telephony, activity trackers, WiFi, etc. to critical emergency networks and defence operation. The RF spectrum spans from 30 Hz to 300 GHz frequency range and its usage is governed by the Nation's Spectrum Policies in association with the International Telecommunication Union (ITU) through its Radio-Communication Sector (ITU-R) [4, 5]. ITU-R is also responsible for standardization activities and best practices for Spectrum Management.

Regardless of the broad RF range, only few frequency bands are successfully used constraints to factors like propagation characteristics, penetration loss, path loss, device compatibility, etc. The demand for services from each coming generation of technology is increasing at a rate, which fail to meet spectrum availability. It is the elementary requirement of the wireless systems to achieve higher data rate. In addition, the concentration of connected devices is enormous and it is expected to be more with 5G and beyond systems. These connected devices are diverse in nature and functionality. These includes mobile phones, autonomous vehicles, Fitness Trackers, Industries, Education services, Healthcare services, aerial vehicles. High-definition (HD) live streaming and many more. Spectrums, being scarce in nature urges for better techniques to incorporate allocation and management of spectrum bands. The broader spectrum or frequency bands support huge data transmission. Figure 1 illustrates the relationship between frequency, data transmission range and capacity. Higher frequencies support short-ranged communication with broader capacity wherein low frequencies support long-range communication but smaller capacity.

2.1 Spectrum Allocation: Licensed, Unlicensed and Shared Spectrum

Developing technologies and connectivity has increased the volume of data transmitted per second and overall congestion in spectrum. This has entailed for efficient techniques to make best use of available and usable accessible frequency spectrum. Spectrum Allocation is governed by individual National policies and usage is regulated through licensing of the spectrum bands. The spectrum bands allocated for exclusive usage are the 'Licensed' bands while the spectrum free to use by devices are categorized as 'Unlicensed' bands. Licensed bands allows efficient usage of assigned frequencies and

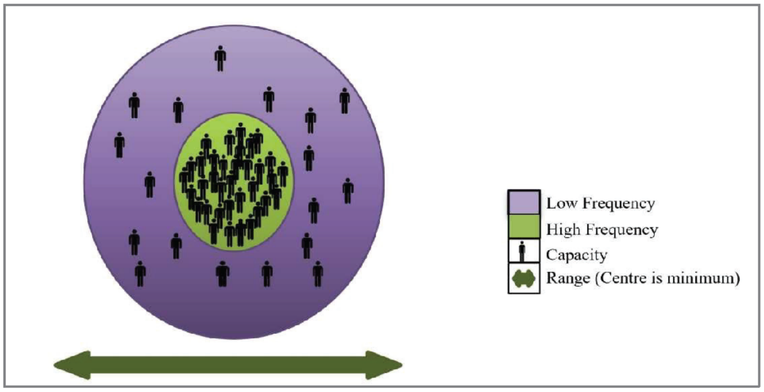

Figure 1 Frequency and capacity mapping.

easy interference management. Unlicensed bands have more devices and it makes interference management difficult because of adjacent devices. 900 MHz, 2.4 GHz and 5.8 GHz frequency bands are exploited under unlicensed category. The 60 GHz band is also in the unlicensed band [8]. The advancing technology has opened up new higher frequencies like above 6 GHz, 24–28 GHz millimetre wave spectrum, Terahertz bands, etc. Although new bands are available but the question remains for the practical accessibility w.r.t. regulations, cost and feasibility.

2.2 Spectrum Sharing

The frequency allocation data affirms the assignment of major part of the frequency bands. This leaves behind a very few unused frequencies for practical use [7]. The fact that there is a possibility that not all the frequencies allocated to a user is operational all the time. This concept is based on the idle time of a licensed band. Techniques to use the free/unused frequencies of the allocated licensed spectrum in certain time or space by other user/service provider, forms the fundamental of spectrum sharing. The techniques like dynamic spectrum access (DSA), opportunistic spectrum access (OSA) supports the dynamic management of the spectrum. The cognitive radio (CR) also provides technique to use unused spectrum from both licensed and unlicensed bands to achieve high spectral efficiency [6]. Spectrum sharing is critical in the future networks to support the millions of internet of things (IoT) devices, connected industries, vehicles, etc. in addition to existing mobile traffic. The different spectrum sharing techniques and regulations are available like citizens broadband radio service (CBRS), TV white space, Spectrum Harmonization [8], Light Licensing, etc. for efficient spectrum utilization. With each generation of mobile communication, new spectrum policies and techniques come. The main aim is to use the available spectrum efficiently. CBRS allows set of techniques for efficient use of the mid-band spectrum (3–24 GHz) where TV white space allows identifying unserved or under-served frequencies in TV spectrum. Spectrum Harmonization indicates the uniform RF spectrum band allocation including technical specifications both at regional and global levels. It aims at minimizing the interference at handovers and expedite global roaming concept. Light licensing technique let the users utilized the frequency in primary secondary usage basis capped with geo-locations and spectrum sensing to avoid interference. It is primarily used in 3.65-3.7 GHz and 70/80 GHz bands. New dimensions will emerge with simultaneous usage of both licensed and unlicensed spectrum. It will provide flexibility for ne deployment scenarios as more spectrum directly proportionate to higher capacity and higher spectral gains. It allows MNOs the freedom to explore new service and business model.

Spectrum sharing (SS) allows having a cost efficient means to utilize available spectrum and sharing the cost for licensing among multiple MNOs if applicable. SS is investigated in various studies in terms of interference minimization, license sharing, spectrum trading, secondary-primary user, etc. In [16], the concept of spectrum pooling and renting. Spectrum pooling allows MNOs to share the licensed bands under national regulatory policies and renting permits MNOs to rent out spectrums owned by other to maximize capacity. Licensed Shared Access (LSA) is the SS technique for licensed bands while Licensed Assisted Access (LAA) facilitate sharing for unlicensed access. LAA is a critical part in LTE-U (LTE Unlicensed) and operates in 60 GHz band [15, 16].

Different SS techniques include trading, relaying, routing, harvesting, etc. of the spectrum [15]. These techniques contribute to enhance the spectral and energy efficiency along with capacity of the system. Spectrum trading is an important consideration as it facilitate economical-efficient use of spectrums [15, 16]. In spectrum trading, a time-based license of the spectrum is allotted to secondary user. Figure 2 illustrates different spectrum sensing facets.

2.3 Spectrum Comparison in Wireless Generations

The spectrum bands and operating frequencies evolve with the each advancing generation of the mobile communication. The past generations of cellular,

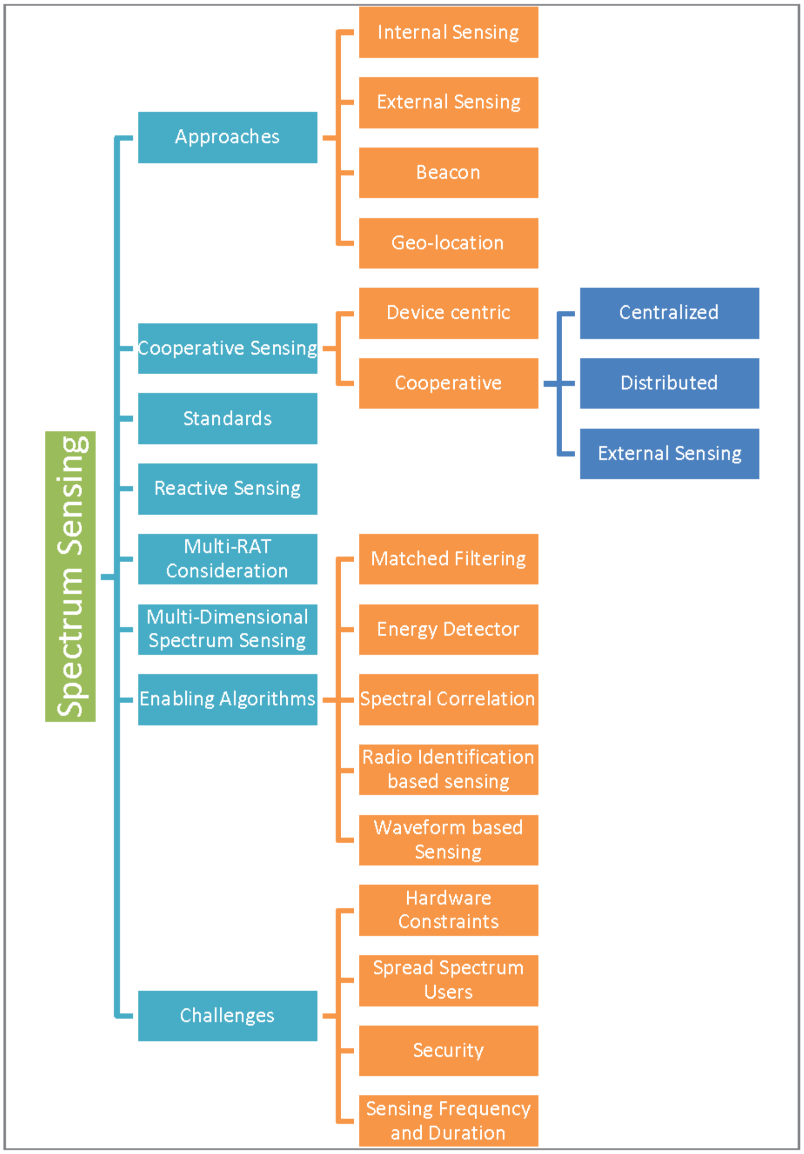

Figure 2 Spectrum sensing facets [23].

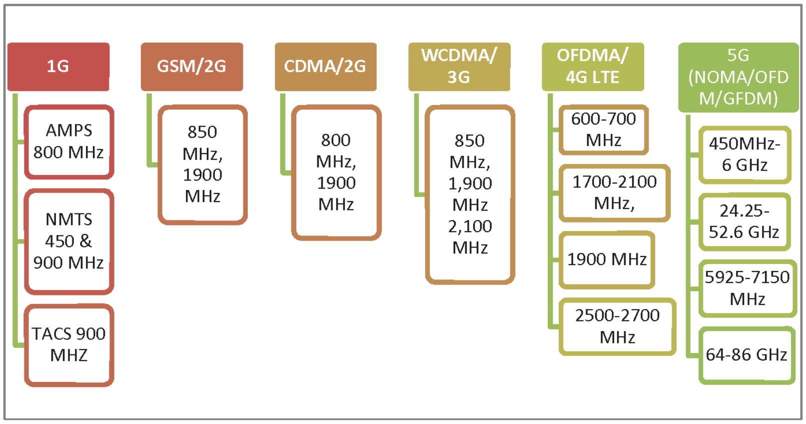

Figure 3 Spectrum bands in cellular generations.

had all licensed spectrum bands. Figure 3 illustrates briefly the spectrum bands associated with previous generations of mobile communications. Different access technologies supported the efficient usage of the same frequency bands in higher generations like Code Division Multiple Access (CDMA), Wideband Code Division Multiple Access (WCDMA), Orthogonal frequency-division multiple access (OFDMA), etc. In 4G LTE, 2.3–2.5 GHz spectrum bands were included in addition to 600 MHz, 700 MHz, etc.

The concern is deeper in case of 5G Spectrum because of the increase in spectrum-hungry applications, congested sub-6 GHz frequency bands [9] and physical constraints in terms of bandwidth and throughput. The addition of unlicensed and shared spectrum bands [10] adds up to the complexities. Three different operating bands are specified for 5G in coexistence with the LTE frequencies that can be exploited using frequency division duplex (FDD) and time division duplex (TDD) technologies to share spectrum. Figure 4 sums up the advantages and disadvantages of the three spectrum bands. The spectrum band ranges from 450 MHz to 6 GHz in sub-6 GHz range, labelled as FR1 and extends up to 52.6 GHz in millimetre waves, labelled as FR2. The 3GPP release 15 [3, 11] outlined 5G New Radio Non-standalone (5G NR) standards and range of frequencies namely FR1 and FR2. The frequencies 5.9–7.125 GHz are being considered for unlicensed bands. It also charted new waveforms like Discrete Fourier Transform Spread Orthogonal Frequency Division Multiplexing (DFT-S-OFDM) and Cyclic Prefix OFDM

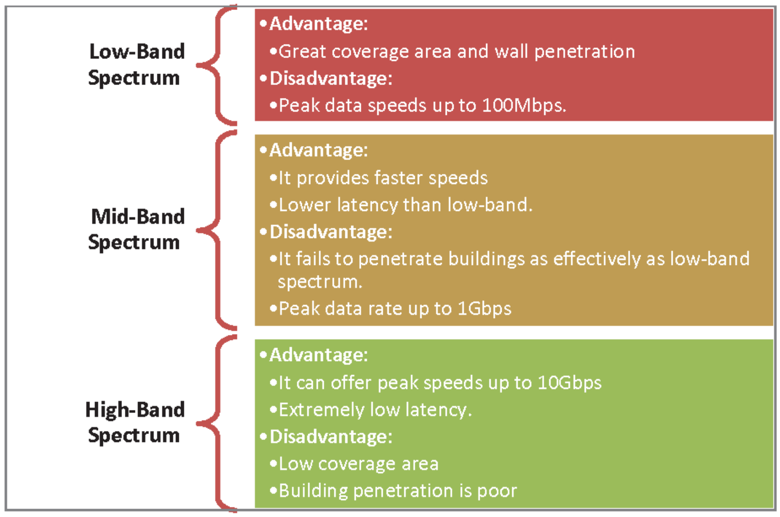

Figure 4 5G spectrum bands.

(CP-OFDM) for FR1, FR2 respectively, and modulation techniques like $\pi/2$ BPSK [3] to incorporate in 5G and beyond network designs. The concept of having small cells [12] derived to mitigate the challenges imposed by high spectrum bands like poor to no penetration capability and low coverage area.

3 Dynamic Spectrum Management

Dynamic spectrum management (DSM) defines a set of efficient spectrum management techniques. The techniques aim to improve either one or many of the key performance parameters like QoS, battery life, energy consumption, interference, etc. by allowing Radios to share multiple frequencies without causing interference. It facilitates sharing of wireless channels on co-primary basis between licensed and unlicensed users [13]. Frequency, space and time are key considerations for DSM. The Dynamic Spectrum Alliance (DSA) [14] supervises the spectrum usage and set required regulations for the same. The frequencies are dynamically allocated, constraint to its availability in terms of space and time. The management of required bandwidth, estimation and mitigation of interference, cross-layer optimization, etc. holds key importance in technical implementation of DSM. The application of artificial

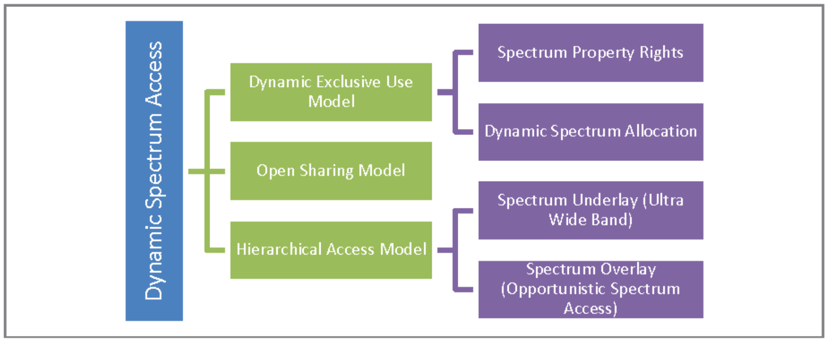

Figure 5 Dynamic spectrum management approaches.

intelligence (AI) and machine learning (ML) in spectrum sensing is useful in future networks.

DSM is one of the core requirement for spectrum sharing techniques especially in case of users with different spectrum requirements. Figure 5 illustrates different dynamic access approach [24]. To make efficient utilization of the idle of TV white space (TVWS) bands, different constraints has been discussed which includes LSA considerations [17] and propagation characteristics of mm-Wave [18]. Opportunistic spectrum sensing (OSS) technique [19] is used for identification of unused or free frequencies in the licensed spectrum that can be allotted to secondary user(s). OSS facilitate freedom to utilize auctioned spectrum band if in idle state. Several algorithms to predict spectrum idle state in order to have intelligent DSM techniques have been proposed that particularly considered factors like user mobility [20], network heterogeneity, vehicular connectivity [21], etc. have been a topic of interest. In [22] proposed layered spectrum management scheme considering poor signal-to-noise environments. They considered the knowledge of the spectrum as the elementary component. AI and ML have shown promising results in implementing DSM schemes [25]. They have shown AI-based solutions are flexible, and adaptive which yields improved spectral efficiency.

4 Conclusions

For 5G and beyond networks DSS and SS techniques are prominent. We presented an overview of spectrum, various aspects of spectrum sharing and dynamic spectrum management techniques that can enhance both spectral and energy efficiency. The survey was highlighted economical as well as technical angles. For spectrum sensing, an AI and ML approach could be beneficial in ultra-dense heterogeneous environment. We have also seen considerable perquisites of employing DSM techniques. Some key advantages are mentioned as following;

- Enhance overall system performance
- Provides flexible platform for dynamic technologies like implementing MIMO systems, cognitive radio, etc.
- High spectral and energy efficiency
- It complements resource management and allocation strategies
- Provide interference management caused by adjacent frequencies
- Provide better frequency reuse technique

Also with new 5G spectrum, integration of different bands will be critical and demand spectrum harmonization. More concrete solutions are needed on spectrum front as with small cell deployments and Internet of things (IoT) densification will add on to the existing spectrum, spectrum sensing and interference challenges. Interference management and awareness schemes can be a promising solution to cater high mobility and capacity demands.

Acknowledgement

This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

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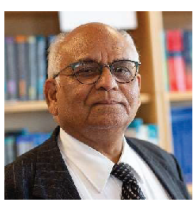

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Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management

2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)

Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management

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***Abstract*— The industries today, are undergoing transformational changes as a result of the growing demand for ubiquitous connectivity. To meet the increasing demand every day, loads of reengineering is required to achieve best-fitted architecture to accommodate more devices, ways to manage available resources, enhanced radio technologies, etc. to deliver more coverage and capacity. This paper aims to study and present different critical features of small cell and ultradense networks. The scope is to summarize various deployment scenarios and challenges. Broadly, the challenges w.r.t resource management, developing flexible architecture, managing the available spectrum and also the use of unlicensed spectrum, etc. will be addressed. The shortcomings in available resource management, interference awareness techniques, spectrum management, etc. will be summarized with different potential technologies. For small cells, it is necessary to understand its interaction with the macro network to demonstrate the overall user experience. Thus, this work will present an elaborated picture of small cell evolution followed by the radio access network (RAN) architecture to achieve a full-heterogeneous and centralized network.**

Keywords— Ultradense Network, Small Cells, RAN, RRM.

I. BACKGROUND

Ubiquitous and seamless connectivity is the stepping stone in everyone's anticipation for the current and upcoming wireless solutions to communication. Today we are in the midst of technological transformation affecting not only an individual's life but adding up a huge percentage to National economy, digital ecosystem, education, health, etc. We are in the initial phase of brewing the foundation for a sustainable solution to all our needs. ITU [1] mentioned 2019 to witness the growth of "Digital Economy" with the online participation of more than half of the world while Ericsson's [2] estimations state that by the end of 2025, 65% of world's population will be under the coverage. Cisco [4] estimated on their Global Mobile Traffic Forecast that by 2021 cellular networks' traffic will be offloaded to Wi-Fi in a ration of 2:6. Sixty percent of total mobile data traffic was offloaded onto the fixed network through Wi-Fi or femtocell in 2016.

The imminent revolutionary fifth generation of mobile communications symbolizes a smart, connected and intelligent generation. 3GPP [3] defined various enabling technologies for 5G. 3GPP defined the concept of small cell and network densification through its various releases along with D2D, LTE TDD-FDD joint operation including Carrier Aggregation, etc. Small Cells was supported in the HSPA and LTE systems alongside macrocells. Switching to Small cells/femtocells/picocells, strong radio evolutions [3] and advancing access technologies will complement the capacity, throughput, costs, smooth interactions with the macro coverage layer, etc.

This paper is organized as follows; Section II and III will introduce the concept of Ultradense Network and Small Cells respectively and discuss their key characteristics, and associated challenges. Section IV, will discuss some performance metrics and Section V, will cover key challenges and section VI will summarize potential technologies and research area and finally, in Section VII paper will be concluded with the findings.

II. ULTRADENSE NETWORK

Ultradense network (UDN) is one of the preeminent solutions to support the infrastructure refurbishment to meet intensified demands. The network densification or UDN is the result of deploying small cells, within the macrocells. It is defined as the networks having a high density of access points than active users i.e. a network where the radio resources are in higher density as compared to current networks [5-7]. Considering different works of literature, UDN can be quantitatively summarized as a network with cell density greater than 1000 cells / Km squared [9]. In [5-6], it is characterized by shorter inter-site distance and sub-linear capacity growth, significantly as higher BS density causes higher interference [10]. Access nodes are placed in closest proximity to the users so provide seamless connectivity.

A. UDN Basic Architecture

Densification refers to the addition of more sectors to macro Base Stations [14] to expand the network by deploying small cells/femtocells/picocells as fully-functional base stations. The deployed base stations are called the iBS-Individual Base Stations. These are replicas of the macrocell with reduced transmit power to provide coverage to a smaller region [9]. Some deployments have extensions to Macrocell-Access Points, referred to the Remote Radio Heads (RRH) to extend signal coverage with some or all physical layer functionalities. *Figure 1*, summaries key features of different types of small cells.

UDN is different from the traditionally deployed cellular networks in terms of footprint, active/idle mode, interference occurrence, frequency reuse pattern, backhaul connectivity, etc. [5, 8-10]. The iBS are deployed close to end-users with smaller coverage area and active sleep mode. Network densification is classified into Vertical and Horizontal

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densifications depending on the cell deployment either on the elevated or the lateral planes [9]. It is also classified into Centralized and Decentralized based on the cell-interaction. *Figure 2*, explains the Densification classification.

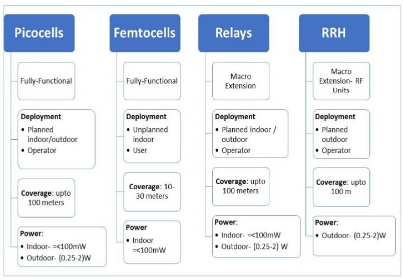

Figure 1 Types of Small Cell

The performance of the network varies with different classification and thus, it requires a different modelling approach [9]. The vertical densification provides better spectral efficiency for the same area as compared to the horizontal densification. In centralized densification, there is a central node that controls other nodes wherein the decentralized approach distributed nodes are coordinated and require D2D communication links [22].

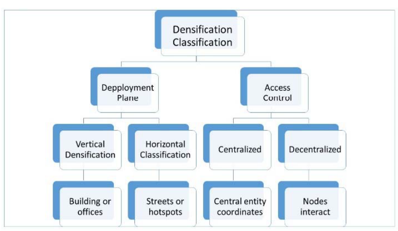

Figure 2 Densification Classification

B. *Enabling Technologies*

To provide the ubiquitous connectivity and meet the 5G and beyond expectations, a plethora of technologies play a vital role. The following section discusses some of the prominent technologies and associated challenges for network densification.

1) *Software-Defined Network (SDN)*

Software-Defined Network, reformulate the network architecture to integrate 5G and beyond needs, by incorporating agility and flexibility to the existing network [23]. The ideology behind SDN is to separate the control plane from the network hardware and articulate external data controller. Network Densification through SDN deployment eliminates multiple infirmities like operational costs, energy consumption, increased signalling overheads, backhaul, etc. by proving programmable capabilities and reconfigurability [9][23].

2) *Massive IoT Environment*

IoT services include a wide range of communication infrastructure including human-to-human (H2H), human-to-machine (H2M), machine-to- human (M2H) and machine to machine (M2M) etc. With such network demand for ubiquitous connectivity and the exponential increase in the number of smart devices, it is required to have technologies such as artificial intelligence, cloud and edge computing, information sensing, etc. to provide a platform for all interconnected services [20].

3) *Massive MIMO Networks*

Massive MIMO signifies spatial densification with hundreds of antennas equipped into the base stations. This will accommodate more users to available resource unit of a given BS and thus yield huge gains. These networks are robust and are high in reliability, throughput and Energy Efficiency [19-20].

4) *mmWave Networks*

The high-frequency bands in the have the potential to support large bandwidths and high data rates, ideal for increasing the capacity of wireless networks due to the short wavelengths. These networks provide large bandwidth, good isolation, better co-existence due to directional antennas, spatial multiplexing gains, etc. [18].

5) *Multi-Radio Access Technologies*

Multi-Radio Access Technologies (Multi-RAT) indicates the coordinated existence of different RATs to enhance the quality of service. In [24], described the technique to offload the traffic to the WiFi layer to mitigate delay using optimized RAT selection algorithms and the offloading mechanisms. WiFi nodes have delivered rates akin to cellular technology. Mobility management, data splitting and control flow across cellular and WiFi nodes is critical and is an open research area.

6) *Proactive Caching*

Proactive caching is the predictive storing of popular content in the BSs or the user equipment (UE) to serve the user demand to this content in peak traffic loads [14]. The storing of such content occurs in off-peak periods to alleviate the load on the wireless and backhaul resources [15]. Advances in context-awareness, social networks, storage, secure communications, and D2D communications have a great influence on the potential gain of content caching, and the efficient use of resources in general [16][20]. The design of caching schemes to be implemented in dense networks requires the understanding of the spatial and social structure of such networks [14].

Following are different types of UDN;

1) *Ultra-Dense HetNets*

Ultra-dense HetNets are densified network of heterogeneous access nodes which includes the traditional high-power macrocells, low-power small cells and other non-cellular communication systems like WLAN, D2D, LPWAN, etc. to meet the high demands for coverage and connectivity. These networks have enhanced coverage, capacity and optimized exploitation of frequency resources through spatial reuse [20].

2) *Ultra-Dense C-RANs*

Ultra-dense C-RANs are the densified network with a cluster of Remote Radio Heads (RRHs) and Radio Frequency parts. RRHs are deployed at the baseband and the RF parts are separated by connecting remote units [20]. Ultra-dense C-RAN is a cost-effective network with improved spectral and energy efficiency due to the centralized resource allocation.

3) Ultra-Dense D2D Networks

Ultra-Dense D2D Network is the one with a large number of D2D enabled users. The data transmission is taking place among the devices bypassing the base stations or core network. The benefits of these networks are increased Spectral and Energy Efficiency, reduced communication delay, network load and power consumption [20].

C. Challenges

UDN is a network with sub-linear capacity growth, as the base station density increases with an increase in the impact of the interference. Interference is one of the major issues in UDN as it becomes severe with high volatility [18]. Active and idle cell states help in improving Energy Efficiency and reducing interference. Optimal resource management in UDN is critical. Failure in optimized resource allocation can lead to high interference situations, which has the potential to trigger issues like unbalanced load distributions, and higher power consumption, etc. [11, 18]. Other challenges in UDN is maintaining QoS with the mobility and handovers. In Multi RAT, QoS is challenging in the simultaneous connection in different RATs [24].

III. Small Cell

With the 4G LTE and upcoming 5G networks, small cell technology has evolved as one of the critical pieces [13]. It has shown remarkable results in enhancing coverage and capacity in densely populated scenarios [3, 12]. These are low-powered Base Stations deployed at closer proximity to the user, unlike traditional macro Base Stations. Small cells intend to increase capacity, improve network performance and service quality in the areas remain in the outage [14] and complements macrocells.

The prediction is that the number of small cells deployed will grow exponentially in the coming years. The small cell technology also provides solutions for outdoor network densification. Small cell technology provides a cost-effective network solution to eliminate the outages with enhances bandwidth. They are one of the promising technology to make room for 5G and beyond networks [12].

A. Key Characteristics

Small cell relates to a network having a dependable coverage, enhanced spectral efficiency, improved capacity, better user experience and performance. It is mainly deployed to solve network capacity issues in the outage-subsets of the macro base stations. Data transmission is improved in small cells as they are capable of transmitting at different bands of both licensed or unlicensed spectrum [11, 14]. This capability of reusing the available spectrum allows small cells to be deployed in high density, increases the overall spectral efficiency of the network in addition to the network bandwidth and speed. These are integrated into the macro networks to spread traffic loads. Few of the other advantages of small cells are that they are easy to install. Small cells draw less power, thus the mobile handsets have extended battery life [13]. Small cell ensures seamless connectivity by occupying less space. They break down a larger site footprint to several smaller cell sites and accommodate more users per unit area.

B. Types of Small Cells

Depending upon the decreasing transmit of the base station power, antenna position and the region, small cells are referred to as macro-, micro-, pico- and femto-cells; listed in order of decreasing base station power [14] and summarized in *Figure 3*.

Figure 3 Types of Small Cells

C. Basic Architecture and Deployment

Small cell hardware is discrete and energy-efficient. Small cell installation consists of small radio equipment and small antennas and is usually placed on existing infrastructures such as streetlights, the sides of buildings or poles. Small Cells can be deployed indoors and outdoors. Installation requires; Power source; Backhaul connection to the core network; and Installation place. Small cells can be deployed broadly as Passive Distributed Antenna Systems, Active Distributed Antenna Systems, Concealed integrated Metrocells or Multibeam Antennas and Sector Splitting [11, 15], summarized in *Figure 4*.

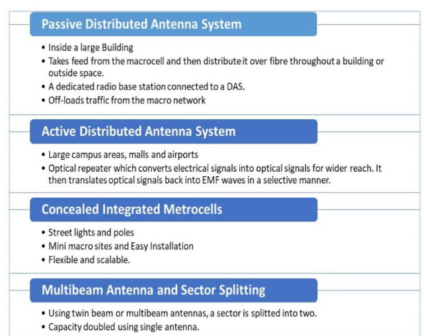

Figure 4 Small Cell Deployment

D. Challenges

Where, small cells complement the main macro base station with extended functionalities, on the other hand, it brings additional complexity to the network design. Small cells challenges are different from those of conventional towers. Identification of potential locations for deployment is one of the key concerns with small cells. The well-equipped network design team are responsible for identifying locations and installations taking into consideration the location of existing fibre and the physical application of the small cell itself [15, 17]. The paradigm shift from the single base station (Macro stations) approach to ubiquitous connectivity with small cells of hundreds of thousands of base stations, demands the network be transparently and securely across licensed and unlicensed spectrums [14]. Some of the key challenges for small cells are Self-organization, backhauling, handover, and interference. These challenges will be discussed in detail in the following section concerning ultra-dense deployments.

IV. PERFORMANCE METRICS

Following are some of the key performance metrics used in modelling Small cells in ultra-dense networks.

A. *Coverage and Outage Probability*

If the SINR (Signal-to-Interference-and-Noise-Ratio) of the randomly selected user in a network is above the threshold then it is termed as coverage probability or the success probability. The SINR value, lower than the threshold value, it is termed as Outage Probability and describes a situation of weak or no connectivity. These probabilities define the quality of the link between the user and the serving BS. This value is significantly associated with User Association [7], Propagation models [18] [26] and Estimation of the UDN Economics [9] [26] [27].

B. *Average Spectral Efficiency*

Spectral Efficiency is defined as the average number of transmitted bits per second per unit bandwidth. Spectrum Efficiency is one of the critical performance metric in 5G dense scenario as Spectrum is a scarce resource and demand is increasing exponentially. The significance of this metric is directly associated with User Associated [7] [26], Interference management [29], Backhauling issues [17], Cost Estimations [9] [27], etc.

C. *Area Spectral Efficiency*

Area Spectral Efficiency is defined as the average achievable data rate per unit bandwidth per unit area. It is an important metric to calibrate the performance of a densely packed network. It is significantly associated in User Associated [7], Propagation modelling [18] [26], Interference Management [29] and Energy Efficiency [30] [31].

D. *Network Throughput*

It is defined as the average number of successfully transmitted bits per sec. per Hz. per unit area [31]. It is closely associated with the calculation of Area spectral efficiency and outage probability. Network throughput holds significance in determining Energy efficiency [30] [31].

E. *Energy Efficiency*

The energy efficiency is a performance indicator that compares the achievable rate to energy costs. It is defined as network throughput to the power consumed per unit area [30]. Energy Efficiency is significant in Interference Management [29], Backhauling issues [17], and Propagation modelling [18] [26].

F. *Fairness*

It indicates the evaluation of a given cell association, scheduling, or resource management scheme between different users. It determines the efficiency of any scheme implemented for resource management or allocation [17].

V. OPEN RESEARCH AREAS

A. *Spectrum*

For Mobile Operators, Spectrum is the key asset and its availability decides coverage. As the requirements are defined, 5G design has to support a wide range of spectrum from 400MHz-90GHz irrespective of spectrum bands i.e. licensed, unlicensed or shared [25]. Under mmWave, the operating frequency is 24-30 GHz with a data rate of 5Gbps and it estimated that higher frequencies will bring more spectrum. Increased spectrum allows users to have an enhanced data rate of 10Gbps. Dealing with high frequency is very critical because of the short propagation distances. Path loss is eminent in higher frequencies. Therefore, it is important to design adequate measurement devices and feasible modelling schemes.

B. *Self-organization*

The cell operations are dependant on self-organizing functionalities with picocells and femtocells, where operator supervision is not required [11]. Self-organising cells must consider various types of coexisting cells and the network parameters before deployment. The self-organizing capability of small cell networks can be generally classified into three processes, and is summarized in *Figure 5*.

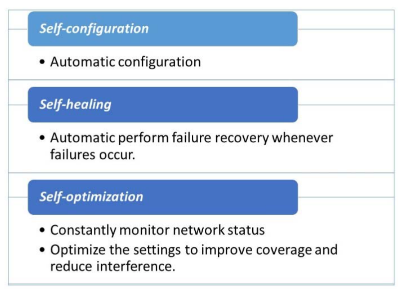

Figure 5 Self-Organizing Cell Types

C. *Backhauling*

Backhaul network design in UDN environments is a major issue because of the coexisting cells. Operators can not guarantee an ideal high-speed low-delay backhaul for each small cell [9, 12]. For instance,

- Picocells require access to infrastructure with power supply and wired network backhauling, which may be potentially expensive.
- Femtocells, with lower backhauling costs, may face difficulties in maintaining the quality of service (QoS) since backhauls rely on consumers' broadband connections.

Therefore, network backhaul must be planned to yield benefits in terms of costs and Quality of Service. Backhaul technologies can be wireless or wired or both, with dedicated interfaces to the core network [7-9, 11].

D. Handover

Efficient Handover guarantees seamless uniform connectivity. It allows users' free movement within and outside of the cell coverage. The probability of handover failure increases the probability of user outage. It also helps in balancing the traffic load [9].

E. Interference

Interference management is very critical in context to the deployment of small cells in a dense environment. Densely populated Mobile Base Stations will cause strong inter-cell, intra-cell and inter-user interferences because of closely associated cell boundaries. This inter-cell interference degrades network performance. Interference issues are much critical in small cells UDN because of the co-existing of multi-tier cell sites. The restricted access control associated with picocells and femtocells may lead to strong interference scenarios in both uplink and downlink since users may not handover to the nearest cells [8-11].

In Release 15 [11], 5G-TDD systems at the network as well as MNO front are synchronized to mitigate Interference between the uplink and downlink. There have been many enabling technologies like permissive techniques, such as Inter-cell User-Association, Interference Coordination, Coordinated Multipoint, and Coordinated Scheduling to mitigate the challenges of Interference to enhance overall service and performance.

VI. CONCLUSIONS AND FUTURE DIRECTION

Upcoming 5g and beyond networks are coupled together with an enormous amount of devices and data traffic. fueled by the forecasts of the imminent traffic. To meet future networks' demand, the densification of the network is the leading candidate. In this paper, we have summarized the concept of UDN, small cell and different considerations important for small cell deployment. The fundamental differences between the UDN and small cell from traditional and HetNet cellular networks. We have also listed challenges and some potential technologies and strategies.

Finally, based on the existing research efforts and other leading techniques, we have identified some potential challenges and open research directions that still need further investigation and study. One of the challenges in the accurate modelling of UDNs is the consideration of vertical densification where the small cell BSs are densified in the elevation plane. Effective network planning is essential to cope with the increasing number of mobile broadband data subscribers and bandwidth-intensive services competing for limited radio resources. To combat the increased complexity, manufacturers have built automated optimization and configuration tools into devices, and they have integrated multiple networking protocols and frequencies into a single package. Innovative frequency reuse techniques are required.

In UDN environments, there would be a need for a paradigm shift in the frequency reuse concept. Drastic interference between neighbouring cells is a limiting factor, thus strict interference management and awareness schemes are needed to mitigate the interference of neighbouring cells. With the scarce spectrum resources, one vital and long-term solution is to increase the reuse per unit area of the existing spectrum.

ACKNOWLEDGMENT

This work has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

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Dynamic Resource Block Allocation in Network Slicing

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***Abstract*—Network slicing is crucial in 5G and its evolution concerning user-centric services. By allocating independent resources, like link bandwidth, computing/processing capabilities and spectrum, to address users' requests, slicing serves the end-to-end verticals or services. gNodeB (gNB) allocates the bandwidth resources to transmit/receive data to User Equipments (UEs). Resources Blocks (RBs) are the smallest resource entities assigned to a single user. In 5G New Radio (NR), the time-domain resource allocation defines the allocated symbols (OFDM symbols), while the frequency-domain allocation illustrates the RBs (sub-carriers) allocation to the UE. RB comprehends 12 sub-carriers in the frequency domain with a flexible RB bandwidth, unlike LTE-A. It is critical to provide enhanced services to different users. There have been several works on challenges to enable a multi-tenant and service RAN while providing isolation to the slices. This work proposes a detailed approach for creating slices based on the demanded services, resource virtualization and isolation. The focus is on resource sharing algorithms at the Slice Orchestrator (SO) level. These virtual network slices support a wide range of services and applications categorized into the Enhanced Mobile Broadband, Ultra-Reliable and Low-Latency Communications and Massive Machine-Type Communications megatrends. The paper also provides an overview of standardization activities and evolving requirements to support use cases and services like Holographic Telepresence, Automotives, among other.**

***Index Terms*—Network Slicing, Communication Service Providers, RB Allocation, Slice Isolation, Holographic Communication, Industry 4.0.**

I. Introduction

The roll-out of fifth-generation (5G) wireless networks has embarked on the concept of Network Slicing (NS) as one of its fundamental technologies. NS facilitates a segmented layer of networks as slices or network slices in addition to the base network architecture [1]. As an integral part of the virtual network, these network slices offer full end-to-end connectivity for user-specific services [2]. The slices forming isolated virtual network layers exhibit all the required functionalities of the shared physical network. It enables the Communication Service Providers (CSPs) to address various inventive business models, use cases, and tailor-made user-specific solutions with guaranteed performance over a prevailing infrastructure. NS diminishes the requirement for new physical networks for dedicated services. The network orchestration helps CSPs to automate the communication on and across the network providing tailored services with guaranteed Quality of Service (QoS) for various usage scenarios, in association with Service Level Agreements (SLAs) [3].

NS Framework was first proposed by the Third Generation Partnership Project (3GPP) in Release 15 [4]. It has gradually evolved, with the technical details and enhancements in the following releases. By employing NS, CSPs can create multiple virtual slices to acknowledge enormous data traffic increases and specific user requirements. Each slice in isolation, i.e., without interfering with the coexisting slices, hosts individual network functions and application services [5]. Various Standard Development Organizations (SDOs) have backed NS to support multi-vendor services [6]. The Next-Generation Mobile Network (NGMN) [1] laid out the detailed principle of creating and managing multiple independent logical mobile networks over shared physical infrastructure.

This work focuses on resource-sharing algorithms at the Slice Orchestrator (SO) level and computing slice's radio resource requirements and usage. The resources are periodically adjusted based on the current Channel Quality Indicator (CQI). The scheduler needs to handle the demand and service quality. As it is essential to efficiently allocate radio resources in dynamic environments, allocating resources to slices distinguishes services to meet user QoS. The proposed method tracks adaptive behaviors of communication services based on the number of active users, data buffer status, and channel condition. Additionally, the paper also provides different use cases enabling future networks and an overview of the standardization activities towards NS.

The remaining paper is organized as follows. Section II discusses the state-of-the-art concerning resource management, NS standardization activities, and requirements. Section III

This work was supported by FCT/MCTES through national funds and when applicable cofounded EU funds under the project UIDB/50008/2020, ORCIP (22141-01/SAICT/2016), COST CA 20120 INTERACT, SNF Scientific Exchange-AISpectrum (project 205842) and TeamUp5G. TeamUp5G has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

summarizes our methodology and assumptions, along with the discussion of the results. Finally, Section IV presents the main conclusions of this work and discusses topics for further research.

II. State-of-the-Art

The evolving services are categorized broadly into the following four classes: (i) enhanced Mobile Broadband (eMBB), (ii) Ultra-Reliable Low-Latency Communications (URLLC), (iii) massive Machine-Type Communications (mMTC), and (iv) Vehicle to Everything (V2X). These services set the Key Parameter Indicators (KPIs) to evaluate the user requirements enabled through network slicing. In 4G networks, NS was limited to service isolation [7]. However, with 5G and beyond networks, NS can facilitate CSPs to provide guaranteed QoS services via virtual network slices, also called "5G Slice". The resources are allocated on-demand with a valid session using existing virtualization techniques. Thus, it adds additional scalability and flexibility to conventional networks. By facilitating resource sharing and automation among independent 5G slices, virtualization and Orchestration technologies are the key enablers of NS [8], [9]. NGMN defined a 3-layer NS framework [1] enabling a flexible and scalable End-to-End (E2E) architecture, consisting of the Radio Access Network (RAN) and core networks [10]. 5G Infrastructure Public-Private Partnership (5G-PPP) proposed an exhaustive 5-layer NS Framework in addition to the NGMN definition, depending on different use cases [6], [11]. To manage the slice sessions and resource management, ETSI defined the Network Function Virtualization (NFV) Management and Network Orchestration (MANO) architecture [9] to facilitate NF management and orchestration, its virtualization and resource allocation through the three following functional blocks: i) the NFV orchestrator, ii) the VNF manager, and iii) virtualized infrastructure manager [12]. Figure 1 illustrates the various layers that conceptualize the NS technology.

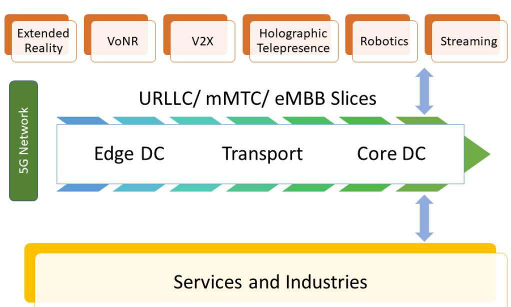

Fig. 1. Layered approach and concept of Network Slicing

A. Resource Block Allocation in Network Slicing

In wireless networks, Dynamic Resource Allocation (DSA) of data packets is critical to support different dynamically active services like real-time (RT), non-real-time (NRT), and control signaling. The gNodeB (gNB) allocates the bandwidth resources to the User Equipment (UE) to facilitate data transmission and reception in both downlink and uplink. The Resource Block (RB) is the smallest resource entity assigned to a single user. The time-domain resource allocation in 5G New Radio (5G NR) defines the allocated symbols (OFDM symbols) from different sub-carriers. In contrast, the frequency domain allocation illustrates the Resource Block (RB) (sub-carriers) allocation to the UE. An RB comprehends 12 sub-carriers in the frequency domain with a flexible RB bandwidth, unlike LTE-A. RB bandwidth depends on sub-carrier spacing. NR provides a higher bandwidth efficiency (up to 99%) than the LTE (90%) [13] and operates at a channel bandwidth of 100 MHz, in the sub-6 GHz bands, and 400 MHz, in the mmWave range, without any reserved Direct Current (DC, the sub-carrier whose frequency is equal to the RF center frequency of the transmitting station) sub-carrier for uplink and downlink. The UEs use a DC subcarrier to identify the OFDM frequency band's center and do not contain any information. The maximum and minimum RBs are defined by means of the 5G New Radio numerology. Hence, the channel bandwidth can be calculated by knowing the given bandwidth of the RB.

Finally, it is worthwhile to mention that the 3GPP specifications define two types of resource allocation in the frequency domain:

- Resource Allocation Type #0 (RAT#0);
- Resource Allocation Type #1 (RAT#1).

Network Slicing scenario deployed with slices created over the same infrastructure demands sharing the same network resources. The Slice Manager (SM) is responsible for allocating resources to individual slices while coordinating with the infrastructure providers. The Virtual Network Operator (VNO) services the slices, commonly known as the slice tenants. SLA is created between SMs and VNOs to regulate the required resources [14]. Authors in [15] have presented an efficient approach for statistical resource distribution among the network slices with strong SLAs. This approach provided a higher trade-off between the resource distribution and system complexity and thus, opened new research questions on the data and cost continuum. In [14], the authors addressed the slicing of RAN resources in multi-tenant scenarios. The resource allocation approach focused on the optimized fairness index, utility gains, and capacity savings. Following this, authors in [16] explored the Deep Reinforcement Learning (DRL) approach to allocate resources in dynamic multi-tenant systems. In [17], authors have proposed an adaptable and flexible 5G network architecture to support cross-domain E2E slicing with well-defined inter-slice control and management functions.

B. Standardization Activities on Network Slicing

Standards administrate the development of products and technologies to ensure requirements, interoperability, and quality [18]. Organizations like Global System for Mobile Communications Association (GSMA) and NGMN have gradually contributed to the high-level system requirements and architecture for Network Slicing. They also regulate the fundamentals for creating slices in an E2E 5G NS framework [19]. GSMA [20] highlighted the need for collaboration in the standardization process from the giants of different verticals, namely academia, industries, CSPs, etc.

3GPP is actively involved in multiple initiatives to support 5G network slicing like SA1 (requirements and use cases), SA2 (NS Architecture) [19], SA3 (Security), SA5 (Slice Management) [21], etc. Similarly, the Internet Engineering Task Force (IETF) contributes to the requirements and applications. The European Telecommunications Standards Institute (ETSI) is working towards NS services, configuration, delivery, assurance of deployment, etc. [9]. The 13th study group (SG13) of International Telecommunication Union - Telecommunication (ITU-T) focuses mainly on the orchestration, network management, and horizontal slicing [22]. Furthermore, the focus group FG-ML 5G defines Machine Learning developments and scopes to the requirements and services [23]. Authors from [6] have mentioned different relevant groups working on NS standardization activities.

C. Requirements for Future Networks

The use cases, service requirements, business models and application areas constantly evolve to meet the diverse demands. This sub-section lists some characteristic use cases and services for 5G and beyond networks [24].

- The underlying requirements are as follows:
  - Holographic Communication - Holographic Telepresence (HT) or communication is the next frontier to provide an immersive experience of distant communication with or without using the Head Mount Devices (HMDs) [25]. It focuses on amalgamating sensory information like touch, smell, and taste into the audio and visual transmission and reception. To facilitate HT, ultra-low latency of 1ms [26] and ultra-high data rate (Tbps) to support 30fps [27] are required, with high computing capabilities.
  - Industrial Automation - The upcoming generation of mobile communication foreseen an industrial revolution and dominance of automated services. The everything-to-everything connection will rule the networking paradigm with an enormous amount of devices. The services demand high QoS and Quality of Experience (QoE). The requirements to support Industry 4.0 and future 5.0 will be Ultra-low latency of 0.1 ms, ultra-high reliability, and ultra-low delay jitter [26], [28].

Figure 2 illustrates the classes of use cases for upcoming communication networks [29].

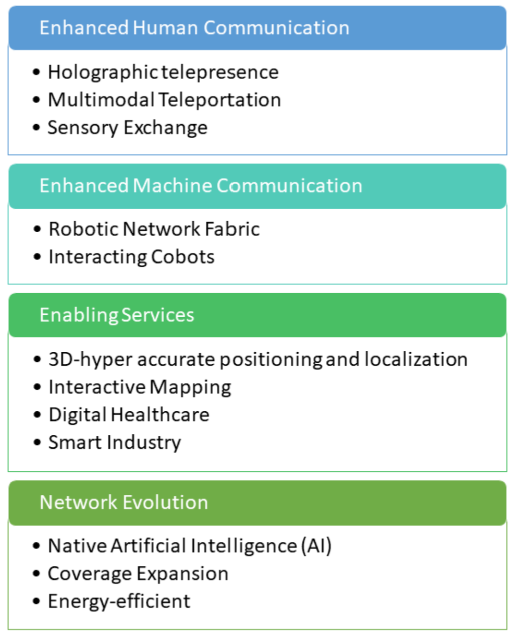

Fig. 2. High-level Use Cases Categorization [29]

III. Methodology and Results

Network slicing enabled the Infrastructure/Slice Providers (SP) to offer resources to the customers as a service for a given cost to maximize the resource usage by accepting slice requests. The customer requests a network slice from SP to get customized services. There is a need for a mechanism/ scheduling scheme in which SPs can entertain the requests, as the SPs are subject to limited resources. Authors from [15] and [30] introduced a two-level scheduler to share the Physical Radio Blocks (pRBs) among slices by abstracting pRBs and using two scheduler levels. Two-level schedulers operation is as follows:

- The first level is slice-specific, allowing each slice to use its internal scheduler and schedule each UE with Virtual Resource Blocks (vRB).
- The second level considers the slice-specific (virtual) resource assignment and maps it to actual pRBs. It controls the number of number of pRBs (NpRBs) assigned to each slice and indicates the maximum NpRB to dedicate to each slice after executing an intra-slice physical resource sharing algorithm.

The aim is to compute the radio resources required in each slice. The resources are periodically adjusted based on the current Channel Quality Indicator (CQI) estimates from the users of the different slices. Assumptions are as follows:

- 5G network which including a SO, to initiate and configure slice resources based on the use case types (eMBB, mMTC or URLLC) and a set of gNBs deployed covering an area.

- The SO communicates with the gNBs using a protocol that allows remote interaction and management.
- The gNB management process consists of
  - RAN information (CQI);
  - gNB configuration.
- A set of UEs is served by/associated with a network slice, spanning a set of gNBs (i.e., different physical locations).
- There are three types of Slices: eMBB and URLLC Slices
- The SO receives the request to instantiate a slice. The Slice request includes
  - Slice type;
  - Duration;
  - Requirements like data rate, application, or latency;
  - List of associated UEs.

We simulated on MATLAB the two-level scheduler for eMBB and URLLC slices for a varying number of users in each slice, keeping the other constant to observe CQI variations. The goal is to improve network performance and introduce flexibility and optimization of the network resources by accurately and dynamically provisioning the activated network slices with the appropriate resources to meet their diverse requirements. The aim is to have a flexibility in RAN resource allocation concerning slicing.

A. Slice Definition and Requirements

For each created slice instance, i

- eMBB Slice Requirements - High Data Rate

$$N_{pRB_{max}}(i) * d_{pRB} = N_{users}(i) * d_{App/user}$$

- URLLC Slice Requirements: Ultra-Low Latency

$$\mu = \frac{N_{pRB} * d_{pRB}}{\text{Average packet size}}$$

where,
$N_{pRB_{max}}(i)$: Required pRBs for each gNB;
$d_{App/user}$: Required Data rate per slice;
N_{users} : the number of active users;
d_{pRB} : maximum data rate provided by one pRB;
pRB : Physical Radio Blocks.
Ideal channel conditions correspond to the maximum CQI = 15.

B. Simulation Results and Discussion

The performance has been evaluated in Matlab as an extension to the referenced work in [15]. We modified the SO and considered eMBB and URLLC slice. We defined each slice with the required data rate, number of users and latency in URLLC slice. The simulations were carried out at varying CQI level, i.e. medium (7) to high (13). The eMBB slice users were fixed to 5 and varied users (up to 20 for medium CQI and up to 30 for high CQI values) in URLLC slice. In the view charts, lat stands for latency.
Figures 3 and 4 present the throughput for the URLLC slice at varying CQI values. Beyond the threshold, slice performance degrades (more in case of high CQI) but it guarantees the required bandwidth until 25 users.

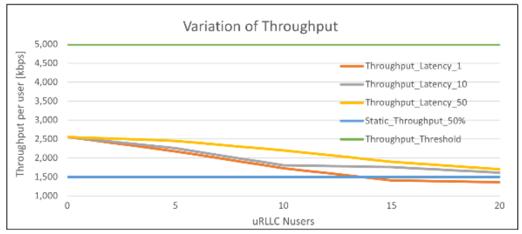

Fig. 3. Variation of throughput per user as a function of the number of users (with Medium CQI value).

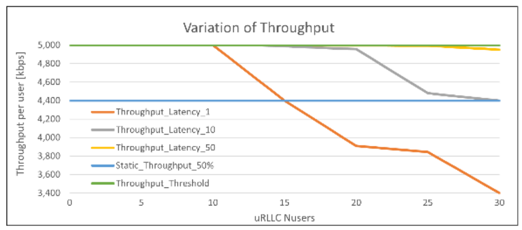

Fig. 4. Variation of throughput per user as a function of the number of users (with High CQI value).

Figures 5 and 6 show the experienced latency as a function of the number of uRLLC users for varying CQI values from 7 to 13. We considered different maximum values for latency, i.e., 1 ms, 10 ms and 50 ms. We observed that the max. latency value was near about maintained for both the value of CQI. High CQI allows higher NpRB compared with the medium CQI by allowing more users. We also observed that fixed number of pRBs cannot guarantee the very low latency requirement.

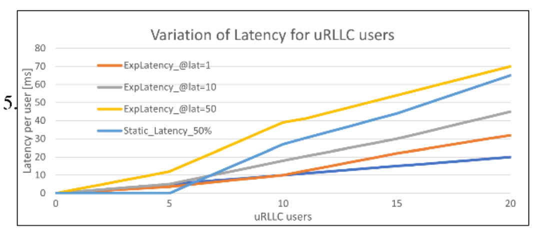

Fig. 5. Variation of latency as a function of the number of users (with Medium CQI value).

The results in Figures 7 and 8 show the estimated NpRB and used by the gNBs for the URLLC slices with varied CQI values. We observed that the estimated NpRB is similar to the one communicated to the gNB until reaching the identified thresholds as shown in Figures 4 and 5. The communicated

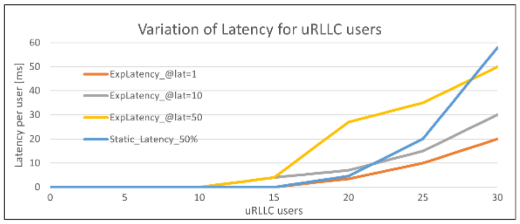

Fig. 6. Variation of latency as a function of the number of users (with High CQI value).

NpRB to gNB is lower than the estimated value on increasing the threshold values.

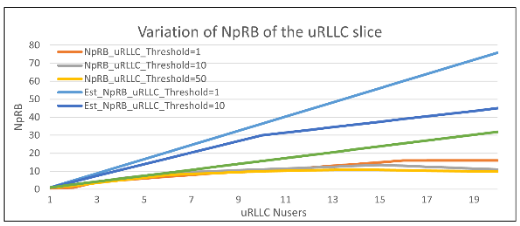

Fig. 7. Variation of NpRB of the URLLC slice as a function of the number of users.

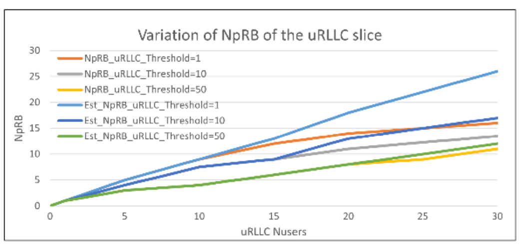

Fig. 8. Variation of NpRB of the URLLC slice as a function of the number of users.

The results in Figures 9 and 10 show the estimated NpRB per user within the gNBs for eMBB slices with varied CQI values. We observed that the estimated NpRB could not be satisfied in case of medium channel quality and required NpRB is higher. Lower dpRB is expected at higher CQI values.

The results show that our proposed algorithm to estimate the required NpRB for eMBB and URLLC slices is accurate and permits sharing of the RAN resources among slices. Hence, the practical feasibility of our proposed solution is verified. We observed that when there is saturation, a reduction of the throughput and NpRBs per user, corresponding to an inflection in the curves for the total NpRBS.

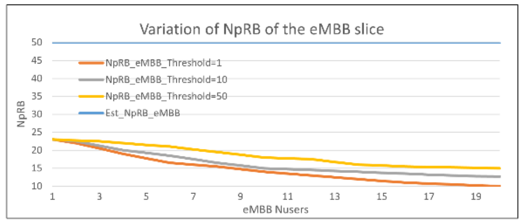

Fig. 9. NpRB per user of the eMBB slice as a function of the number of users.

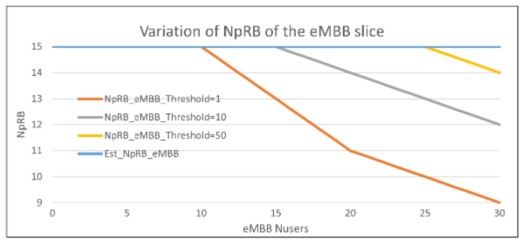

Fig. 10. NpRB per user of the eMBB slice as a function of the number of users.

IV. Conclusions and Future Work

This paper proposes slice creation and allocation of resource blocks while isolating the slices for eMBB and URLLC by using the two-level scheduling introduced in the referenced work. We have introduced algorithms to estimate the required RAN resources for the eMBB and URLLC slices while evaluating the performance under varying CQI values at the SO level. Heterogeneous Networks (HetNets) optimization is an open research area concerning Network Slicing. Also, 3GPP's functional splits [20] have huge potentials to be implemented with slicing to manage the network function virtualization and softwarization of RAN resources. Besides, there is a need to develop novel meta-learning models for ML-enabled network slicing, an open research area.

The main foreseen challenge in 5G New Radio dynamic resource allocation is the associated overhead when we extract the information from the base station (UE provides CQI to the base stations) to the SO. Thus, to eliminate/ minimize the communication overhead, we will simultaneously propose the following steps:

- A machine learning approach to infer the stability of UE channel conditions;
- Propose a predictive scheme to efficiently reduce the dependency on the network's configuration to address the various service and demands;
- Admission Control Policy/ Decision based on Q-Learning and Regret Matching for the SP to manage the slice requests (we will then validate the mechanism concerning the SP serving the network requests).

Further, we obtained the results to illustrate our proposed algorithm for estimating the number of physical resource blocks by the eMBB and URLLC slices. We successfully demonstrated the slice creation and resource allocation. Our future work will involve the enhancement of the algorithm employing deep reinforcement learning and intelligence into resource sharing mechanisms.

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A Study on Cross-Carrier Scheduler for Carrier Aggregation in Beyond 5G Networks

3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

A Study on Cross-Carrier Scheduler for Carrier Aggregation in Beyond 5G Networks

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Abstract

This work aims to provide a detailed study on Carrier Aggregation (CA) techniques for 5G New Radio (5G NR) networks while elaborating on CA deployment scenarios, CA-enabled 5G networks, and resource management and scheduling techniques. CA empowers the User Equipment (UE) and the network to aggregate carrier frequencies in licensed, unlicensed, or Shared Access (SA) bands of the same or different spectrum bands to boost the achieved data rates. We also analyze the cross-carrier scheduling scheme in CA-enabled 5G networks for Downlink (DL) resource allocation. The requirements, challenges, and opportunities are addressed in the allocation of Resource Blocks (RBs) and Component Carriers (CCs). The study and analysis of various multi-band scheduling techniques are made while keeping in mind that high throughput and reduced power usage needs to be achieved at the UE. Finally, we present CA as the critical enabler to advanced systems while discussing how it meets the demands and holds the potential to support beyond 5G networks. To conclude, we discuss many open issues in resource allocation and scheduling techniques.

1. Introduction

Coverage and capacity for the 5G user experience are the essential elements. Carrier Aggregation (CA) emerged as one of the key technologies for 5G that can extend the coverage by considering the mid, low, and high bands leading to increased capacity. CA and the coordination of Radio Access Network (RAN) are possible solutions for low latency, high capacity, and optimized coverage for 5G mid-band and high-band deployment. To overcome the demands of wireless data and applications, the service providers need to research the new spectrum source that can be using the existing spectrum efficiently. 5G enables a new spectrum source, both the mid-band and high-band radio frequencies, to enable the latest applications and provide better data speeds. Getting more benefits from these new spectrum bands, solutions are needed to extend cell coverage. CA is one of the solutions that use the spectrum efficiently. Third Generation Partnership Project (3GPP) Release 15 [1] introduced 5G New Radio (NR) in 2018 as the global standard for the air interface and explained CA in licensed and unlicensed bands and consider aggregation in shared spectrum scenarios as well. A solution that allows expanding the spectrum assets when deploying 5G is Inter-band NR CA. This type of CA can extend the cell coverage area of mid-band Time Division Duplex (TDD) by a factor of 2.5 [2]. On the other hand, carrier aggregation with NR in the highest frequency bands (i.e., millimeter wavebands) allows coverage area extension by a factor of four.

In Release 16, the number of rate-matching patterns available in NR has been increased to allow spectrum sharing when CA is used for LTE. Besides, Release 16 reduces latency for setup and activation of CA/Dual Connectivity (DC), by this means leading to improved system capacity and the aptitude to achieve higher data rates. Unlike Release 15, where measurement configuration and reporting does not take place until the UE comes into the fully connected state, in Release 16 the connection can be resumed after periods of inactivity without the need for extensive signaling for configuration and reporting [3]. Additionally, Release 16 introduces a periodic triggering of Channel State Information (CSI) reference signal transmissions in case of the aggregation of carriers with different numerology. In the Release 17 Enhanced Mobile Broadband (eMBB) trend, NR frequency range will be extended to allow for exploiting more spectrum (above 52.6 GHz), including the 60 GHz unlicensed band while defining new Orthogonal Frequency Division Multiplexing (OFDM) numerology and channel access mechanism to comply with regulatory requirements applicable to unlicensed spectrum.

The rest of the paper is structured as follows. Section II addresses the CA-enabled 5G networks. Section III describes various resource management and scheduling techniques. In Section IV, we discuss the research challenges. In section V, the role of standards and relevant standardization bodies is discussed. Finally, conclusions are drawn in Section VI.

2. Carrier Aggregation Enabled 5G Networks

3GPP has parted the band into three parts for 5G services [2]. The frequency band of less than 1 GHz is considered a low-band, while the 2.4 GHz - 40 GHz is a high band and 1GHz - 2.6 GHz and then 3.5 GHz- 6 GHz is considered a mid-band.

With the combination of these bands, the deployment of 5G and beyond will support a high data rate and less resource utilization. The range of a single low band (below 7 GHz

Frequency Division Duplex, FDD) can cover hundreds of square miles considering 5G services whose speed range is from 30 to 250 megabits per second (Mbps) These are the most common services to deploy, providing a wide area coverage. The mid-band (below 7 GHz, Time Division Duplex, TDD) can provide up to a several-mile radius with currently goodput ranging from 100 to 900 Mbps. While the high band (above 2.4 GHz) is just covering the shortest cell radius with a goodput range from 1 up to 3 Gbps. By deploying 5G networks in these combinations of frequency bands/ranges and speeds the networks not only support a high data rate but also provides the best solution for 5G spectrum requirements.

Carrier Aggregation with Millimetre Wavebands

Millimetre Wave (mmWave) is one of the promising technologies to address the shortage of spectrum in a wireless network. It became the redeemer of 4G/5G mobile operators. It will be suitable for its coexistence with the LTE network [4]. CA and mmWave band scenarios are extensively researched in [5][6]. These papers consider the channel state information and low computational complexity to improve carrier aggregation technique and reduce energy consumption in 5G scenarios. The aggregation of the mmWave and sub-6 GHz frequencies is the need of the network. It can deliver the massive capacity and multi-Gigabit speeds desired for consumers and enterprise applications. Combining the different combinations of spectrum resources will make it possible for 5G devices to achieve wired broadband-class speeds wirelessly.

5G Networks in Unlicensed Spectrum

5G's essential design model intends to support diversified spectrum bands. 3GPP introduced unlicensed spectrum bands for 5G NR as Unlicensed 5G NR (5G NR-U) to enhance the LTE's Licensed Assisted Access (LAA) with the release 16 [1]. It also marked 5G NR-U deployments in the license-exempted 5 GHz and 6 GHz bands. The supported deployment modes for 5G NR-U are (i) Carrier Aggregation, (ii) Dual Connectivity (DC), and (iii) Standalone. In both CA and DC deployment modes, the unlicensed bands support the amplification of the user-plane capacity in DL. In dual connectivity mode, NR-U supports Uplink (UL) in addition to the DL. CA deployment mode is built on LTE-LAA, where the DC deployment mode is based on the extended LAA (eLAA) []. In either deployment mode, the control-plane data resides over the licensed bands. The standalone mode relies independently on the unlicensed spectrum for control and user plane operations. It will lead to an open 5G network to eliminate dependencies on the licensed mobile network operators (MNOs). With its underlying enhancements, NR-U is foreseen to bring new opportunities to enhance spectral efficiency.

Carrier Aggregation in Heterogeneous Networks

CA and Heterogeneous networks (HetNets) are two distinct features of the beyond 5G cellular networks [7]. The Small Cell (SC) deployment in HetNets is advantageous for data offloading, coverage, and improved cell edge spectral efficiency. CA facilitates increased transmission bandwidth and capacity by scheduling the multiple Component Carriers (CC) on the physical layer [8]. The general realization of CA is facilitated by the addition and removal of a secondary CC without interrupting resource allocation. The resources are made available to the users from SCs within the macrocell topology. Fronthaul network connects the Remote Radio Heads (RRHs) to the Baseband Unit (BBU) same as the Macro and Small Cell. Figure 1 illustrates the conventional CA deployment in the same macrocell site.

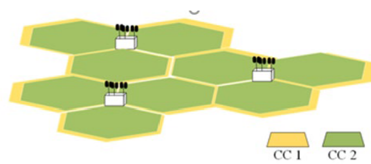

Figure 1. Carrier Aggregation Deployment in the same Macrocell.

Enormous traffic and connection requests are eminent in dense heterogeneous networks with SCs, making the establishment of multimedia sessions critical. CA offers a great solution in such scenarios by facilitating SC deployments inside macrocells. The evolved NodeB (eNBs) offload the high traffic on the small cells with CA. Figure 2 illustrates the CA deployment between macro and small cells.

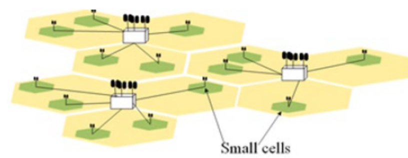

Figure 2. Carrier Aggregation Deployment between Macrocell and Small Cell.

Next Generation NodeB (gNBs) deployments by the Mobile Network Operators (MNOs) ensure better services by increasing the system capacity. Small cells enable flexible deployments while ensuring affordability in price and enhanced energy and spectral efficiency. SC technologies integrate multiple radio access (CA) technologies to increase the coverage capacity and service availability. CA-enabled SC deployments exploit lesser physical space as compared to the macro cell deployments [9]. The deployment of small cells with carrier aggregation within the macro cell becomes a viable and economical solution to improve the performance of the entire 5G NR network.

Cell Dormancy

3GPP Release 16 introduced the concept of small cell dormancy, which improves the power consumption in CA-enabled scenarios. The considered dormant cell device stops the monitoring of the physical downlink control channel while keeping the channel state information measurements and beam management [10]. This method did not consider the dormant cell deactivated, but comparatively, fewer activities save power. For power saving, deactivation is also another possibility. With deactivation, it does not provide the channel state information reports. Also, reactivation of the small cell takes longer time than returning from dormancy [7].

3. Resource Management and Scheduling Techniques

Cross-Carrier Scheduling

In CA-enabled scenarios, the UE is served by more than one CCs either from the same or different macro/small cells. The resources are scheduled based on the Scheduling Grants (SG) and the Scheduling Assignments (SA) corresponding to the data. The scheduler decides for each carrier and transmits individual SAs. Thus, a device receives multiple Physical Downlink Control Channels (PDCCHs). Scheduling is called "Self-Scheduling" when the SG and SA are transmitted on the same cell as the data, and it is known as Cross-Carrier Scheduling (CCS) when SG and SA are transmitted on different cells than the data. For CCS, the Downlink Control Information (DCI) accommodating the SG for a carrier is received on a different carrier [11]. CCS was initially introduced in 3GPP Release 10 with a carrier indicator field (CIF) limited to 3 bits to support aggregation up to 5 CCs. When a UE is in search mode, the CIF value affects the DL control channel and defines the carrier for SG. In the primary cell (PC) configuration, CIF-Presence-r10 indicates the availability of CIF in PDCCH DCI. A CIF value of 0 indicates PC, while another indicates the secondary cells (SCs). To support 32 CCs enhancements for CA with the latest 3GPP releases, the CIF length increased from 3 to 5 bits.

Packet Scheduling Schemes

Packet Scheduling Algorithms (PCA) hold utmost importance in Radio Resource Management as they indicate how transmission occurs. An efficient PCA in a CA environment has the following requirements [12] for (i) tolerant to multi-CCs environment, (ii) high QoS, (iii) high system throughput, (iv) optimized fairness and (v) low complexity.

In [13], authors have proposed an improved proportional fair (PF) scheduling algorithm for a multi-carrier system. A novel carrier weight factor (CWF) is used to limit the usage accessibility of the CCs. CWF defines the carrier coverage weight factor and the user category weight factor. In [14], authors have addressed the resource scheduling with CA and demonstrated enhanced spectral efficiency and reduced energy consumption. They used a discontinuous reception mechanism from LTE-LAA, allowing UEs to go into sleep when inactive and addressed CCs scheduling mechanisms to reduce the wake-up time. In [15], authors have proposed multi-band scheduling strategies to optimize RBs distribution in the multiple CCs environment with strict QoS constraints. The implementation is demonstrated using the LTE-SIM framework and proposed migration to the 5G framework.

Scheduler Structure for CA

To allocate resource blocks (RBs) in CA, the eNB requests UE for the carrier specifications, including QoS. eNB takes calls for carrier activators and PC assignments for the UE and indicates through the PDCCH signals for fixed time slots. Delay is observed in the case of larger time slots. Thus, the scheduler response time is critical in CA systems to manage delay and throughput trade-offs with the UE [16].

In [16, 17], the authors have explained two scheduler structures, Disjoint Queue Scheduler (DQS) and Joint Queue Scheduler (JQS), to optimize the time slot to enhance the QoS at the UE. DQS allows users to have independent traffic queues on each CCs, whereas JQS allows the users have a shared/joint queue to access the CCs, resulting in a single-layer scheduling platform.

Intelligent Spectrum Management

Different Spectrum Sharing and Management techniques allow cooperative and simultaneous use of the under-utilized radio and statically assigned frequency spectrum [18] by several independent entities in a particular geographical area. Licensed Shared Access (LSA) can effectively exploit the white spaces. Also, application Machine Learning (ML) and Artificial Intelligence (AI) at various levels of the network can provide scalable and flexible solutions to manage complex generations of communication. AI can administer MNOs in determining demand and re-configuring the network. In CA-enabled networks application of ML algorithms can determine the CCs to select based on the available spectrums [18, 19].

4. Open Research Issues

Efficient and intelligent future usage of frequency spectrum will need to be addressed for beyond 5G. The mobile communication sector is requesting more and more spectrum to accommodate higher traffic volumes and more demanding quality of service requirements. Traditionally, greater throughput was mainly obtained by increasing the available spectrum bandwidth and deploying more infrastructure. Providing greater throughput without wasting precious spectrum requires more and more complex radio spectrum management. AI-based spectrum management solutions have not yet been fully exploited since [19]. Future mobile and wireless networks will comprise heterogeneous, small cells overlaid with macro and microcells. Flying UAVs acting as relays are also of great interest in these beyond 5G ecosystems, as well as studies on the resulting cost/revenue trade-off and business plans. Different solutions based on intelligent interference management (or avoidance), evolved multi-band scheduling (on top of packet scheduling to manage radio resources), big data and machine learning strategies. Both sub-6 GHz bands and future mmWaves needed to be investigated [20].

5. Conclusions

In this paper, we have presented CA techniques and enhancements concerning the latest 3GPP releases on enhancements. Different scheduling techniques have been discussed. CA enabled 5G networks have been discussed in detail with various opportunities in licensed, unlicensed spectrum bands, mmWave bands, and HetNets. The structure for the schedulers has been discussed in detail as well. Finally, we have presented an overview of the CA scheduling techniques and introduced the scope of AI/ML in-network sensing and management aspects.

6. Acknowledgements

This work was supported by FCT/MCTES through national funds and cofounded EU funds under the project UIDB/50008/2020, ORCIP (22141-01/SAICT/2016) and TeamUp5G (MSCA-ETN grant agreement No. 813391).

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Business Opportunities for Beyond 5G and 6G Networks

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***Abstract*—In this work, we intend to present various aspects of the business model associated with technology. We presented a detailed description of beyond 5G and 6G networks with the potential use cases and applications. We mapped the use cases to different potential business opportunities. We also described why Network slicing is an essential enabler for future networks and its importance for creating new businesses. We stressed the multi-business model approach to defining the business model concerning Network slicing and other applications. Thus, this paper will address the business value creation through technology for the beyond 5G and 6G networks.**

***Index Terms*—Beyond 5G, 6G, Network Slicing, 6G Use Cases, Holographic Communication, Business Models, Multi-Business Model.**

I. Introduction

With the deployment of the Fifth-Generation (5G) mobile networks, we are witnessing the advancing research and development towards the Sixth Generation (6G) networks. Academia and industry joined hands to support the timely development and deployment. 5G networks offered massive connectivity, higher bandwidth, minimal latency, and several services and applications as an advantage over its predecessor. The expectations from 6G networks are even higher; for instance, sensory experience, interactive communications through holograms, and the internet of the networks [1]. It assures an energy-efficient, reliable, robust, and secure platform that will open up opportunities for new businesses. 6G networks have the potential and capability to support diverse verticals with varied requirements. These varying requirements need optimized and blended techniques and algorithms with built-in intelligence to enable different parallel applications.

The core requirement from 6G networks includes spectrum/resource management techniques, broader bandwidth, and a new radio spectrum to achieve higher data rates and lower latency. The estimated data rates and latency can be around the scale of Terabit/second and 0.1 milliseconds, respectively. The Third Generation Partnership Project (3GPP) introduced 5G Service Based Architecture (SBA) [2] to support the coexistence of heterogeneous network requirements in its technical specification 23.501 [3]. SBA incorporates a scalable, flexible, cost-efficient, and programmable platform to accommodate simultaneous services. SBA enables Network Functions (NF) and facilitates Network Function Virtualization (NFV) to provide services to other authorized NFs, through APIs, cloud technologies, and a client-server model. NFV, Software Defined Network (SDN), and cloud computing technologies allow the creation of ”Network Slices” over a shared physical network infrastructure. The technology to create logically isolated slices is called Network Slicing (NS) [4] and facilitates end-to-end connectivity [5]. The Communication Service Providers (CSPs) can cater to diverse user-specific demands through slicing with guaranteed Quality-of-Service (QoS). The main advantage of deploying NS is that no new physical network is required for dedicated services. CSPs take advantage of the network orchestration and virtualization to provide real-time services based on the Service Level Agreements (SLAs) [6].

The development of 6G technology needs a holistic and multidimensional approach to integrate technologies and support businesses to flourish. 6G defines an integrated network with built-in control systems that execute technologies for societal, environmental, and economic benefit. 6G systems are advocating more towards a sustainable solution. The Mobile Network Operators (MNOs) intend to create new businesses and business models for the advancing technologies. A 5G and beyond network will have a user-centric approach toward business models and aim to solve the issues of the customers [7]. Changes in the Telecom landscape are evident and reflected through the value and supply chain revolution. The deployment of 5G is eminent among the public networks and is being embraced in diversified industrial and consumer use cases. 6G development will drive the supply chain transformation to allow new verticals to establish. It is essential to focus on the business value creation in addition to the customers’ needs and challenges. 6G will redefine the creation, delivery, and consumption of the network resources and services, irrespective of the verticals and applications [8]. Thus, this paper will address the business value creation through technology for the beyond 5G and 6G networks.

The remaining paper is organized as follows. Section II will highlight beyond 5G and 6G technologies and use cases from business creation perspective. Section III will explain further the mapping of beyond 5G and 6G use cases to businesses. Section IV will introduce the business modelling concept. Finally, Section V presents the conclusions and open research

This work was supported by EU funds under the project TeamUp5G. TeamUp5G has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

areas.

II. Beyond 5G and 6G Networks

As cited by Juniper's research article [9], the 5G voice users will surpass the 2.5 billion mark by 2026. 5G New Radio (5G NR) architecture supports simultaneous use cases in heterogeneous scenarios [10]. The essential building blocks for 5G networks are defined by the following three categories of use case classes: (i) enhanced Mobile Broadband (eMBB), (ii) Ultra-Reliable Low-Latency Communications (URLLC), and (iii) massive Machine-Type Communications (mMTC). In a nutshell, (i) eMBB services demand very high peak data rates, (ii) mMTC supports massive connective devices/nodes, and (iii) URLLC supports ultra-low latency requirements and high reliability. These characteristic features will also form the basis for 6G research and development.

A. Network Slicing as 6G Enabler

6G systems will evolve on the 5G SBA architecture [2] [3] to meet the core requirements, including spectrum/resource management techniques, broader bandwidth, and a new radio spectrum to achieve higher data rates and lower latency. SBA enables Network Slicing to facilitate end-to-end connectivity and user-specific services [5]. The CSPs and MNOs exhibit guaranteed QoS in catering to user demands for specific services. Beyond 5G and 6G networks intend to have a user-centric approach toward business models and aim to solve the issues of the customers [7] as well as the operators. These networks aim for the flexible, agile, and scalable core in addition to the leverage of implementing new services on-demand by the CSPs and MNOs. Figure 1 illustrates the operators' requirements for the upcoming generation of wireless communication [11].

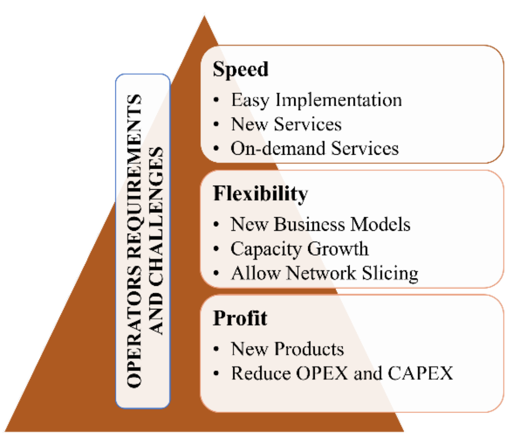

Fig. 1. Requirements Mapping from Operators Perspective for 6G Networks [11]

Virtualization techniques and cloud technologies enabled the network to have independent network functions [12]. The vendors must have the usage flexibility in computation, storage, and accessibility to private/public clouds to reduce both CAPEX and OPEX. Network Slicing (NS) is seen as the solution from both an architecture and business perspective [13]. 3GPP introduced the slicing framework in Release 15 [14], which gradually matured in the following releases. It supports multiple virtual network instances operating on the same physical hardware and provides varying individual services to slices [4]. It allows MNOs to partition the networks to cater to specific service requests. SDN, NFV, orchestration, and service provisioning together enable NS architecture. The SDN facilitates the control and user plane separation, where the physical resources are virtualized, implementing NFV. The organizations like Global System for Mobile Communications Association (GSMA) [15] and Next-Generation Mobile Network (NGMN) [4] are constantly involved in defining standards for slicing framework and architecture. 3GPP has various study groups that monitor and regulate NS standardization activities on specific areas like requirements, use cases, NS Architecture, slice creation and security [16] [17]. GSMA and NGMN are also involved in defining the business drivers and requirements together with the MNOs and CSPs [18].

B. Application Areas and Use Cases

Future networks will have more versatile and diversified demands in addition to the constantly evolving use cases based on the service requirements and new businesses [19]. On the societal side, 6G applications are foreseen to address collaboration, digital equity, and social sustainability challenges. 6G network design aims to reduce CO2 emissions and improve energy efficiency [20], [21].

Authors in [21] have defined the following classes as illustrated in Figure 2 for the 6G use cases. The Next G Alliance report [20] on "6G Applications and Use Cases" has provided different categories for the 6G applications and use cases.

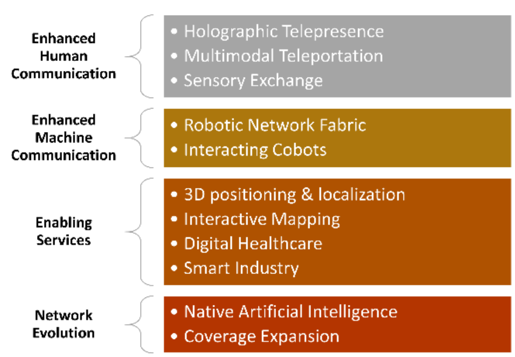

Fig. 2. High-level Use Cases Categorization [21]

Figure 3 illustrates the categories of 6G application while the four sub-classes for the use cases are: (i) Network-Enabled Robotics and Autonomous Systems, (ii) Multi-sensory Extended Reality, (ii) Distributed Sensing and Communications, and (iv) Personalized User Experiences.

Everyday Living	Applications to improve daily quality of living.
Experience	Applications dedicated to enhancing user experience and enabling immersive communication.
Critical Roles	The 6G applications that aid critical functions in healthcare, manufacturing, agriculture, and public safety are categorized under this vertical.
Societal Goals	This category includes 6G applications that cater to overall societal, environmental, and economic issues. These also align with 17 UN Sustainable goals.

Fig. 3. High-level Categorization of 6G Applications [21]

C. Technical Requirements for the Use Cases [20], [22]

This section briefly covers the system requirements for the 6G use cases. 6G networks are expected to support existing 5G services, applications and tools as well. Some of the basic requirements [20] that 6G networks should allow for facilitating coexistence must include the support for voice calls, messaging, 5G handoffs, and security and privacy by design. The ITU-T [23] also has published system requirements for Network 2030. The Key Parameter Indicators (KPI) for 6G is illustrated in Figure 4 as comparison with the 5G networks [22].

KPI	5G	6G
Operating Bandwidth	400 MHz (sub-6 GHz bands) 3.25GHz (mmWave bands)	400 MHz (sub-6 GHz bands) 3.25GHz (mmWave bands) 10-100 GHz [Indicative] (THz bands)
Carrier Bandwidth	400 MHz	To be defined
Peak Data Rate	20 Gbps	≥1 Tbps
User Experience Rate	100 Mbps	1 Gbps
Average Spectral Efficiency	7.8 bps/Hz (DL) 5.4 bps/Hz (UL)	1 x that of 5G
Connection Density	10^6 devices/km^2	10^7 devices/km^2
User Plane Latency	4 ms (eMBB) 1 ms (uRLLC)	25 µs to 1 ms
Control Plane Latency	20 ms	20 ms
Mobility	500 km/h	1000 km/h
Mobility Interruption Time	0 ms (uRLLC)	0 ms

Fig. 4. KPIs Mapping of 6G Networks

- Holographic Type Communication (HTC) is foreseen as one of the key evolutions to enable the immersive three-dimensional experience. HTC blends the audio/visual transmission with multi-sensory data, including touch, smell, and taste [24]. High computational capabilities, compression techniques, ultra-high data rates, and ultra-low latency are the essential requirements for interactive holographic communications [25], [26] [27]. A human-sized hologram demands a data rate of around 4.3 Tb/s and a submillisecond latency. Synchronization and security will be critical in the real-time integration of various scenarios and sensor feeds.
- Industrial Automation: 6G will witness a revolution in manufacturing industries fostered by human-machine in Cyber-Physical Systems (CPSs) [28]. These massively connected machine interactions, robotics, and remote management-control of industrial systems are essentials of Industry 4.0. Ultra-low latency of 0.1 ms and ultra-high reliability [29] guarantees real-time monitoring and control to enable high Quality of Service (QoS) and Quality of Experience (QoE). VR or HTC integration into Industry 4.0 will enable remote monitor/control services. Based on the application requirement, data rate varies from 1–5 Mb/s (1080p high-definition video), 15–25 Mb/s (4K 360 degree video) to a whopping 0.5–2 Gb/s (small holograms) up to 4.2 Tb/s for human-sized holograms [22]. Latency in order of 1ms to submillisecond, high-end synchronization, and security to avoid hazards and life threats.
- Service Robots for Healthcare: With the recent advancements, robotic applications will play a key role in various aspects of human lives. After demonstrating their significance in manufacturing and industrial automation, robots are all set to enhance our everyday life. 6G will see the rise of Service Robots [20] with ambient intelligence to enhance everyday activities (caregiving, travel assistance, ambient assisted living), healthcare pursuits (surgery robots), and critical roles (search and rescue operations, firefighter training). Field robots will be helpful in monitoring and maintaining hard-to-access locations. A very high level of clock synchronization, ultra-low latency, high reliability, accuracy in positioning and localization, self-healing techniques, and shorter re-establish time in connection failures are critical requirements for the service robots.
- Multi-Sensory Extended Reality (XR) Interactive Sports (Drone Racing): Drone racing is an example to catalog the potential of the 6G network in a highly interactive scenario. the first drone racing was exhibited in the World Drone Prix, Dubai (2016) [30] using the 5G network. With 6G, in a 360 degree spherical display, it is expected to have more than 2x16K resolution images with a latency of less than 20 ms. The image resolution and latency are critical parameters of drone racing. A transmission data rate varies from a minimum of 60 Mbps (8K screen), 2 Gbps (16K screen), and 4 Gbps to stream 2x16K with 6 Degree of Freedom (DoF [20]. Throughput, latency, and mobility are essentials for this use case.

III. Mapping of Beyond 5G and 6G Essentials to Business Opportunities [1], [20] [26]

The recent advancements have resulted in the multidimensional integration of industrial verticals. There are enormous opportunities for businesses to grow and integrate cutting-edge technologies. Integrating technology in business to provide solutions intends to bring added value to customers and industries. This section will map various use cases and applications to potential business opportunities beyond 5G and 6G networks.

*a) **Networked-enabled Robotics:*** Networked robotics is critically important for Industry 4.0 and beyond, providing an additional layer of benefits for enterprises and related industry. It also is necessary for some critical factors that our daily living environments have already begun to face. The following is a list of societal implications of networked robotics.

1) **Manufacturing and Logistic Industry** Industrial robots have massive potential in production and operation management industries.
2) **Human Resource Management** Robots are proving their efficiency in performing scheduled tasks like mobile inspection and maintenance at remote locations.
3) **Retirement Homes** Robots can be deployed to provide care to older adults. It can also be used to monitor basic health parameters. Interactive robots are even used to provide ambient assisted living.

*b) **Multi-sensory XR:*** Interactive XR capabilities converging AR/VR technologies have huge potential in services that provide immersive real-time experiences.

1) **Interactive Unmanned Aerial Vehicles (UAVs)** Self-connected and configurable drones are helpful in verticals like agriculture and transportation.
2) **Immersive Communication** has huge potential in realizing new standards for long-distance and remote interactions through XR conferencing and holographic communication.
3) **Mixed Reality Collaborations** has found new definitions to provide co-creation platforms in education, training, music concerts, etc.

*c) **Distributed Sensing:*** These use cases enable autonomous systems with sensors coupled with communications.

1) **Remote Data Collection** IoT industries are utilized in health care, smart homes, education, and logistic tracking systems for data collection for various applications.
2) **Healthcare-Wearables and Implants** There is an exponential rise in the number of wearables to monitor daily activities like heart rate, sleep, steps, and stress levels.

IV. Introduction to Business Models

A Business Model (BM) represents a business in an abstract form to depict a company's plan to maximize its profit [31]. It entails an organization's blueprint to create, deliver, and capture value, considering various factors. As cited by Ericsson [32] beyond 5G, and 6G networks enable various new business opportunities in the telecom sector sectors in the top 60%. Figure 5 [32] illustrates different industries with business opportunities. BM represents a high-level business plan based on the target market. A value proposition, an essential entity of a BM, describes the offered services/products considering customers' requirements and overall impact. It refers to the promises made by the company toward customers.

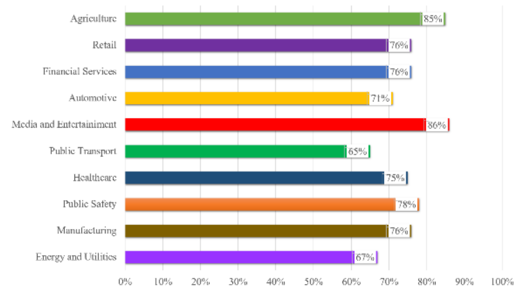

Fig. 5. Business Opportunities in different Industries

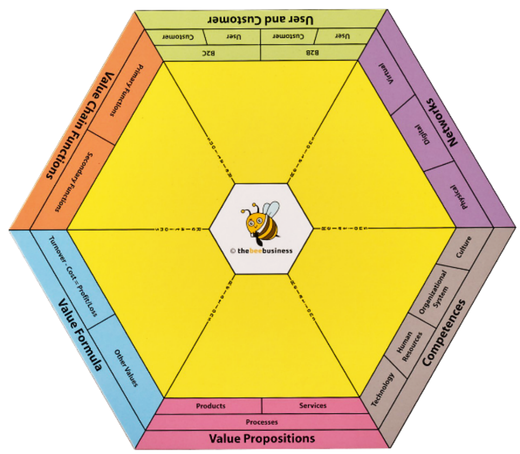

Fig. 6. Multi Business Model Innovation Illustration

This section describes the Multi Business Model Innovation approach [33] to map business opportunities associated with 6G networks and network slicing. Figure 6 illustrates various verticals of a business model from customer-end to the provider-end. This model helpful in creating and capturing essentials of the "AS IS" BM and maps the requirements of "TO BE" BMs. It explains a general model to run a business with profit. Its different arms as mentioned below and in Figure 6 shows perspective to create BM from different angles.

1) **Value Propositions** includes the promises made by the MNOs and CSPs toward customers. It involves the processes and different product and services offered to the customer. For instance; ultra-high bandwidth support to enable real-time multiplayer gaming experience.
2) **Value Formula** covers the company's expenses and give profit or loss numbers. It also includes installation and maintenance costs.
3) **Value Chain Functions** describes all the tasks involved to create a product or service.

4) **User and Customer** includes either or both of the B2B or B2C model to capture the relationship matrix between users and providers.
5) **Networks** denote the channel through which services or products reach its desired customers.
6) **Competences** capture the technological advancements including tangible and non-tangible resources.

V. Conclusions and Open Research Area

There are many technical and commercial bottlenecks with the NS implementation. The main challenge is to manage standardization associated with the network slices in generating new businesses, where industrial giants come together. On the one hand, where NS brings flexibility and connectivity to various industrial verticals, it demands revolutionary changes in every aspect of operations (integrating automation and intelligence). Network slicing provides MNOs, CSPs, and industries with the most needed value proposition to create new business models. The value creation depends on the service and applied configurations [1]. The telco giants control the end-to-end value chain in Business-to-Customer (B2C) and Business-to-Business (B2B) sectors.

Resource Management will also be critical in specific applications with rigid bandwidth, latency, and computation requirements. The spectrum is an expensive and scarce resource. Thus, enabling critical services with dedicated resources can be expensive. Other critical and open issues include QoS associated with roaming and inter-slice security. Roaming that fails due to a lack of established standards and security becomes critical when we have services delivered by different operators with varying security protocols on shared physical infrastructure. Developing new businesses need clarity in the requirements like service life-cycle, resource allocation (estimated and actual), and other varying parameters like leasing costs and SLAs. Some identified challenges associated with slicing and slices include mobility, dynamic slice creation/management, QoS, slice isolation, handovers, and latency. Apart from technical bottlenecks, we have regulatory challenges that include business ethics, political (geographical regions) and governmental laws.

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Overview of Network Slicing: Business and Standards Perspective for Beyond 5G Networks

2021 IEEE Conference on Standards for Communications and Networking (CSCN)

Overview of Network Slicing: Business and Standards Perspective for Beyond 5G Networks

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2021 IEEE Conference on Standards for Communications and Networking (CSCN) | 978-1-6654-2349-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/CSCN53733.2021.9686125

***Abstract*—The deployment of fifth-generation wireless communications (5G) networks brought a significant difference in the data rate and throughput to the wireless systems. It ensures ultra-low latency and high reliability. In particular, Network Slicing (NS), one of the enablers for the 5G phase-II and beyond, has opened enormous opportunities for the Communications Service Provider (CSPs). NS allows CSPs to create independent virtual networks in the same physical network to guarantee high service levels. This paper provides an overview of the advances in NS from the perspective of the business opportunities and associated standardization activities. Standardization is critical in research as it intends to maintain interoperability among multi-vendor scenarios in telcos. We emphasize highlighting the technical facets of slicing within the business implementation and industry standardization process. Additionally, we address the application of Artificial Intelligence (AI) and Machine Learning (ML) to NS-enabled future networks deployments. A set of use cases and the underlying specific requirements challenges are discussed as well. Finally, future research directions are addressed in detail.**

***Index Terms*—Network Slicing, Communication Service Providers, Artificial Intelligence, Machine Learning, Standards, Standard Development Organizations.**

I. Introduction

The evolution of the mobile and wireless networks sector enabled by emerging 5G New Radio (NR) technologies and massively connected devices supports a significant increase in data traffic demand. As a result, new business models and services are available, e.g., supported by ultra-low latency and ultra-high throughput networks. The need for diverse applications and seamless connectivity involves critical requirements and implies supporting on-demand services. With the roll-out of fifth-generation (5G) wireless networks, Network Slicing (NS) evolved as a fundamental feature to facilitate segmented layers of networks in addition to the base network architecture [1].

In reality, NS provides a paradigm shift from the conventional approach towards traffic and network management [2]. It allows virtual logical network layers to enable all the functionalities of a shared physical network. Furthermore, it sub-divides the network into several isolated virtual networks leading to a dedicated channel to provide resources to serve the user demands. Thus, slicing empowers conventional networks to support a wide range of use cases and business models. Additionally, while enabling enhanced service quality, NS supports tailor-made user-specific solutions. For instance, the latency requirement for emergency services is more stringent than for agriculture-based applications (to maintain crop health). Thus, it will make current networks dynamic, flexible and scalable whilst accommodating growing demand, from various applications, with diverse requirements.

Unlike conventional networks, 5G networks are enabled with networking slicing. 5G evolution opens up many services and use cases. New physical networks are not required anymore to facilitate dedicated service. As proposed by the Third Generation Partnership Project (3GPP), the introduction of NS is established in the framework of release 15 [3] and is regularly updated for the required technical details and enhancements. 3GPP has specified that, for Communications Service Provider (CSPs), NS is significant for creating new services and generating new business models. NS allows CSPs to create multiple virtual slices to encompass colossal traffic increase and specific user requirements. As a consequence of this evolution, Working Groups from various Standard Development Organizations (SDOs) entered into force to support a multi-vendor landscape that develops NS specifications and guidelines.

CSPs benefit by implementing network orchestration, the automated communication among various entities on and across the network to meet network and user requirements. It sets guidelines to establish connections through the network while offering services with the associated Service Level Agreements (SLAs) [4].

In the scope of this paper, we provide an overview of new services and use case scenarios by the CSPs, together with the presentation of associated standardization activities. In addition, we shed light on the implementation of Artificial Intelligence (AI) and Machine Learning (ML) techniques for NS and management as a whole.

The remaining of the paper is organized as follows. Section II discusses the state-of-the-art and Section III describes the standardization activities addressing the NS. In Section IV, the challenges and requirements are addressed. Finally, Section

V presents the main conclusions of this work and addresses topics for further research.

II. State-of-the-Art

A network slice (often referred to as "5G Slice") incorporates the Network Functions (NF) and settings that encompass the supported use case or applications being served. It facilitates resources on-demand by incorporating existing virtualization and computing techniques. Slices make the resources modular while introducing flexibility into the network. In [5], authors have defined different layers of 5G slices, as shown in Figure 1.

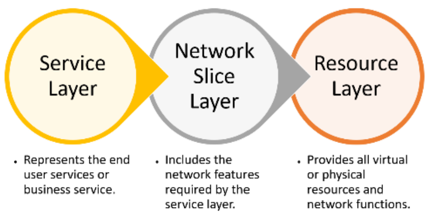

Fig. 1. Different Layers of Network Slicing

The two key enablers of Network Slicing are described as follow:

a) Virtualization Technologies: Virtualization facilitates resource sharing on the 5G Slice and removes dedicated hardware dependency. As the resources are independent of the physical hardware, slices are easy to deploy and manage as a modular block on a 5G network [5]. Interfacing the independent modules of resources is critical and needs assistance for resource allocation purposes.

b) Management and Orchestration: Automated orchestration and management techniques help regulate and manage many network slices in a complex environment. Besides, according to [6], it facilitates network slice management functions.

A. 5G-PPP and NGMN Architectural Vision

Next Generation Mobile Networks (NGMNs) vision is to enhance their flexible softwarization. The NGMN architecture is subdivided into three layers, as follows: i) business application, ii) infrastructure resource, and iii) its business enabling [1]. It is characterized by an End-to-End (E2E) scope encompassing the Radio Access Network (RAN) and core networks [7]. 5G Infrastructure Public-Private Partnership (5G-PPP) elaborates on roles and relationships among different parts of the 5G network. It generally shares the NGMN perspective that the 5G architecture must flexibly support softwarization for different use cases. Besides, it is worthwhile to note that the NGMN 5G-PPP architectural proposal is divided into five layers, namely service, infrastructure, business function, network function, and orchestration layers [8].

B. ETSI NFV MANO Management Architecture Evolution

NF Virtualization (NFV) enables broadening the upgraded capabilities of communication networks. These capabilities are flexible enough to instantiate the NFs where needed, e.g., in the data centre or network, and provide elasticity in allocating extra resources to these NFs. However, management and orchestration functions require new algorithms that handle essential resources and control the VNFs lifecycle. To manage the VNF lifecycle and resource allocation, the ETSI has added an NFV Management and Network Orchestration (MANO) architecture. It primarily provides the management and orchestration of network services, VNF, and all resources in a data centre (virtual machine resources, networking, computation, and storage) [6]. The three functional blocks of NFV MANO are i) the NFV orchestrator, ii) the VNF manager, and iii) virtualized infrastructure manager [9].

C. Slice Creation and Isolation

Depending on use cases requirements, 5G heterogeneous network nature allows for designing different network slices. For example, an ultra-low-latency slice will be supported irrespectively of general network requirements if the use case requires short delays.

Slice isolation consists of creating slices and then distinguishing them by considering the assisted use cases. Thus, it facilitates the simultaneous coexistence of multiple slices in the same network without affecting their performance. In fact, in-built security and privacy will be induced in the design by isolating the slices over the shared infrastructure [10].

III. Standardization Activities on Network Slicing

Standards are the guiding force behind research, development, innovation, policy establishment, and industries. It regulates the execution of productive tasks and implementation of the products while assuring quality [11]. In addition, standards ensure interoperability among research techniques or products.

There are different types of Standards Development Organizations (SDOs) working towards proposing standards within various verticals. In the context of 5G New Radio, it is essential to have collaborative standardization in E2E network slicing architectures [12], as it includes widespread coverage domains and application areas and is opening up new research opportunities. Therefore, SDOs and academia, together with industries, need to collaborate on standardization efforts to facilitate interoperability [11].

A. Worldwide Standardization approaches on 5G Network Slicing

Different telecommunications standardization bodies and industries are shown in Figure 2 together with their efforts on network slicing. Global System for Mobile Communications

Association (GSMA) and Next Generation Mobile Network (NGMN) contribute to the investigation of high-level requirements and architecture, as well as to the creation of the concepts of E2E 5G network slicing and business initiatives [13]. Currently, the industry focuses on investigating network slicing requirements while analyzing their influence on different network layers, e.g., core network or RAN. Different SDOs have been defined as technical specifications for many domains, as follows:

- Global System for Mobile Communications Association (GSMA) is a global organization that develops a unified mobile ecosystem that supports research and innovation in the mobile communications industry sector while integrating industry solutions, including network slicing. For example, the recently published white paper on "E2E Network Slicing Architecture" [12] describes industries, operators, and vendors' requirements and the need to collaborate in standardization activities to achieve a unified solution for the NS architecture. The white paper further explains E2E NS architecture, high-level requirements, and ongoing initiatives from various SDOs.
- 3GPP, one of the main standardization bodies, encompasses several active working and study groups to support 5G network slicing. For example, the SA1 group of 3GPP focuses on use cases and requirements. The SA2 working group defines the architecture selection to support network slicing [13]. The SA3 working group addresses security while SA5 addresses slice management [14]. The NS concept was introduced in 3GPP's Release 15 [3] and has further been enhanced within Releases 16 [15] and 17 [16]. Release 16 added authentication and authorization controls, enhancements to network automation, and service-based architecture to the 5G slicing. Release 17 adds enhancements for phase 2 of the NS architecture and outlines support to the GSMA defined Generic Network Slice Template (GST) attributes. It also addresses simultaneous usage of network slices in 5G-assisted networks.
- The European Telecommunications Standards Institute (ETSI) activities for 5G network slicing address the optimization of 5G services, configuration, delivery, and assurance of deployment, enabling complete automation. It also provides a solution for computing and storage [6].
- The Internet Engineering Task Force (IETF) standardization activities address the general requirements and development of the 5G network slicing architecture. Besides, they consider the orchestration mechanisms and network slice management. Their latest work includes gateway function for network slicing, the applicability of abstraction, and control of traffic-engineered networks to network slicing.
- The Broadband Forum (BBF) involves the activities to term the slicing management architecture for transport networks. Moreover, the BBF standardization activities contain the sharing of broadband network infrastructure between different service providers while providing resource control support [17].

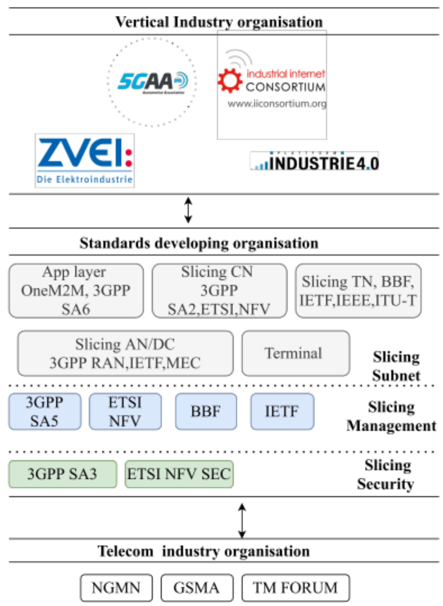

Fig. 2. Standardisation Groups and SDOs for Network Slicing [18], [19].

- The International Telecommunication Union - Telecommunication (ITU-T) encourages different functionality of E2E network slicing to provide reliability to customers. ITU-T functionality contains softwarization, network capability exposure, requirements of mobility, and diverse E2E Quality of Service (QoS) with distributed nature, the support of edge cloud, control, and user plane separations. ITU-T Study Group 13 (SG13) [20] works in orchestration, network management, and horizontal slicing standardization activities. It also addresses the data plane programmability and defines high-level network softwarization. An ITU-T SG13 Focus Group (FG) on ML for future networks, including 5G (FG-ML5G) [21], has catalogued its deliverable, which had specific requirements that include details for interfacing, network architectures, protocols, algorithms, and data formats. Deliverables related to network slicing and ML are as follows [21];
  - ITU-T Y.3172 [22]: Architectural Framework for Machine Learning in Future Networks including IMT-2020;

- ITU-T Y.3176 [23]: ML Marketplace Integration in Future Networks including IMT-2020;
- Requirements, Architecture and Design for Machine Learning function orchestrator;
- Serving Framework for ML models in Future Networks including IMT-2020;
- Machine Learning Sandbox for Future Networks including IMT-2020: Requirements and Architecture Framework;
- Machine Learning-based End-to-End Network Slice Management and Orchestration;
- Vertical-assisted Network Slicing based on a Cognitive Framework.

- The Open Networking Foundation (ONF) studies network slicing connectivity for high bandwidth 5G services by considering low latency and secure virtual subsets of the network [24].
- The Open Network Automation Platform (ONAP) [25] is an open community by operators for next-generation network automation platforms. It focuses on unifying standards and open source activities while promoting cross-organizational collaborations. Recently, ONAP has published a series of white papers related to technical challenges associated with 5G slices. It emphasized the following four design goals:
  - Communication Service Template (CST) to collect SLA requirements by users;
  - Service Descriptor (SD) records the user requirements collected by CST and facilitates slice creation by converting them into network requirements;
  - Network Slice Template (NST) describes the deployment information of slice instances;
  - Network Slice Subnet Template (NSST) deploys slice subnet instances.

B. Network Slicing and ML/AL

ML and AI have recently become very important in different fields of activity. It makes the system intelligent so that human intervention can be avoided. For example, Telecommunications operators use ML in analyzing the customer experience, network automation, and business process automation [19]. ML and big data are also needed to facilitate intelligent capabilities and integration for network slicing. Besides, ML and AI can be the best solution for self-optimization, self-configuration, and fault management functionalities, as well as network security and malware detection [26]. Table I presents different techniques considering ML/AI applied to the implementation of network slicing available in the literature.

IV. Opportunities for Service Providers

Mobile Network Operators (MNOs) consider network slices as an isolated independent network segment self-sufficient in resources and provides services at approved QoS. MNOs can implement slicing while maintaining transparency with the end-users. NS ensures connectivity tailored-made service delivery. MNOs maintain SLAs to administer the offered services, data rate, QoS, latency, reliability, and security. MNOs can implement either single or multiple slices in the network to offer services to varied requirements of different genres. Some of the prominent industries that can benefit from 5G slicing are the following ones:

TABLE I
Papers with concepts using ML/AL for Network Slicing.

Papers	Algorithms covered in different papers using ML/AI considering Network Slicing
[27]	Cellular and IoT networks resource management techniques using ML
[28]	Implementation of deep learning neural network, considering the network availability and network-load efficiency.
[29]	Network-slicing for the vehicle-to-everything service, intelligent network architecture that influences the recent ML techniques.
[30]	Resource mapping algorithm for 5G network slicing using deep reinforcement learning.
[31]	A deep reinforcement learning optimization model for slice configuration.

- Logistics;
- Media & Entertainment (Augmented/Virtual Reality);
- Automotive;
- Industrial Internet;
- Financial Sectors;
- Health & Wellness;
- Smart Cities.

To meet the diverse service requirements and demands, conventional business models are evolving as well. Therefore, new use cases are being defined. The underlying market ecosystem is divided into three categories, as follows [1].

- Asset Provider: performs infrastructure leasing to the third party;
- Connectivity Provider: facilitates essential connectivity delivery at high-speed to meet QoS requirements, including latency ;
- Partner Service Provider: enables enhanced communication services to end-users &/or to third-parties.

A. Evolved Use Cases [18] [14]

This section describes some of the evolved use cases and lists the required services from different industrial verticals.

- Massive IoT - An enormous amount of required smart services and connected devices will constitute massive IoT devices within the 5G evolution. These connections require high QoS and Quality of Experience (QoE). Varied applications have specific and different requirements that MNOs and CSPs can meet through network slicing. The user will pay to access network resources and functionality usage based on the SLA.
- Automotive - Connected vehicles demand high precision with ultra-low latency requirements. Therefore, Cellular

Vehicle-to-Everything (CV2X) and Vehicle-to-Everything (V2X) are considered critical use cases for 5G. Nevertheless, V2X requires communication between vehicles, emergency services, etc.; thus, these services account for high reliability. CV2X, while enabling communication among vehicles and infrastructure, creates new business opportunities, e.g., the infotainment service uses in-built sensors, cameras, and navigation modules. These services are not critical but intend to provide an enhanced driving experience. Hence, a high-speed and dedicated network is not required; instead, Mobile Broadband (MBB) connectivity will be sufficient. With network slicing, MNOs can provide ultra-low latency and high precision networks without creating a new physical dedicated network.

- Healthcare - Healthcare industries have several sub-use cases like hospital maintenance services, care-giving services, health tracking or remote monitoring. Different use cases account for different requirements. For instance, remote healthcare diagnosis requires a high data rate and low latency, while hospital maintenance is non-critical.
- Industry 4.0 - Industry 4.0 defines the automation of the traditional manufacturing industries and thus, results in a large-scale connected sensor, devices, monitoring units, and intelligent productions. Different industries have different requirements, e.g., Augmented Reality (AR) can support shop-floor workers in monitoring processing flows and instruction-based tasks while in control panels with safety hazards, where human beings are involved are critical areas.
- Smart Cities - Smart cities lay down a complete infrastructure development that includes planning, deployment, management, usage, monitoring, control, and maintenance. As they aim at lifestyle enhancement and accessibility, diverse opportunities have been open in various sectors, including education, transport, basic amenities, utilities, entertainment and healthcare. Requirements vary with varying use cases. Some notable use cases include smart metering, public safety and smart street lights.

V. Challenges and Open Research Areas

Network slicing is a promising paradigm for 5G and beyond networks, but its introduction faces various challenges [2].

In [5], NGMN has explained that sharing the resources between slice tenants is the most challenging issue for network slicing. Resource sharing can be either by static partition or by elastically dynamic sharing. One of the major open problems for resource sharing is standardizing a proper scheduling mechanism that can allocate radio resources among different slices while providing computational resource sharing and slice isolation mechanisms. Besides, network reconstruction is required in 5G and beyond, as the resulting ultra-dense network will comprise cooperative macro-cells and small-cells networks while addressing the slicing demands (high transmission throughput, fairness, short delay, and reliability).

Today, we lack on integrating network slicing with NFV and Cloud RAN (CRAN) to facilitate supporting point-to-point connections among radio equipment controllers and physical radio equipment. To fill this gap, network slicing requires cooperation with other 5G technologies, such as mobile cloud engineering, broadband transmission and NFV.

Designing new virtualization mechanisms is required to make the sharing of resources efficient and give strong support for implementing radio access network slicing. In addition, with multi-domain infrastructure, security issues turn out to be more complex. Therefore, defining security mechanism policies between several infrastructure domains is required.

Resource scheduling in RAN slicing is challenging due to performance isolation, diversified service requirements, and network dynamics (including user mobility and channel states).

Although different service providers and operators work on industrial solutions for network slicing and its management [32], some open management challenges include NS activation and deactivation at the service level, QoS maintenance at the network level, intra-slice resource sharing, and load balance.

NS creates separate logical networks on a shared physical infrastructure specific to use cases, realizes automation across various operational, management and business processes, and scales up the business without increasing OPEX. The commercial usage of network slicing in industries, intelligent configuration, SLA guarantees, and integration with vertical industries needs improvement. 3GPP defines the NF parameter for the slice and slice-subnet management accompanied by the related interfaces. However, it still needs further research to manage the automatic and intelligent closed-loop controls and SLA requirements. 5G network slice coordination is critical to guarantee high QoE. Use-cases and business requirements need to be considered by operators to enable new approaches that result in easy maintenance of the networks.

The open areas for future research activities include support for heterogeneous networks (HetNets) for availing intelligent services in Internet-of-Everything (IoE) scenarios, in addition to support for various kinds of realities (augmented, virtual, extended), connected autonomous systems or drone-based networks. The management and orchestration requirements vary indistinctively in drone-based networks and conventional networks. ML and AI capabilities enable intelligent radios to support various new services while incorporating fast and efficient training and tuning ML models. Besides, there is a need to develop novel meta-learning models for ML-enabled network slicing, an open research area.

VI. Conclusions

In this paper, we have provided a research-based overview of the current and ongoing work on Network Slicing within different Standard Development Organizations. It includes a detailed study on application/use cases, requirements, and challenges for network slicing in the light of standardization.

In 5G phase-2 and future communication generations, network slicing is expected to be one of the most influential technologies and provide solutions tailored to specific end-users, varying from residential to industrial or corporate. It can evolve and shift the telecommunication industry to the next level by allowing more flexible and reliable design. It is required to enhance network infrastructure and incorporates virtualization and softwarization to make the best use of services provided by network slices. It will allow operators to offer premium services to their customers. Moreover, NS will enhance the business opportunities in many sectors, which will gain attraction by increasing revenues. It is worth noting that network slicing supports the economic model and service differentiation that meets the end-user Service Level Agreements. Finally, we have identified some open issues [25] that require standardization, e.g., cross-domain inter-working, as well as SLA assurance, intelligence and automation.

ACKNOWLEDGMENT

This work was supported by FCT/MCTES through national funds and, when applicable, co-founded EU funds under the project UIDB/50008/2020, ORCIP (22141-01/SAICT/2016) and TeamUp5G. TeamUp5G has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

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Latent Space Transformers for Generalizing Deep Networks

2021 IEEE Conference on Standards for Communications and Networking (CSCN)

Latent Space Transformers for Generalizing Deep Networks

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2021 IEEE Conference on Standards for Communications and Networking (CSCN) | 978-1-6654-2349-6/21/$31.00 ©2021 IEEE | DOI: 10.1109/CSCN53733.2021.9686099

***Abstract*—Sharing information between deep networks is not a simple task nowadays. In a traditional approach, researchers change and train layers at the end of a pretrained deep network while the other layers remain the same to adapt it to their purposes or develop a new deep network. In this paper, we propose a novel concept for interoperability in deep networks. Generalizing such networks' usability will facilitate the creation of new hybrid models promoting innovation and disruptive use cases for deep networks in the fifth generation of wireless communications (5G) networks and increasing the accessibility, usability, and affordability for these products. The main idea is to use standard latent space transformation to share information between such networks. First, each deep network should be split into two parts by creators. After that, they should provide access to standard latent space. As each deep network should do that, we suggest the standard for the procedure. By adding the latent space, we can combine two deep networks using the latent transformer block, the only block that needs to train while connecting different pretrained deep networks. The results from the combination create a new network with a unique ability. This paper contributes to a concept related to the generalization of deep networks using latent transformers, optimizing the utilization of the edge and cloud in 5G telecommunication, controlling load balancing, saving bandwidth, and decreasing the latency caused by cumbersome computations. We provide a review of the current standardization associated with deep networks and Artificial Intelligence in general. Lastly, we present some use cases in 5G supporting the proposed concept.**

***Index Terms*—Deep learning, sharing information, latent space, standardization**

I. Introduction

Recommendable advances in Machine Learning (ML) algorithms, computational capacities, processing, preprocessing techniques, and computer hardware have resulted in efficient training methods for Deep Neural Networks (DNNs). In addition, deep feedforward networks have recently provided enhanced acoustic modelling [1]. As a result, the number of use cases for the DNNs in varied fields will witness exponential growth in the future. Increasing demands will make processing time and techniques, parallel computing, and latency highly critical to the connected users. Technologies such as 5G- Ultra-Reliable Low Latency Communications (URLLC), edge, and cloud computing enable the development of applications using deep networks to provide high Quality of Services (QoS) for users with these needs. At the same time, researchers increase the utilization of the mixed deep networks to achieve better performance and higher accuracy. In addition, the innovations with computational techniques and training models will result in evolving neural networks.

To have seamless integration beyond the fifth generation of wireless communications (5G) networks and deep hybrid networks have some open challenges. Standards support innovations, research organizations to build new training models and network architecture to facilitate enormous data and processing capabilities. It is speculated that standardization on latent space will boost research activities towards innovative hybrid networks with reduced or no retraining requirements. Latent spaces define the data representation in another domain space. For instance, it is the space that resulted in modifying some data features like the mathematical transformations. For example, selecting, extracting, and transforming to new domains happens automatically in deep networks, and there are no rules on the number of layers and units per layer. However, because these variables are hyper-parameters and based on the performance achieved. Thus, we propose to use the latent space to reduce the amount of retraining by separating deep networks. The contributions of this paper are the following:

1) A concept for sharing information between several trained deep networks from different fields (e.g. text and speech and images, resource allocation and security algorithms and, others) is able to decrease latency and computation requirements in deep networks applications reducing training processing costs;
2) New concepts for training techniques to create hybrid networks from pretrained networks;
3) New transfer learning methods for using pretrained deep networks with small datasets.

This paper is organized as follows. Section II discusses the state-of-the-art and Section III presents the standardization activities concerning the AI, ML, and deep networks. Section

IV provided limitations of state-of-the-art associated with standardization activities, and Section V addressed the novel concept of reducing the retraining activity and proposes the new concept for sharing information between deep networks. Section VI discusses an integrated view between the proposed idea and the uses cases for 5G networks. Finally, Section VII presents the main conclusions of this work.

I. State-of-The-Art

Artificial Neural Networks (ANN) are networks of connected nodes guided by the associated weights to facilitate the implementation of Artificial Intelligence (AI) to solve real-life problems. ANNs are useful in designing prediction models, automation and control, and applications requiring trained datasets to make decisions or identify patterns. ANNs are adaptive to the learnings from the information they carry. This information is processed using mathematical/ computational models. The nodes are assembled into layers that perform transformation operations to the inputs [2]. Information travels through multiple layers. ANNs are trained by adapting to network parameters and environment. There are various ways to train a network, for example, supervised learning, unsupervised learning, reinforcement learning, self-learning and, so on [3]. Deep Learning (DL) is an approach where the network observes, identifies, and learns the representations required to process and categorize the raw data. A multi- layered ANN capable of modelling complex linear or non- linear relationships is a Deep Neural Network (DNN). DNN formulates compositional models from the structured or unstructured input datasets and extracts features from different layers. These networks are well-versed to create approximate models with the provided data input. The data flow from the input layer to the output layer, and thus, these networks are also called feedforward networks.

The flow of data can be expressed as follows;

1) The weights of neurons in a DNN is initialized by the random numbers.
2) The output is generated using the activation function after multiplying the inputs with the associated weights.
3) An optimization algorithm will update the weights if the desired accuracy is not achieved.

A. Hybrid Deep Networks and Sharing Information

The researchers mention two kinds of hybrid deep net- works in the literature—the combination of one deep network followed by machine learning algorithms such as Support Vector Machines (SVMs). For example, in [4], the hybrid combination of Convolutional Neural Network (CNN) and Long Short-Term Memory (LSTM) with SVM is compared to achieve higher accuracy for sentiment analysis. In different methods like in [5], several deep networks such as CNN, LSTM, Bidirectionally Long Short-Term Memory (BiLSTM), Gated Recurrent Unit (GRU) were used separately to extract the features, and by concatenating all of these features followed by the Softmax layer, the hybrid network was created and was used for sentiment classification. In another way of the combination of deep networks as a series, one followed after another like [6], the authors for analysis Human Activity Recognition (HAR), used the CNN network followed by another RNN network type, e.g., LSTM, BiLSTM, GRU, and Bidirectional Gated Recurrent Unit (BiGRU). In the other fields, such as security, we were using hybrid deep networks increasing. Another hybrid method was used in [7] for attack detection in the Internet of Things (IoT). As in [6], they used the LSTM network after extracting futures by the CNN network. The recent researchers proved that using hybrid deep networks can improve the performance in many different use cases.

This paper proposes a new concept for standardization related to sharing information between the deep networks without changing the last layers, developing a new individual network, or retraining the pretrained networks. Standards for deep networks are critical because several fields use such networks nowadays (e.g., health, telecommunications, gaming). With standardization, the use cases of deep networks are publicly available, which promotes dissemination and broad application. Furthermore, standardization helps prevent market fragmentation, which inhibits growth, and mutually incompatible solutions are avoided.

II. Standardization Activities

Standards are essential to driving research, innovations, policymakers, and industries. They form a set of guidelines that validate requirements specifications and assure quality [8]. In addition, they align various approaches to have interoperable solutions as we are advancing every day with technology and its vast usages.

There are different types of Standards Development Organizations (SDOs) working towards standards for AI applications. SDOs are categorized at International, National, and Regional levels. Some of the renowned SDOs are ISO (International Organization for Standardization), IEC (International Electrotechnical Commission), ITU (International Telecommunication Union), European Telecommunications Standards Institute (ETSI), etc. In addition, organizations like the 3rd Generation Partnership Project (3GPP), Institute of Electrical and Electronics Engineers (IEEE), and oneM2M are examples of Standard Initiatives groups that collaborate and coordinate standardization efforts on different subjects [8].

A. Standards in Artificial Intelligence

Table I summarizes some of the ongoing standardization initiatives concerning AI/ML architectures and techniques. For the AI ecosystem, standards and specifications are indispensable as they ensure a safer and reliable future. Furthermore, the connected, intelligent devices generate enormous data and the information required for the training models. Furthermore, data is critical and essential in intelligent environments as they include personal as well professional details. For instance, in healthcare scenarios, data cannot be shared or used for training purposes [20]. Thus, it is of utmost importance to have a specified requirement to regulate data

TABLE I

STANDARDIZATION ACTIVITIES CONCERNING AI/ML/DL

	Standards	Summarized Activities
1	IEEE P2830, Std for Technical Framework & Requirements of Shared Machine Learning ITU T Y.3172 [9]	This standard defines the framework and architecture for the training model using multi-source encrypted data in a trusted third-party environment. Its emphasis is on the use of a third-party execution environment to process encrypted data. The standard intends to provide a verifiable basis for trust and security and outlines functional components, workflows, security requirements, technical requirements, and protocols.
2	P3333.1.3/D2-IEEE Draft Standard for the DeepLearning-Based Assessment of Visual Experience Based on Human Factors [10]	This standard defines deep learning-based metrics of content analysis and QoE assessment for visual content. It targets to contribute to an enhanced user experience. To achieve high QoE, this working group is focused on areas concerning perceptual quality and virtual reality (VR) cybersickness. Its DL models count for affecting human factors, reliable test methodology & a database construction procedure. It also defines cases for deep analysis of clinical and psychophysical data, deep personalized preference assessment of visual contents, and building image and video databases.
3	Focus Group on Machine Learning for Future Networks including 5G (FG-ML5G) [11]	FG-ML-5G is an ITU-T Study Group 13 (SG13) Focus Group on Machine Learning for Future Networks, including 5G. It has documented ten technical specifications for ML for future networks, including interfaces, network architectures, protocols, algorithms, and data formats. It was active from January 2018 until July 2020. Following are some relevant contributions from this focus group concerning the proposed work. 1) ITU-T Y.3172: Architectural framework for machine learning in future networks. 2) ITU-T Y.3173: Framework for evaluating intelligence levels of future networks. 3) ITU-T Y.3174: Framework for data handling to enable ML in future networks. 4) ITU-T Y.3176: ML marketplace integration in future networks, including IMT-2020. 5) Serving framework for ML models in future networks, including IMT-2020.
4	ITU-T Y.3172 [12]	ITU-T Y.3172 provides an architectural framework for machine learning in future networks including IMT-2020. It specifies a set of architectural requirements, components and, their integration guidelines. It defines an ML pipeline, ML management and, orchestration functionalities.
5	ITU-T Y.3173 [13]	ITU-T Y.3173 specifies a framework for evaluating the intelligence of future networks & introduces a method to assess the intelligence levels. It defines an architectural view for evaluating network intelligence levels based on the recommendation in ITU-T Y.3172.
6	ITU-T Y.3174 [14]	ITU-T Y.3174 Framework for data handling enables machine learning in future networks. It describes the requirements for data collection and processing mechanisms in various usage scenarios for ML and drafts a generic framework for data handling.
7	ITU-T Y.3176 [15]	It provides ML marketplace integration in future networks & provides a high-level requirements and the architecture for integrating ML marketplaces based on the ITU-T Y.3172 needs.
8	AI Ecosystem Standardization Program at the EC Workshop [16]	IEC and ISO organized a workshop on the AI Ecosystem Standardization Program to fully exploit the potential of AI across Europe and guarantee Europe's leading position in AI. It summarizes varied initiatives in individual EU nations and provides an initial snapshot of the European AI landscape.
9	Securing AI [ETSI GR SAI 005) [17]	ETSI GR SAI 005 focuses on deep learning and explores the existing mitigating countermeasure attacks. It describes the workflow of machine learning models where the model life cycle includes both development and deployment stages.
10	ITU-WHO FG AI4H [18]	The ITU/WHO Focus Group on AI for Health focuses on creating a standardized assessment framework for AI methods in health. The FG constitutes members from various research organizations, government agencies, and healthcare facilities. It is an ITU-WHO initiative.
11	ITU-WHO FG AI4NDM [19]	AI for Natural Disaster Management (NDM) focuses on establishing a roadmap for effective and secure use of AI methods for NDM. The FG activities include data collection and handling, improving modeling across spatiotemporal scales, and providing effective communication.

sharing and analysis. IEEE is working towards the Ethically Aligned Design for AI [21], and also European Union's (EU) General Data Protection Regulation (GDPR) [22] sets regulations on how the data can be used. AI and ML is an extensive and open area where the details at each level are crucial.

I. SHORTCOMINGS

In the following, we summarize the limitations in the current standardization related to deep networks, which motivate us to propose new standards related to sharing content between such networks.

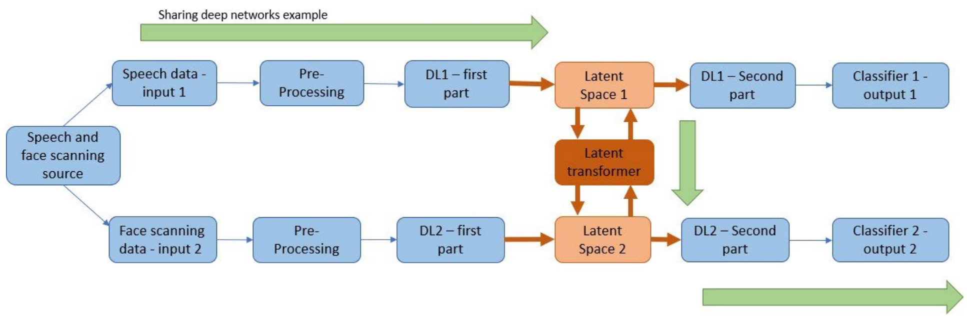

Fig. 1. Latent Transformer to Mix Two Deep Networks with Different Purposes (e.g. speech and face scanning)

A. Limitations on the State of the Art

There are limited algorithms like SVMs supported by a solid mathematical background in machine learning and deep networks literature. However, these methods still need user intervention in selecting some hyper-parameters such as kernel-trick mode or the value of regularization, which are difficult to define in deep networks. These parameters are tuned commonly by grid searching on all possible domain values. This limitation causes the training of deep networks to be computationally costly for researchers, and improving the deep networks is possible for only a few organizations or labs that have access to enough hardware and data resources. Based on this lack, the methods like transfer learning were invented to retrain the pretrained deep networks by the new small datasets used by different researchers. However, these replacement methods suffer from complexity and also low compatibility with new other datasets. Based on the number of samples contained in each new dataset and the similarity between the original dataset used to train the deep network and the new dataset, which will be used on the same network, this complexity can be varied. It can cause to change only a few last deep network layers and train only them, or retrain the whole deep network.

B. Limitations on the Standards

Studying various standardization activities concerning AI and ML, few standards are available for defining the architecture for preprocessing data and preparing them for machine learning algorithms. Also, there is some guidance for using different blocks and techniques in the typical programming frameworks like Pytorch or TensorFlow for deep networks. However, improving the performance of deep networks needs some standardization beyond the existing ones. The two usual ways for enhancing the existing deep networks are using more data or adding more layers. Nonetheless, methods such as distillation may help reduce the size of deep networks, but they are not enough. Therefore, new standardization needs to separate Deep networks into independent parts. These parts enable researchers with low resources to use the parts, improving or replacing parts of their networks without training. In addition, the combination of different trained parts from several deep networks will be provided.

I. Proposed Idea

According to [23], latent space is a different domain space where data can be decreased to represent new optimal features adequately. The new features may be more distinguishable per each class which facilitates solving classification prob- lems. Typically, when we modify data features, such as some mathematical transformation, those features will be converted to another domain known as latent space In deep networks, features selection and extraction happen automatically. After each layer, the features are converted into a new domain known as latent space. There are no rules on the number of layers and units per layer. Moreover, the result of each layer may depend on the data availability.

Both the number of units and layers are hyper-parameters and, based on the performance achieved in results, will be changed and are varied from one researcher to another. The concept of separating deep networks into at least two parts is to access latent space defined by a specific standard. However, this latent space should follow some rules and standards, and the number of network layers before it should provide some required quality. A practical example of this idea can be the deep hybrid networks using the encoder parts of autoencoders to transfer features in the new latent space, but not standardized, and then feeding to another deep network.

This specification offers a new level of generality for the latent spaces and the network layers before and after them. In addition, these parts of deep networks will be made reusable without needing retraining by the new dataset. By doing these changes, new transfer learning techniques will emerge, and interoperability between deep networks with different datasets will be possible.

Figure 1 depicts the procedure to mix two deep networks with different purposes (e.g., speech and face scanning) by only training the latent transformer unit, using the elements of two deep networks with the different tasks using the latent transformers. The arrows include the process steps and the parts which were chosen from each deep network. In the first path, the source generates speech data, followed by pre-processing. It is fed in the first part of the deep network - DL1 and then converted to latent space1. Traditionally, the data would be fed to the second part of the deep network 1 - DL1 and, after classification/regression, we would be able to see the results. The face-scanning data would follow the same method in input 2 toward the deep network 2. Using standarized latent spaces, the latent transformer block could convert data from one latent space to another. This conversion makes it possible to create two other paths using the first part from one network and the second part from another network, as highlighted in Figure 1. Using latent transformers and conversion from one latent space to another enables multiple types of data accepted as input or be created as output. By dividing the pipeline into small parts and replacing only some elements may improve the performance and accuracy of the whole process significantly because the raw data is pre-processed and prepared in the deep network's first part. Furthermore, adding new features and maintenance may be more accessible. Besides mixing both networks, we can create mixed data, increasing the feeling analysis. This new technique also works for parallel-connected deep networks. For example, in the ensemble technique, only the first part of each network needs to be used. By ensemble latents, the amount of prediction calculation in ensembling methods will be expected to decrease because there is no need for the second part of the networks while the final performance increases. It causes the latency prediction of networks also to be improved. A critical implementation of standard latent spaces is providing information sharing and transforming between different deep networks. The idea is that instead of training networks for particular purposes, we can use the combination of general networks, and only the transformer units between them should be trained. It will be happening by generalization provided by standardization of latent spaces in deep networks under the same framework.

The importance of using parts of one deep network combined with the elements of another deep network will be revealed while enough edge computation or bandwidth will not be available for the users. In this situation, the different latent spaces of deep networks with various fields produce different data sizes in latent space. So, this combination can make the same result but with lower edge computation or bandwidth for transferring.

With this standard related to latent spaces available in the research community and between European countries, the ability to use the series of deep networks by using latent transformers will be possible. It makes the complicated tasks more manageable than before, which concludes the integration of multi-services. For example, by combining different elements of deep speech transcription, deep translation, profound text to speech, and finally, deep fake technology, we can have the users from various countries and languages communicating their native languages. It is only one example of how we can, with less effort, facilitate the interaction between humans in real-time. To achieve this, the latent transformers need to be trained and create the required compatibility. This process also can make the new generation of transfer learning for deep networks. Recording data of one latent space can further be analyzed by other techniques and deep networks later.

I. Generalization of Deep Networks in 5G Communications

Deep Networks generalization by standards in Research and Development (R&D) reduces training processing costs, increases investment in security, provides an innovative solution with information advantage over future competitors in 5G markets and provided experience exchange with essential participants in the standardization process. Thus, standardization generates innovation, expands business access, and internationalizes new technological advances.

The development of the telecommunication systems 5G coincides with the emergence of the IoT, extended reality new use cases, and improvements in deep learning techniques, leading to the development of applications combining them in the future to provide high Quality of Services (QoS). Therefore, it affects accessing the high bandwidth with low latency will be required more than before, and cause to creating the massive amount of transferred data from the edge to cloud for processing. Splitting deep network parts between edge and cloud and transferring the represented latent data can provide a new opportunity for developers to create and improve the new cloud services based on the standard latent domains for deep networks.

Conversion data into common latent space should happen on the edge side to remove the redundancy from data, decrease the data dimension, and apply the super compression techniques as illustrated in Figure 2. The deep network that implements resource allocation algorithms is integrated with the security in the edge using latent spaces transformers and the neural network processing computes the result of the mixed deep network in the cloud. These steps of data reduction followed by the existing or new security standards can provide a high level of personal data protection without significantly increasing the amount of final data rather than the initial for transferring to the cloud. Also, other deep networks related to resource allocation and security techniques can be merged creating, a new secure, optimized algorithm. This process is expected to create an innovative competition between several industries to improve and create better standards for latent spaces or improve the following parts based on the existing latent standards.

In the future, we envisage that a latent space with high quality of service will be a commodity that people will rent or buy to provide services. Hence, we can expect different versions of latent spaces with various QoS requested by the users or the available network bandwidth. This concept also fits the described solution to be compatible with different network bandwidths.

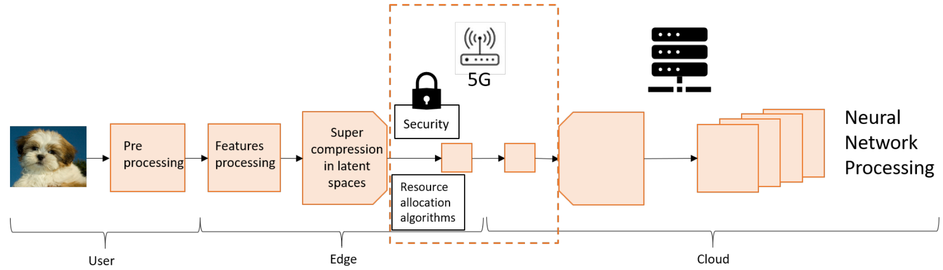

Fig. 2. Use Case for 5G using Deep Networks

I. Conclusions

Generalizing deep networks by sharing information between them using latent transformers may reduce the costs of the training process. This generalization can be implemented throughout standardization. Additionally, it might create an opportunity for innovation by combining pretrained deep networks to generate other hybrid networks for new purposes, research, and development. There are several standards available for Artificial Intelligence and Deep Learning. However, none of them considers the possibility of using latent transformers blocks for sharing information. Unfortunately, the standards activities are not public, so researchers do not have easy accessibility to all developments and proposed frameworks. Therefore, at this point, assuming the area that we are covering is not in the standards, it is an open research area, and we propose the requirements and related guidelines to develop our concept. Moreover, we showed several use cases applications for this standard (e.g., processing image and sounds, mixing security and resource allocation algorithms in 5G networks and IoT devices, ensembling multiple deep networks and extended reality scenarios).

Acknowledgment

This research received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Project Number 813391.

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Cost Revenue Trade-off for the 5G NR Small Cell Network in the Sub-6 GHz Operating Band

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***Abstract*—5G Radio Access Network (RAN) dis-aggregation has opened up opportunities toward the 2nd phase of 5G. 3GPP and Telecom industries have defined backhaul, fronthaul, and mid-haul transport interfaces, as well as functional splits to incorporate network flexibility and openness. In this work, splits 6 and 7 (7.2) of 3GPP are addressed for implementing sub-6 GHz future wireless mobile communication networks. The 5G-air-simulator has been considered to simulate New Radio 2.6 GHz, 3.5 GHz, and 5.62 GHz frequency bands by using Video (VI) and Video plus Best-Effort (VI+BE) with the Proportional Fair (PF) packet scheduler. The split 6 is ideal for small cell deployment, while split seven, (mainly sub-split 7.2) requires high fiber capacity, which may increase the price of the fronthaul. In the simulations, we have considered a uniform user distribution and reuse pattern three. By assuming a set of cost parameters and a given price for the traffic, we have analysed the cost/revenue trade-off of outdoor pico/micro cells, while comparing the implementation of functional split six and seven with scenarios without splitting. It is shown that for cell radii up to 500-600 m the split 6 provides higher revenue and profit compared to split 7 for all bands.**

***Index Terms*—Functional Splits, 5G Air Simulator, Goodput, PLR, Cost/Revenue Trade-off.**

I. Introduction

In the era of the digitization and industrial expansion, Industry 4.0 is thriving on the foundation of the connected society and emerging technologies. The evolving industrial age will significantly advance the value-chain automation, security, and business models [1]. Mobile operators worldwide are in the deployment phase of the Fifth Generation (5G) networks, which have become critical for the smart industries. 5G New Radio (NR) offers higher bandwidth, lower latency, and a huge device density than the existing mobile network.

The 5G NR was introduced by 3GPP in Release 15 [2], followed by enhancements in succeeding Releases. The recent Release 17 [3] NR's non-terrestrial deployments, improved uplink control and data channel design, and support for the Frequency Range 2 (FR2) and 60 GHz unlicensed bands. It has also specified improved massive MIMO multi-transmission and reception points (TRP) and multi-beam operation. In 2015, the International Telecommunication Union (ITU)- Radiocommunication Sector published requirements for 5G networks and services [4]. It defined enhanced Mobile Broadband (eMBB), Ultra-Reliable Low Latency Communications (URLLC), and massive Machine Type Communications (mMTC) as the main trends of 5G. ITU-R, 3GPP, ETSI and other organizations have published the specifications and recommendations for 5G and beyond networks tackling growing requirements, architectural needs, and various radio access technologies like 5G NR, LTE-M and NB-IoT, driving the design of next-generation RAN [5]. During the 41st meeting, ITU-R study group 5 (Working Party 5D (WP 5D)) [6] discussed the ongoing initiatives and research towards "IMT Vision 2030 and Beyond" [7].

5G Radio Access Network (RAN) dis-aggregation has opened doors for new opportunities. 3GPP and Telecom industries have defined transport interfaces (backhaul, fronthaul, and mid-haul) and functional splits to incorporate network flexibility and openness. Network Functions Virtualization (NFV) enabled the Mobile Network Operators (MNOs) to implement fully–centralized Cloud–RAN (C–RAN) and dis-aggregated RAN architectures. 3GPP's Release 15 [2] defines a flexible 5G RAN architecture with the gNodeB split into the Central Unit (CU), Distributed Unit (DU), and Radio Unit (RU), as shown in Figure 1. The operators use CU and DU to implement different split options. The high-level functions are distributed over the mid-haul (CU and DU). Among the eight main split options, split seven is further sub-divided into 7.1, 7.2, and 7.3, as discussed in detail in the following section.

By 2026, it is expected that there will be around 2.5 billion 5G voice users [8], experiencing high-end interactive calling features. Endless scopes and opportunities have opened up new business and investment models for providers and users. The transforming technologies evolve and develop hand-in-hand with significant revenue opportunities. Companies are significantly making investments in 5G and beyond technologies. The critical attributes for the telecommunication sector are revenue and profit. There is disruptive cross-sector competition among the MNOs and vendors. The MNOs expected to implement business models to support 5G services to serve the goal of ubiquitous connectivity.

This paper aims to understand the cost/revenue trade-off of a 5G pico/micro scenario by using the 5G-air-simulator [9]. The

This work was supported by FCT/MCTES through national funds and when applicable cofunded EU funds under the project UIDB/50008/2020, ORCIP (22141-01/SAICT/2016), COST CA 20120 INTERACT, SNF Scientific Exchange-AISpectrum (project 205842) and TeamUp5G. TeamUp5G has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

output of the simulations enables to analyze the Packet Loss Ratio (PLR), average delay, goodput and number of supported users for the 2.6 GHz, 3.5 GHz and 5.62 GHz frequency bands. Supported goodput curves for video (VI) and VI+best effort(BE) are used as an input to the cost/benefit analysis whilst comparing functional splits six and seven with cases where functional splitting is not considered at all.

The remaining of the paper is organized as follows. Section II briefly discusses the 3GPP functional splitting. Section III presents the motivation and goals, followed by Section IV's scenario and approach description. Section V discusses the achieved, followed by the cost/revenue, and profit analysis in Section VI. Finally, in Section VII, the main conclusions of this work are drawn.

II. 3GPP Functional Splitting

3GPP has defined functional splitting while suggesting eight split options and extending them to further sub-splitting possibilities [10]. DUs' functions reside near the user and will be placed at the antenna side. The functions in the CU will benefit from centralization processes and the high processing power within data centers. The functional splits proposed by 3GPP and enhanced Common Public Radio Interface (eCPRI), Small cell forum, and Next Generation Mobile Networks (NGMN) [11], are presented in Figure 1.

Authors in [12] have proposed different functional splitting in higher-layer to enhance the CPRI requirements, while the authors in [13] proposed to shift the radio processing functions from the BBU to the Remote Radio Head (RRH) to decrease the load on the fronthaul.

Split seven has further sub-splits that include RRH functionalities like Inverse Fast Fourier Transform (IFFT), resource mapping, precoding, and cyclic prefix addition that reduces the load on the fronthaul. The lower physical layer (in some cases higher physical layer) is processed at the RRH, while the other functions are processed at the edge of the cloud. 3GPP suggests that the MAC-PHY split (six) between the Media Access Control (MAC) and Physical Layer (PHY) shifts the RF, PHY and other functionalities to the RRH.

Split one is the split between the Radio Resource Control (RRC) and the Packet Data Convergence Protocol (PDCP), while split two is the split between the PDCP and Radio Link Control (RLC). In split 2, the RRC and PDCP are kept in the BBU, and all the other processing functionalities (RLC, MAC, PHY, and RF) are processed at the RRH.

Split option 1 to option 6 are well-thought-out with higher layer splitting suggestion [14]. The eCPRI specification defines the split options with different nomenclatures like A, B, C, D, ID, IID and E [14], [15] eCPRI considered the splits ID, IID, within the PHY layer corresponding to the option seven. It also considers the split E, corresponding to option eight, in line with the usual functional split used by CPRI, where the D splits are taken as split six.

III. Scenario and Approach

In the scope of this paper, the cost/revenue trade-off of splits 6 and 7 (two options that encourage the centralization concept) are analyzed in the small cell environment. Based on our assumptions for a micro cellular scenario, we explored whether split 6 is the best solution for small cell deployments [16], as it can improve not only the data rate but also reduce the cost of the network and power consumption.

The one-to-many configuration between the BBU and RRH exhibits efficient resource management while, in the one-to-one configurations, as illustrated in Figure 2 (a), each RRH is connected to one single BBU. The users in each RRH are scheduled in different frames. All the bandwidth is allocated to one RRH, and the spectrum is reused for each cell. In Figure 2 (b), the BBU connects to multiple RRHs, and the users in different RRHs share the same resource units of only one BBU whilst scheduling it within the same frame. If the user is unavailable or the traffic is low, the nearby cell zooms out while the quiet traffic cells go to sleep This procedure reduces the power consumption and the complexity of the shared BBU.

We have simulated a scenario with nineteen cells in the 5G-air-simulator [9] and considered the Proportional-Fair (PF) packet scheduler. The central cell is the cell of interest and only communicates with User Equipment (UE). The UEs are deployed inside the central cell, and the remaining 18 cells are only interfering cells. The procedure for deploying users with a uniform distribution in the 5G-air simulator [9]. The deployed users are limited to the central cell and can not leave the central cell to nearby cells, as shown in Figure 3. The reuse pattern three (k = 3) is considered. From this analysis, we can determine the number of supported users and goodput.

We have considered functional split 6 and split 7 (7.2) [10]. The split 6 is ideal for small cell deployment, while split 7 (mainly sub split 7.2) requires high fibre capacity, which increases the fronthaul price.

For this simulation, we have compared the 5G radio performance of the NR operating bands (2.6 GHz, 3.5 GHz and 5.62 GHz) for Video (VI) and Video plus Best-Effort (VI+BE) by considering the Proportional Fair (PF) packet scheduler whilst comparing the scenarios of functional split six and seven with the plan without splitting. Assumptions are as follows:

- For the best effort flows, we have considered infinite buffer sources [17].
- For video only, we have considered a trace of the simulator [17].
- PF schedules the traffic of a user when its instantaneous channel quality is relatively high compared to its own average channel condition over time. The PF scheduler is used as a typical way to find a trade-off between requirements on fairness and spectral efficiency scheme. It is effective in reducing variations in user bit rates with little average bit rate degradation, as long as user average values of SINR are fairly uniform [18].

The simulation parameters are presented in Table I. Numerology zero with a sub-carrier spacing of 15 kHz is considered, with ten subframes in a single frame. Each single frame duration is 10 ms, while each sub-frame is 1 ms. Every sub frame further contains one slot which carries 14 symbols. The height of the base station is settled to h_{Bs} = 10 m in the

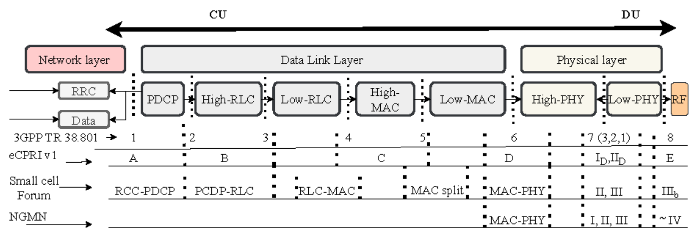


Fig. 1: Different Functional Splits proposed by 3GPP [10].

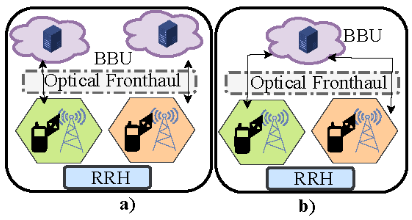


Fig. 2: BBU with RRH (a) one to one and Multiple RRH (b) one to many.

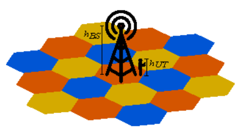


Fig. 3: Micro cell with interfaces with one cell having users while others are interfering.

TABLE I: Simulations Parameters

Frequency Band [GHz]	2.6	3.5	5.62
NR operating band	n7	n78	n46
Numerology μ	0		
Frame duration [ms]	10		
Subcarrier spacing	15 KHz		
Number of subframes per radio frame	10		
Number of slots per subframe	1		
Number of symbols per slot	14		
Number of slots	10		
Transmitter power small cells [dBm]	40	42.2478	46.6953
Transmitter power UT [dBm]	23		
Number of BS	19		
Reutilization	3		
Bandwidth per tier [MHz]	20		
Cell radius [m]	1000		
Effective UT height [m]	1.5		
Effective BS height [m]	10		
Scheduler	PF		
Applications	VI and VI+BE		
Video bit rate [Mb/s]	3.1		
Number of simulations	50		
Simulation duration [s]	46		
Flows duration [s]	40		

simulated scenario. The cell radius varies from 15 m to 1000 m. The transmission time interval (TTI) is 1 ms. The actual time for the simulations is 46 s, and the period of each one of the video streams is 40 s. The results are obtained by getting an average of 50 simulations.

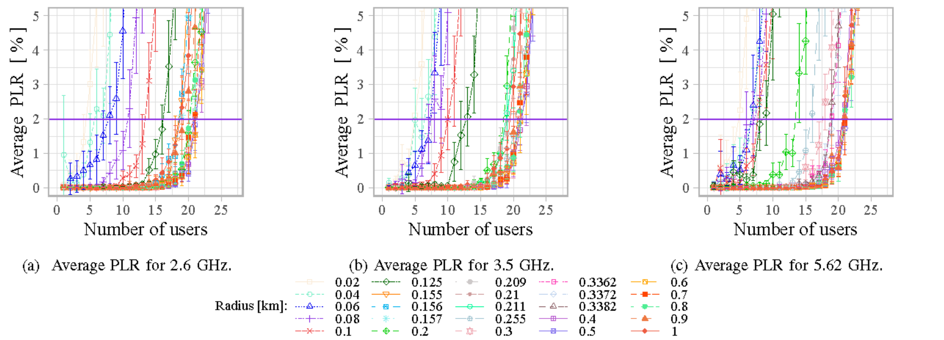
IV. Simulation Results

The scenario from Figure 3 has been simulated to obtain the packet loss ratio. As shown in Figure 4, for the longest values of the cell radius, the minimum value for PLR occurs at 5.62 GHz fro long cell radius, but PLR=2% occurs at the same number of users as for the shortest cell radius at lower frrequency bands. The PLR at 2.6 GHz is less than 3.5 GHz and 5.62 GHz. For example, if we consider the case 0.04 km, then in Figure 4 a) for 2.6 GHz it supports almost five users with minimum PLR compared to others, at the same radius in Figure 4 b) the 3.5 GHz goes up above 2% PLR at 5 number of users. The 5.62 GHz cross the 2%, for the same cell radius, six users are supported, while 2.6 GHz supports almost nine users (with PLR less than 2%) at the same cell radius. For cell radius of 1 km, the 5.62 GHz frequency band performs better than the 2.6 GHz and 3.5 GHz bands.

Figure 5 shows the goodput as a function of the cell radius, varying from from 0.015 to 1 km. To obtain these results, we have first performed the simulation for Video (VI) and then performed simulations with the same set of parameters for Video Plus Best Effort (VI+BE). It is demonstrated that, for the shortest cell radii, at 2.6 GHz, VI+BE provides a higher supported goodput than the 2.6 GHz VI case . Besides, with VI+BE, in comparison to the 5.62 GHz and 3.5 GHz frequency bands, the 2.6 GHz frequency has better performance. Furthermore, the 3.5 GHz VI+BE and VI case serve better than the 5.62 GHz VI+BE and VI cases, respectively, for a shorter cell radius range (up to circa 400 m). As in a shorter cell radius range, the 5.62 GHz band has a higher value of PLR (above 2%). For values of cell radius beyond 0.6 km, the 5.62 GHz band provides higher goodput than the 2.6 and 3.5 GHz bands.

Figure 6 shows the number of supported users as a function of the cell radius. It clearly shows that the 2.6 GHz band supports a higher number of users for the shortest cell radius.

As shown in Figure 6, for the shortest cell radius, up to 400 m, the 2.6 GHz band supports 21 users (its maximum value



(a) Average PLR for 2.6 GHz.

(b) Average PLR for 3.5 GHz.

(c) Average PLR for 5.62 GHz.

Fig. 4: Average PLR for 2.6 GHz, 3.5 GHz,and 5.62 GHz with number of supported users.

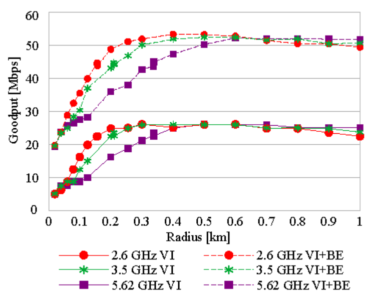


Fig. 5: Goodput for 2.6 GHz, 3.5 GHz, and 5.62 GHz with the case VI and VI+BE.

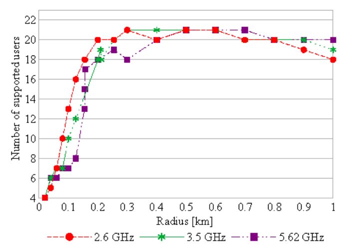


Fig. 6: Number of supported users.

among the bands). Above 700 m, the 5.62 GHz supports a higher number of users.

V. Revenue, Cost and Profit analysis

To analyse the cost/revenue trade-off with functional splits 6 and 7, the models from [19] have been considered in [20]. The revenues per cell, $R_v/cell$[€], can be achieved as a function of the throughput per Base Station (BS), $R_{(b-sup)}$ BS [kbps], and the revenue of a channel with a data rate $R_{b[\text{kbps}]}$, $R_{R_b[€}$ [€/min], and T_{bh} corresponding the equivalent duration of busy hours per day [21], R_v/cell[€] can be obtained by following equation. The revenue per coverage zone can be calculated as follows:

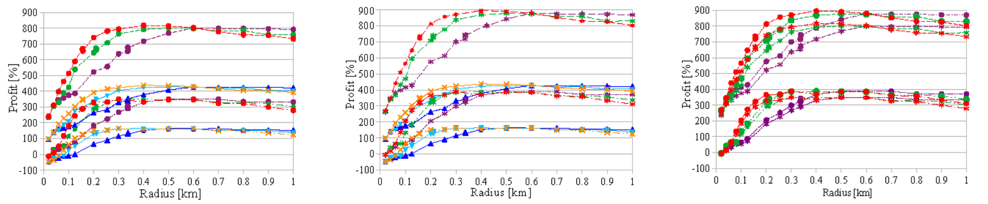
$$(Rv)_{\text{cov-zone}} = \frac{N_{\text{hex.}}\, R_{(b-sup)equiv} \cdot T_{bh} \cdot R_{R_b[€/\min]}}{R_{b-ch[kbps]}} \quad (1)$$

where $R_{R_b[e/\min]}$ is the revenue of a channel with data rate $R_{b[\text{kbps}]}$, N_{hex/km^2} is the number of hexagonal areas,$R_{b-ch[\text{kbps}]}$ is the channel's data rate and T_{bh} represents busy hours per day and the number of busy days per year. With the above equation, one can obtain the revenue per unit area by considering the revenue per cell and the number of cells per unit of area.

TABLE II: Values for cost revenue analysis with split 6 and split 7.

Parameters	Without splitting	Split 6	Split 7
BS_{cost}	100%	25%	20%
C_{BS} [€]	5700	1425	1140
C_{BBU+FH} [€]	2000	1067	1333
$C_{BBU+RRH}$ [€]	5700	1482+1140	1000+1425
C_{BH}[€]	2000 (3000 € for fiber instead of FSO)		
C_{inst} [€]	200		
R_{b-ch} [kb/s]	144		
$C_{M\&O}$ [€]	200		
C_{Bh}[€/km^2]	3000		
C_{fi} [€/km^2]	13.01 (2.6 GHz)		
C_{fi} [€/km^2]	10.58 (3.5 GHz)		
C_{fi} [€/km^2]	0 (5.62 GHz)		
Auction [€]	6000000 (2.6 GHz)		
Auction [€]	4880000 (3.5 GHz)		
T_{bh}	86400		
C_b without splitting [€]	2380		
C_b for Split 6 [€]	1281.4		
C_b for Split 7 [€]	1338.4		
R_{Rb} [€/min]	0.0004		
Total area of Portugal [km^2]	92212		
Project duration [Years]	5		

The analysis proposed in this work considers that the costs will be evaluated on an annual basis. Parameters are presented



(a) Comparison of profit in percentage between split 7 and without splitting.

(b) Comparison of profit in percentage between split 6 and without splitting.

(c) Comparison of profit in percentage between split 6 split 7.

Fig. 7: Profit in percentage for 5 years of project for split 6, 7, without and between them, considering also without scenario and both cases VI and VI+BE.

in Table 4. First, we define the price per unit of area as follows:

$$C_{[€/km^2]} = C_{fi[€/km^2]} + C_b \cdot N_{hex/km^2} \quad (2)$$

$C_{fi[€/km2]}$ Represents the fixed terms of the costs, C_b is the cost per BS given by equation 3 and N_{hex/km^2} is the number of hexagonal coverage zones per unit of area and is given by equation 4:

$$C_b = \frac{C_{BS} + C_{Bh} + C_{\text{inst}}}{N_{year}} + C_{M\&O} \quad (3)$$

$$N_{hex/km^2} = \frac{2}{3 \cdot \sqrt{3} \cdot R^2} \quad (4)$$

where C_{BS} is the cost of the Base station (BS), C_{Bh} is the cost of the backhaul, C_{inst} is the installation cost of the BS and $C_{M\&O}$ is the operation and maintenance cost its values are presented in Table II.

We did our analysis based in the main land of Portugal, and we assume the licence value from the auction of ANACOM for the 3.5GHz band, which is 36.90 million €, while for the 2.6 GHz band it is 6 million €, and zero € for the 5.62 GHz unlicensed band, for 20 MHz bandwidth (for k = 3, with 30 lots of 10 MHz). By dividing this cost per square kilometre, by the number of years for the project, one obtains an annual fixed cost of 79.38 $€/\text{km}^2$ for the 3.5 GHz bands [10], as follows:

$$C_{fi[€/km^2]} = \frac{\frac{\text{licence price}}{\text{country area}}}{N_{\text{year}}} \quad (5)$$

N_{year} represents the project's lifetime.

The profit is presented in percentage terms in Figure 7 for split 7 and for split 6 , one can get these results by considering equations 1 and 5 to get profit equation 6. The profit is given by equation 6:

$$P_{ft[€/km^2]=} R_v - C \quad (6)$$

while the net revenue gives the profit in percentage, i.e., the difference between the revenue and cost, normalized by the cost, as follows, equation 7:

$$P_{ft[\%]} = \frac{R_{v[€/km^2]} - C_{[€/km^2]}}{C_{[€/km^2]}} \quad (7)$$

Revenue of VI and VI+BE per km can be calculated according to equation 8.

$$R_{V[€/km^2]} = N_{hex[km^2]*} \frac{R_{b-\sup[kbps]} \cdot 60 \cdot 6 \cdot 240 \cdot R_{R_{b[€/min]}}}{R_{b-ch[kbps]}} \quad (8)$$

Revenues are considered on an annual basis, where we thought six busy hours per day, 240 busy days per year [22], and the price of a 3.1 Mbps channel per minute (corresponding to the price of $\approx$ 1MB), [€/min] = 0.0004, which is very low as compared to the value considered in [23].

Although the curves with the cost and revenue, per square kilometer, as a function of the cell radius, are not represented, we can mention that the VI+BE traffic gives the best revenue per kilometre square compared to VI. The 2.6 GHz revenue is higher for both VI+BE and VI cases than the 3.5 GHz and 5.62 GHz bands. Moreover, the cost for 2.6 GHz, 3.5 GHz and 5.62 GHz are compared with the values of revenue but the cost of 2.6 GHz is lower than at the 3.5 GHz band (and higher than at the 5.62 GHz unlicensed band, meaning that the auction for this band is zero). For all of the frequencies bands, the cost with functional split consideration is less than in the case where there is no functional splitting (without scenario).

With split 6, results for the cost and revenue indicate that the cost for the 2.6 GHz band is lower than for the 3.5 GHz band and higher again than in the 5.62 GHz band.Split six revenues for the 2.6 GHz band for VI+BE and VI cases are higher than in the 3.5 GHz and 5.62 GHz bands.

In Figure 7, the profit for all the frequencies with case VI and VI+BE are shown, where the scenario split seven and without splitting are mentioned with case VI and VI+BE. It is observed that the profit of the split 7 with case VI+BE is higher than split 7 cases VI shown in Figure 7 a). For example, if we look at the 2.6 GHz frequency, in the scenario of split 7, as shown in Figure 7 a), in the case of VI+BE, one gets the most elevated peak of the supported goodput (xcorresponding to PLR of 2%) touches 800% profit for the shortest values of the cell radius of 400 m (microcell or picocell). In the scenario of split 7 with the case VI+BE and VI, for the 2.6 GHz frequency band performs better than all other frequencies.

Figure 7 b) plots the split six profit with case VI and VI+BE for the three frequency bands. Again, it is found that the 2.6 GHz band VI+BE performs better than hen supporting VI alone. For a cell radius of 400 m, the peak profit achieves 900%. Figure 7 c) plots the chart for both split seven and six. It is found that for 2.6 GHz frequency, with VI+BE and split six, the profit in percentage terms is 100% higher than for the 2.6 GHz band with VI+BE and split seven. At 3.5 GHz, with VI+BE with split 6, the profit is 890%, while for 3.5 GHz VI+BE with split 7 it is 788% (almost almost 100% difference). For the 5.62 GHz frequency band, the profit for cell radius of 400 m, with case VI+BE and split 7, is 700%, while for split six radius and a cell radius of 400 m with case VI+BE is 800% which is again 100 percent higher in case of split 6.

VI. Conclusions

The paper provides a complete set of cost/trade-off analyses for functional split seven and split six with two different cases, VI+BE and VI, for three frequency bands (2.6 GHz, 3.5GHz and 5.62 GHz). First, the simulation results are held by deploying the 19 cells. Based on those results, the goodput, the number of supported users and PLR are evaluated for three frequency bands. A cost and trade-off analysis for splits seven and six with the concern of goodput, several supported users and PLR for 2.6 GHz, 3.5 GHz and 5.62 GHz are analyzed. Based on our analysis in the perspective of the VI+BE, the 2.6 GHz frequency band VI+BE supports higher goodput in the range of shorter cell radius (pico cells) with lower PLR. For longer cell radii values, the 5.62 GHz GHz VI+BE, provides higher goodput, but it is not in the range of the pico cells. In comparison, 3.5 GHz VI+BE provides goodput and PLR (lower) better than 5.62 GHz VI+BE in lower value of radius (small cell). For the shortest cell radius values, the best is to select the 2.6 GHz VI+BE to achieve lower PLR and to support a higher number of users and better goodput. Overall, it indicated that the best revenues are achievable with split 6 for 2.6 GHz with case VI+BE, with low cost and higher profitability. It is shown that for cell radii up to 500-600 m the split 6 provides higher revenue and profit compared to split 7 for all frequency bands, with maximum for cell radius of circa 400 m at 2.6 GHz.

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2022 31st Annual Conference of the European Association for Education in Electrical and Information Engineering (EAEEIE) | 978-1-6654-8442-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/EAEEIE54893.2022.9819989

MOOC on "Ultra-dense Networks for 5G and its Evolution": Challenges and Lessons Learned

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***Abstract*—Many of the new mobile communication devices will be things that power and monitor our homes, city infrastructure and transport. Controlling drones thousands of miles away, performing remote surgeries or being immersed in video with no latency will also be a huge game changer. Those are some of the few things that make the fifth generation (5G) a revolution expected to be a thrust to the economy. To that end, the design and density of deployment of new networks is also changing becoming more dense, what introduces new challenges into play. What else will it add to previous generations? The MOOC about Ultra-dense networks for 5G and its evolution has been prepared by the researchers of an European MSCA ITN, named TeamUp5G, and introduces the most important technologies that support 5G mobile communications, with an emphasis on increasing capacity and reducing power. The content spans from aspects of communication technologies to use cases, prototyping and the future ahead, not forgetting issues like interference management, energy efficiency or spectrum management. The aim of the MOOC is to fill the gap in graduation and post-graduation learning on content related to emerging 5G technologies and its applications, including the future 6G. The target audience involves engineers, researchers, practitioners and students. This paper describes the content and the learning outcomes of the MOOC, the main tasks and resources involved in its creation, the joint contributions from the academic and non-academic sector, and aspects like copyright compliance, quality assurance, testing and details on communication and enrollment, followed by the discussion of the lessons learned.**

***Index Terms*—Small Cells, energy efficiency, spectrum and interference management, HetNets, IoT, massive MIMO, cell-free, mmWave, VLC, prototyping, UAV, AR/VR, MOOC**

This work has received funding from the European Union Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie ETN TeamUp5G, grant agreement No. 813391.

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I. Introduction

A. Motivation and objectives

Massive Online Open Courses (MOOCs) are widely available for everybody with an internet connection. MOOCs are designed to acquire new skills, develop your career, and provide high-quality educational experiences to a large audience in a more affordable and flexible way. Millions of people use MOOCs throughout the world, for professional progress, career transition, and basically any professional training. Several universities and institutions have created and shared their own experience on virtual and remote content creation through MOOC development over the years. Authors from [1] submitted experimental findings from the Virtual Instrument Systems in Reality laboratory. The authors of [2] compared the results of several courses on signal processing and digital communication they had created over the years. In [3], a study about MOOCs' effectiveness in improving undergraduate students' performance in a normal Digital Signal Processing (DSP) class was conducted. There is also a discussion in [4] on the advantages and disadvantages of MOOC courses for microelectronics. The number of discussions in the literature is large, but to the best of our knowledge, there was no MOOC focusing on the 5^{th} generation of mobile communications (5G) and its advancement, which led to the creation of the MOOC addressed in this paper.

The project "New RAN TEchniques for 5G UltrA-dense Mobile networks" (TeamUp5G) [5] is a prestigious Marie Skłodowska-Curie Innovative Training Networks (MSCA ITN) in the frame of the European Commission's Horizon 2020 framework [6], with grant-agreement number 813391. The team is investigating the evolution of the 5G wireless communications and has been preparing an extensive MOOC under the scope of "Ultra-Dense Networks for 5G and Its Evolution". The goal is sharing the recent research advances and the knowledge about the main technological innovations and new 5G mobile networks applications. Motivated by MOOCs' role in the scope of higher education while providing a positive impact on student's performance, a well-designed, structured, and open comprehensive accessible online course has been prepared by the TeamUp5G team. As an outcome of this join effort, this paper provides the detailed steps and procedures about the methodology adopted and experienced during the preparation of the MOOC, highlighting the experience acquired, challenges, and potential opportunities.

A. Targeted audience

The MOOC was prepared to be simple, understandable and intelligible to the majority of users. In this sense, it can be used for professionals and students who are related to the research and development of 5G New Radio networks and their evolution. Based on the targets for learning outcomes, the transfer of basic concepts is eloquently expressed for beginners and students to make it easier to understand. People with a background in telecommunications can be familiar with the latest objectives and state-of-the-art research areas in which the EU and related companies are willing to invest, research, and develop. Finally, teachers who want to transfer the fundamentals and basic concepts of the 5G networks to their students can also benefit from this MOOC.

B. Content formatting

The "Ultra-dense Networks For 5G And Its Evolution" MOOC [7] is prepared by 14 Early-Stage Researchers (ESRs) under the supervision of an international team of highly qualified professors from different backgrounds and disciplines. The course is divided into six modules and each module contains five different items to cover a wide range of concepts and enabling technologies for the 5G and future 6G. For each item, learning, evaluation, and motivational materials have been created, as shown in Fig.1.

Video-recorded presentations and textual extensions are the main learning materials. The script documents were prepared to assist the presenter in recording the video and to make text transcription easier on the edX platform. The textual extensions have been devised to present students with both reading and hearing information in addition to the video, along with some extra information. The assessment procedure was developed as a method for reviewing the educational material. It is composed of four question types: true/false, multiple-choice, drag and drop, and input number type. Additionally, open questions after each module encourage students to reflect more deeply on the subject through a forum discussion. In this forum, the students and teachers can interact for learning engagement purposes. In total, roughly 2 hours of material was generated for each item, split among 10 minutes of video content each week, 50 minutes of written information to support the video material, plus 1 hour of questions and forum discussion.

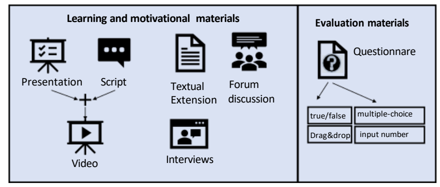

Fig. 1. Block diagram of the content formatting to summarize the contents.

C. Paper Organization

The remainder of the paper is organized as follows: Section II outlines the objective of the MOOC, Section III describes the available resources, Section IV presents the production process, Section V addresses the beta testing and broadcast and Section VI concludes the paper.

I. Objective

The technological development has grown continuously and fast, and the discoveries made by the scientific community and the emergence of new patents bring new challenges at a time when such innovations need to be inserted into people's daily lives. Qualified professionals capable of assimilating new technologies and making good use of them in society are needed. The ESRs, with the help of their supervisors, have observed a gap between innovative evolutionary technologies and the current students' vision over 5G and beyond networks. Addressing this gap is beneficial for students, professionals, and researchers to get updated and understand the latest novel technologies in communication and computer networks. Indeed, after looking more closely at the scope of the necessary road map of the target technologies and their evolution impacting the telecommunications industry, we identified the gaps that could be covered through our MOOC. It is worthwhile to mention that there could be a mismatch between materials provided at university bachelor levels and the online resources from the internet. In general, they do not focus on summarizing the target technologies in a well-developed plan. There is also a mismatch between the research publications which need a prior understanding of the related topic and a very high level of knowledge. They would not be at the level of young students and motivated target researchers.

The goal of this MOOC is to minimize these gaps through efficiently disseminating current research by sharing it into a simple and understandable way to students and young researchers as illustrated in Fig.2. The aim is to deliver this knowledge not only in a high-level view of the 5G mobile network but also exploring the beyond enabling technologies and technical aspects behind each. It is important to consider the need for a creative method for such knowledge sharing to attain effective results. Therefore, the production of the current MOOC package efficiently covers the high-level vision and digs into the technical perspective over the "Ultra-dense Networks for 5G and its Evolution".

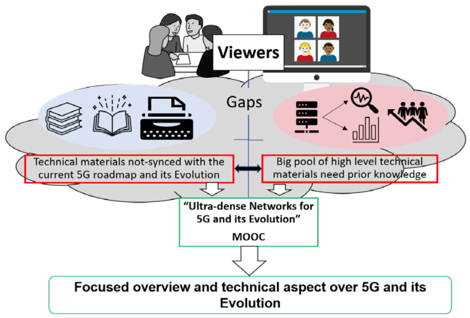

Fig. 2. Showcasing of the objectives (created from free open license CC).

As learning outcomes, this MOOC focuses on understanding, designing and optimizing the 5G heterogeneous small cell ultra-dense networks. Several topics are covered mainly related to 5G and its evolution, its system requirements and new transmission technologies such as beamforming, full-duplex communication, among other. Aspects of interference management and energy efficiency, low power networks, packet and multi-band scheduling, data sensing, spectrum sharing, carrier aggregation, use cases and prototypes (such as augmented and virtual reality), security, unmanned aerial vehicles (UAVs), simultaneous radar and communications (RADCOM), followed by a vision on the future ahead (e.g., 6G and terahertz communications) are also addressed in this MOOC. Students, researchers and practitioners will understand how, motivated by user needs, mobile networks are evolving toward 5G new radios, and how this evolution enable other industrial sectors, such as medical science, transport, entertainment, and education. Practical considerations on these topics are complemented by development and deployment aspects.

Through our produced visionary MOOC, we target the transfer of knowledge in a crystal-clear technical language. After developing a good understanding of the vision for the audience, we share the technical perspective of each key technology player in a smooth manner. It would enable the audience to get the readiness for understanding the latest developments. So, their mind's creativity for contribution in their future careers would be enhanced.

I. Resources

A. Team and project

TeamUp5G is a multi-partner research training network whose beneficiaries come from academic and non-academic sectors to form a structured, international, intersectoral, and interdisciplinary research and training environment for PhD students and young researchers, which is spread in different countries in Europe. It aims to optimize the existing 5G in various domains in terms of throughput, energy and spectral efficiency. Some challenges are the demand for increasing data rates and users served per km^2 and the energy efficiency of the entire system. The goal of the ETN is to propose metrics and develop energy-aware algorithms and protocols to enhance small cells in ultra-dense deployments, making use of massive antenna solutions (mMIMO), millimeter wave (mmWave) bands and Visible Light Communications (VLC), in relevant scenarios, through a combination of analytical work, simulation and prototyping. The details and information regarding our ESRs, their works, and the hosting institutions can be found in [5].

B. University facilities and prior experience

The technical team of Universidad Carlos III de Madrid (UC3M) and some of the involved supervisors had prior experience creating and organizing MOOCs [8]. UC3M provided around 35 different MOOCs both in English and Spanish in the edX and MiriadaX platforms. For instance, the course on mobile communications from the Signal Theory and Communications department at UC3M is published in edX [9]. This MOOC is open to the public, and targets an audience who have no previous knowledge on mobile communications. UC3M experience guided the journey of this MOOC and helped the team to overcome the challenges.

The MOOC was fully recorded at UC3M, utilizing the in-campus Audio/Video (AV) facilities. UC3M has three recording studios, to allow university staff and students to generate teaching materials for various purposes, such as MOOCs or teaching innovation projects. The rooms are provided with all the recording facilities such as HD cameras, a system for mixing and compositing images in HD, special background lighting for generating virtual background, and a teleprompter, as shown in Fig. 3. Concerning the prior experiences in MOOC production, UC3M has experienced staff for editing, mixing, and processing videos. UC3M also provides support for creative process such as covers, course images, and original creation of materials, like animations or even small interactive materials.

Fig. 3. Recording room facilities available at UC3M Leganés Campus.

C. ETN contributions and resources

The MOOC "Ultra-Dense Networks for 5G and its Evolution" results from a great teamwork, supervision and constant guidance. In its production, 14 ESRs and 9 supervisors have participated. From the 14 ESRs, 2 acted as both producers and supervisors of the MOOC, as it happened with 3 of the supervisors of the TeamUp5G project. The other 12 ESRs and the other 6 supervisors acted only as producers and as supervisors of the MOOC, respectively. Each producer was responsible for the content of the MOOC relevant to one's research area. The contributions by the supervisors were invaluable in coordinating the teams, reviewing and providing continuous insights on improving the content. In Section IV, the MOOC's structure and contents are discussed in detail. To ensure high-quality videos and synchronization, UC3M took the responsibility of recording and coordinating the MOOC. Some producers could not travel to the UC3M premises amid the COVID-19 pandemic. For this reason, some of the producers residing in Madrid recorded most of the videos.

I. Production of the MOOC

This Section includes information about the timeline of the main tasks, the creation of the material, the copyright compliance, the contribution from the non-academic sector and the quality assurance. Fig. 4 shows an overview of the timeline, involved tasks, copyright, and quality processes of the production of the MOOC.

A. Main tasks and timeline

The kick-off meeting was in early March 2021, when the MOOC structure was defined. The two major goals were to begin the video production phase in late July 2021 and to finish the entire MOOC in January 2022, in order to begin the lessons at the end of February 2022. Six different modules were identified, each one divided into five items, spanning from introductory topics to more technical ones. To structure the overall work, a table of contents for each item was proposed in April 2021. Based on this defined structure, the production of the presentations and scripts of all the modules was carried out during May and June 2021. A common template was used to maintain a homogeneous environment throughout the entire MOOC. We focused on having as less text as possible in the videos, in order to keep an adequate level of attention. Also, a great number of illustrations (both images and schematics) were used to take advantage of visual learning. In the end, this phase has proven to be the most challenging one, both in terms of research and time. Since the maximum duration for each video was set to 7 minutes, the use of written scripts became essential to ensure compliance with this limitation.

The videos were recorded during June, July, and September 2021, supported by the presentations and scripts. Among the parties involved, only the UC3M had adequate facilities for multimedia production (i.e., filming and video production) and the best way to have a centralized quality control was to record all the videos in the UC3M, using a small selected group of people, containing both instructors and speakers. The filming process took about three months.

Apart from the video, a textual extension as additional studying material was provided. The starting point for the textual extensions was the previously written scripts. In addition, some particularly complex topics were further extended to provide a more complete information. In order to provide a homogeneous result, a common template was used for all textual extensions. The textual extensions were created in October and November 2021.

The evaluation questions were also created during these months. Two different evaluation phases were defined: a test related to each item and a more general test for the entire module. The item-wise test contained 6 questions and a starting point topic (including references) to be used for general discussion purposes. The module-wise test featured 10 questions regarding every item included in the module. Both the item and module tests featured different test modalities (true/false, multiple-choice, drag&drop, and numerical answer), to avoid them becoming tedious.

Besides, a forum discussion was proposed in each item to motivate the active participation of all the students of the MOOC. December 2021 was used as a quality assurance month of the contents produced to correct them and to ensure a proper quality. Finally, the beta testing was realized in January and February 2022. Fig. 4 shows the general timeline of the MOOC.

B. Organization and creation of the study material

The content of the MOOC was divided into six modules, each with 5 items:

- Module 1 – "Ultra-dense networks and small cells" introduces to the audience the ultra-dense network, 5G, new scenarios as well as innovative applications. Besides, it introduces the emerging technologies for 5G.
- Module 2 – "New transmission technologies" focuses on the physical layer transmission technologies like massive MIMO, beamforming and full-duplex technologies, as well as VLC.
- Module 3 – "Interference management and energy efficiency" presents scheduling mechanisms, the cell-free paradigm and approaches for energy efficiency.
- Module 4 – "Spectrum sharing and carrier aggregation" introduces the fundamentals of Carrier Aggregation (CA), the coexistence of small cells and Low Power Wide Area Networks and architectures for spectrum sharing.
- Module 5 – "Use cases and prototyping" presents testbeds, the privacy issue in communications and some insight about AR/VR and immersive rendering.
- Module 6 – "The future ahead" introduces emerging technologies like RADCOM, THz communications, and early discussion about what 6G will be. Besides, it summarizes the own experience of the TeamUp5G ETN.

The content for each of the items was created by the ESRs and supervisors within the TeamUp5G ETN. Besides, it is important to highlight that TeamUp5G members are spread all over Europe. Therefore, the pandemic situation originated by COVID-19 highly limited the planning and brainstorming events for the MOOC. This meant that almost all the content creation process was carried out online, mainly with email exchange and teleconference meetings.

After defining the MOOC structure and recording capabilities (i.e., facilities and human resources), the specific content of each item was discussed between the members of each module, targeting coherence, and avoiding content overlap between items. This discussion was a nice experience that

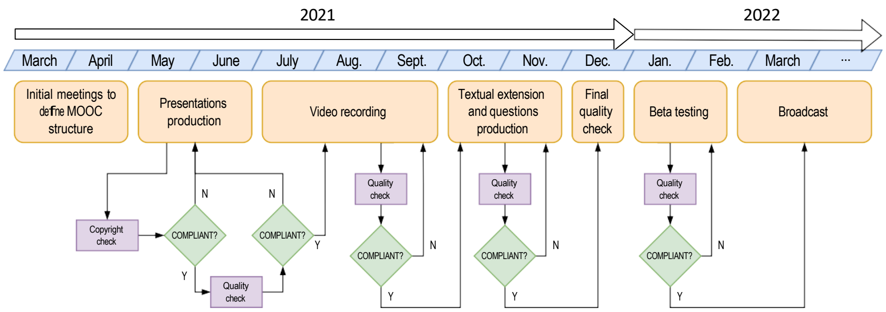

Fig. 4. Overview of the production timeline, involved tasks and copyright and quality processes of the production of the MOOC.

allowed ESRs and supervisors to share knowledge and find ideas for networking. The next step was the writing of the main ideas for the script of the video and initial structure of the items. This initial content was reviewed by the supervisors of each module and feedback was given to the researches in charge of the items. The initial iteration identified several issues like the heterogeneity of the slideshows (e.g., design, animations, fonts, and number of slides) and the use of images with poor quality or subject to copyright. Many of the original images were used in the classroom during teaching activities, so they did not fulfill the required quality for a MOOC. Consequently, in a second iteration, a slideshow/video template and specific guidelines were provided for the content creation, which ensured homogeneity between items. When the slideshows and scripts were ready, the video recording process started, which led to the production team to provide specific guidelines for recording, but induced changes in the already approved slideshows. Some of the main issues found were the use of a large amount of text in the slideshows. Replacing it with illustrations was challenging because of the copyright constraint of the MOOC, explained in the next Section. The videos did not exceed the seven-minute timing constraint and achieved the required presentation quality.

A. Copyright compliance

Any useful lecture requires well designed illustrations to provide useful and complementary visual information to the explained topic. Public and massive lectures as the one in a MOOC not only require the quality and suitability of the selected illustrations to be high, but also to ensure that all of them, with no exception, are copyright compliant. The selection process is more complex, as the content creators not only need to find or produce high quality illustrations but ensure only the ones with appropriate licensing are selected. We mainly used the following sources: commercial or license-free online repositories, proprietary academic or industrial resources, and custom-made illustrations by the MOOC contributors. Even though all the MOOC authors were very cautious with the aforementioned requirements, all the used resources were double checked by the UC3M production team, which validated each resource's license individually.

B. Contribution from the non-academic sector

The TeamUp5G consortium involves multiple non-academic partners which contributed to give the MOOC a practical approach:

- Nokia Bell Labs: the team from Madrid is focused on the study of the most relevant use cases for 5G and beyond ecosystems. Their research is focused on immersive media offloading and industry 4.0. They have produced or revised the lectures related to the description and analysis of 5G use cases.
- PDMFC: a Portuguese company with the goal of providing solutions in areas such as digital transformation, big data, cloud or security. The contributing team have developed the modules related to network security and how it can be improved with the use of machine learning.
- IS-Wireless: a Polish company that targets software-defined 4G and 5G deployments, with a strong support to the Open RAN community. Their knowledge has been gathered in a module focused on cell-free communications.

C. Quality assurance

A successful MOOC requires high quality content, which demands updated and relevant topics, which have to be adequately explained, up to date and with a professional appearance. For this reason, we have followed a multi-layer quality assurance approach. The first quality check came from the authors themselves: we strongly encourage all the authors to make a huge effort to produce high quality content with the goal of reducing the overhead from successive quality checks. Most of the authors were PhD students. Consequently, the second checking layer were their supervisors, which had a crucial role in the development of the MOOC. To add an extra layer for quality checking, we used a peer-to-peer approach, in which the authors and contributors had to check other contributors' work. In every production step, each author had to review at least two other contributions. We believe this process has helped us accelerating the production of the MOOC while ensuring high quality standards. Finally, all the content was checked by the production team, who was in charge of evaluating the quality from the audiovisual point of view. Each of the mentioned layers involved several iterations: feedback was given, and new versions were produced. Quality assurance requires available time and effort, and in this MOOC we have committed ourselves to both of them.

I. Tests and broadcasts

A. Beta-testing

After the MOOC was uploaded to edX, a beta-testing process was done by the producers of the MOOC, to find possible deficiencies. A total of 2 weeks were allocated to this process, and the work was divided among the beta-testers, with at least 3 beta testers (2 ESRs and 1 supervisor) per module, to ensure enough people to review each module. After feedback was provided, any remaining issues were corrected.

B. Communication and enrollment

The dissemination of the MOOC was mainly conducted via social networks, email messages, and webpage announcement. Announcements were done using the TeamUp5G project social networks, and the researches involved in the creation of the MOOC were also invited to advertise the MOOC. Several colleagues in academia and industry were contacted, and the MOOC was announced via specialized mailing lists, such as that of the IEEE Communications Society. In each outreach event where the TeamUp5G members participated, the MOOC was advertised. The industry actors involved in the creation of the MOOC were also involved in the communication. The enrollment started 3 months before the broadcast, which was scheduled for the 22^{nd} of February 2022, and a strong communication campaign started 3 weeks before this date, i.e. the 1^{st} of February 2022. A total of 144 students were enrolled at the start date of broadcast, and it finished with a bit less than 250 students, with a diverse geographical distribution of about 65 countries/regions and a diverse education distribution from secondary school to doctorate, with the masters being the most representative and the secondary the less representative.

C. Broadcast

The broadcast started on February 22nd, 2022. Two ESRs which were part of the main authors, were actively involved in the forums to respond to doubts and to ensure no inappropriate messages were posted. Active participation among students was suggested and positively followed by them, and supported by the two above mentioned ESRs, with positive feedback. Some corrections were made during the broadcast whenever necessary, by supporting on the comments from students.

II. Lessons learned and conclusions

The production of a MOOC involves a great amount of work. The most complex task was not only the production of the content itself, but also the coordination of the producers and supervisors. More than 20 people from 5 different coun- tries have been involved in the production of this MOOC and all the work has been carried out online. Therefore, although our project is composed of great professionals, there were some coordination and miscommunication problems between the supervisors and the content producers causing some delays. Besides, the resources to guarantee the recording quality were available at the UC3M premises in Madrid. Hence, some items were not recorded by the authors but by producers residing in Madrid. All these coordination issues implied that efforts had to be doubled to achieve a high-quality outcome.

MOOC planning is a crucial task. From the beginning, it is necessary to have a well-defined structure with all the expected content, and the resources available to produce this content. The deadlines for the production, review, and acceptance of the content with the expected quality should be properly scheduled. Periodic monitoring should be planned to check the work progress and to ensure there are no doubts on the producers. In addition, the active cooperation of all authors of the MOOC is essential. Although, in general, many of the MOOC producers were not initially aware of the work required to create high-quality content that meets the expectations of a well-prepared audience, they all agree that it has been a rewarding learning experience.

To conclude, the MOOC on "Ultra-dense Networks for 5G and its Evolution" has been presented. We have addressed the objectives, the resources that were available, the production of the MOOC itself and its broadcast. Although there have been some mistakes during content creation and recording, lessons have been learned and important conclusions have been drawn to improve future MOOC recordings.

Acknowledgements

We would like to acknowledge the audiovisual team at UC3M in charge of the edition and the support team in charge of copyright checking and uploading the content to the edX platform. We would also like to acknowledge the work of all the people involved in the development of this MOOC who do not explicitly appear as authors of this manuscript.

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Increasing Reliability on UAV Fading Scenarios

IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received January 6, 2022, accepted January 28, 2022, date of publication February 7, 2022, date of current version March 24, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3149588

Increasing Reliability on UAV Fading Scenarios

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This work was supported by the European Union's Horizon 2020 Research and Innovation Programme through the Marie Sklodowska-Curie Project under Grant 813391.

ABSTRACT Unmanned aerial vehicles (UAVs) are the next technology to be incorporated into a telecommunications network to improve command and control on a large scale in both line-of-sight (LOS) and non-line-of-sight (NLOS) conditions. However, there is still room for improvement in terms of reliability. This paper investigates Constant Packet Combining (CPC) and Adaptive Packet Combining (APC) techniques applied to Unmanned Aerial Vehicle (UAV) communication in the presence of large-scale fading, where the channels are subject to sudden degradation for long periods due to obstructions. We use Single Carrier (SC) Frequency Domain Equalization (FDE) combined with the Iterative Block Decision-Feedback Equalizer (IB-DFE) to handle command and control messages mapped for UAV use cases. We present closed-form equations for the equalization design as well as the performance parameters such as Bit Error Rate (BER), the Packet Error Rate (PER), the throughput, the retransmissions amount, the goodput (the transmission rate without the retransmissions quantity), and the outage probability. Then, we analyze the system performance using correlated, independent, and equal channels. There is a trade-off between the overall available power, throughput, and reliability. For instance, more retransmissions result in higher reliability, power consumption and lower goodputs (effective data rates). CPC validates the transmission system and confirms the improvement of BER and PER parameters without energy efficiency optimization. APC is appealing because it can reduce the number of retransmissions for all channels used with the advantage of meeting energy efficiency requirements by adapting the overall power to the scenario experienced by the UAV.

INDEX TERMS Dynamic networks, disasters, drone simulation, packet combining, reliability, UAV, unmanned aerial vehicles, 4G, 5G.

I. INTRODUCTION

It is essential to have a reliable communication system, especially in unfortunate events, disasters, and emergencies. Hence, the environmental unpredictability and vulnerability in global systems, such as the fixed telecommunication system, has recently gained much attention among the research community in order to improve recovery and resilience mechanisms [1]. UAVs are now a part of our lives across several industries, i.e., the military, corporate logistics, gaming, and city maintenance. Studies from [2] validate UAV participation in the 5G Radio Access Network (RAN), which may improve several services, i.e., cloud, safety/proximity, best effort, high capacity, and mobility. UAV's characteristic features like low-power, low-cost, fast deployment, and Line-of-Sight (LoS) links can benefit from 5G hybrid networks and provide new services in several vertical industries [3]. Reliability is critical when a UAV experiences blind spots or blockages while being stationary or moving aerially either as a mobile base station or a relay. Moreover, transmitting and receiving status updates regarding UAVs' locations, positions and conditions under dynamic, unforeseen situations and environments periodically utilizing Command and Control (C2) Links is essential. This is the next step to ensure drone communication in the Ultra Reliable Communications paradigm for UAVs.

According to Mozzafari *et al.* [4], and Geraci *et al.* [5], three elements estimate blockage probability: the altitude of

The associate editor coordinating the review of this manuscript and approving it for publication was Miguel López-Benítez.

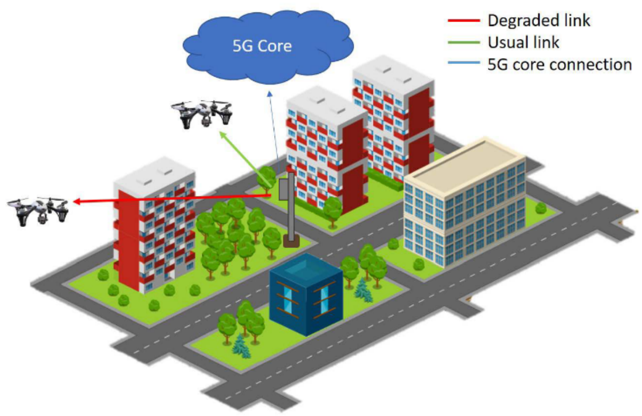

FIGURE 1. Obstruction scenario.

the UAV, the position of the obstacle sources (i.e., buildings, trees, and moving objects), and the relative position from the communication transceiver and receiver. Furthermore, there is a relationship between the high LoS links and the UAV' altitude above the ground. As the obstacle density decreases with altitude, the risk of a blockage (outage) rises inversely proportionate to the drones' height. Consequently, unblocked links are more common in Air-to-Air (A2A) connections at high altitudes than in Air-to-Ground (A2G) links. As we see with cellular communication, these blockages may produce different arrival time intervals between the first and last multipath signal components generating delay spread in drone communication. Furthermore, when the multipath fading channel has a very long path length, the different signals may be received after one symbol duration, which causes Inter-Symbol Interference (ISI). Consequently, this increases the Bit Error Rate (BER) and decreases reliability.

When the user experiences a blockage in fixed telecommunication infrastructure also referred to as a coverage hole or a weak signal zone in the telecommunication infrastructure; the instantaneous reaction is to change positions since in moving scenarios, handovers might occur. Another possibility is to wait for improvements in the channel condition and request retransmissions, which is known as the Automatic Repeat Request (ARQ) mechanism. A third option uses the modulation scheme adaptation at higher layers as this method is well adapted in the communication system.

Assuming the UAV works as aerial user equipment (AUE) connected to a terrestrial network susceptible to interference and obstacles in the environment, the UAV normally follows an optimal precalculated path to complete its mission. The European Union Aviation Safety Agency (EASA) is establishing rules and routes to limit the circulation of UAVs in the sky. Under these guidelines and circumstances, there might be situations where the UAV has poor connection and it cannot change the predefined path in the system to a new one that takes into account the signal strength. Furthermore, objects like trees and barriers are inevitable as the city is in constant transformation. Also, timing is critical in unfortunate circumstances. Therefore, ideally, blockages should not limit UAV operations, either increasing decision-making delays at higher layers or increasing the intermittent UAV connection between two or more smallcells using the Reference Signal Received Power (RSRP) known as handover burn.

According to the definition, reliability means guaranteeing that the transmission BER is lower than 10^{-4}; in other words, users receive 99.0% or more of the forwarded messages. On the other hand, unreliable communication indicates that several channel realizations do not support the transmission rate T. Unfortunately, reliability draws limited attention in the research community, where trajectory optimization and increasing coverage seem to be in the spotlight. Usually, there is a trade-off between the data rate, energy, and reliable communications. Therefore, we explore both network characteristics and discover an optimal trade-off mechanism that is applicable to UAV scenarios. This mechanism adjusts the required power according to the surrounding environment using the information obtained from NACK packets after the retransmission attempt, saving resources by avoiding unsuccessful packet transmission on a continuous basis.

A. RELATED WORK

Most of the work on reliability issues proposes an arrangement between terrestrial and aerial links or optimizes interference, packet sizes, and non payload packets in the control plane, the channel model, and its derivations. For example, in paper [6], the solution to increase reliability was interference management and antenna beam selection. Ming-min *et al.* [7] demonstrates that reliability is proportional to the data rate and accessible energy. The author from [8] establishes reliability criteria that takes into account the minimum amount of links between drones to assure connectivity in failure scenarios. She *et al.* [9] suggests an algorithm for control and non payload packets in the URLLC scenarios. Alef *et al.* [10] derives a mathematical model message delay distribution between vehicles and road-side-units. In [11], the author contribute to a framework to increase reliability in UAVs considering small-scale fading. Han *et al.* [12] proposes a two-step protocol using D2D communications for UAV swarm scenarios. Also, the author of [13] provides some insights about reliability with respect to UAV heights presenting an experimental study where latency was measured in term of reliability e.g expecting packet arrival. Shafique *et al.* [14] evaluates a transmission-reception system using ARQ retransmission and explains several topics in channel modelling including: frame structure, channel modeling, UAV relay analysis, cooperation schemes, and diversity techniques.

In terms of channel modeling, Bithas *et al.* [15] suggests a channel model for drone communications. In [16], a way to improve channel estimation using golden sequences is introduced. Kumari *et al.* [17] describes a way to equalize the channel and the carrier frequency offset using Deep learning techniques. Ji *et al.* [18] uses multiple relay energy harvesting schemes to control large-scale fading in drone scenarios. Khuwaja *et al.* [19] describes the outage probability as a function of user mobility, propagation environment, and channel fading models in UAV scenarios. Ernest *et al.* [20] uses Non-Orthogonal Multiple Access (NOMA) to estimate performance in UAV communication systems over Rician fading channels. In [21] a trajectory optimization in Rician fading channels for data harvesting is proposed. Cui *et al.* [22] presents measurements for Air-to-Ground (A2G) channels across several frequencies. Liu *et al.* [23] characterizes and develops a model for UAV Air-to-Air (A2A) channels with Low-Altitude based on field measurements. The authors from [24] define a model for high-altitude fixed-wing UAV A2G channel communications between aerial base stations. Wang *et al.* [25] suggests coverage optimization considering small-scale and large-scale fading channels. Pereira [26] analyzes packet combining techniques using SC-FDE in terrestrial networks. We propose a different approach mixing reliability with a power controlled mechanism using CPC and APC techniques.

B. NOTATIONS AND DEFINITIONS

Lower-case letters ($a, b, \ldots$) denote scalar variables, boldface lower-case letters ($\mathbf{a}, \mathbf{c}, \ldots$) represent vectors, and boldface capitals (A, B, …) correspond to matrices. Furthermore, lower case letters express time-domain variables and upper case letters indicate frequency-domain letters; Next, $\tilde{x}$, $\hat{x}$ and $\bar{x}$ represent sample estimates, "hard decision" estimates, and "soft decision" estimates of x, respectively.

TABLE 1. Abbreviation list.

Abbreviation	Definition
CPC	Constant Packet Combining
APC	Adaptive Packet Combining
UAV	Unmanned Aerial Vehicle
SC	Single Carrier
FDE	Frequency Domain Equalization
IB-DFE	Iterative Block Decision- Feedback Equalizer
D2X	Drone-to-Everything
BER	Bit Error Rate
PER	Packet Error Rate
RAN	Radio Access Network
LoS	Non Line of Sight
NLoS	Line of Sight
C2	Command and Control
A2A	Air to Air
A2G	Air to ground
URLLC	Ultra Reliable Low Latency Communications
ARQ	Automatic Repeat Request
AUE	Aerial User Equipment
RSRP	Reference Signal Received Power
NOMA	Non-Orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
SNR	Signal to Noise Ratio
IC	Independent Channels
CC	Correlated Channels
EC	Equal Channels
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Intersymbolic Interference
NACK	Negative Acknowledgement
DFT	Discrete Fourier Transform
QPSK	Quadrature Phase Shift keying

C. MOTIVATION AND CONTRIBUTIONS

This paper studies the combination of Constant Packet Combining (CPC) and Adaptive Packet Combining (APC) with the Iterative Block Decision Feedback Equalizer (IB-DFE) and its application to UAV physical layer communications. Additionally, we add Markov chains to simulate blocking situations that may occur in the environment. Finally, we use the SC-FDE technique for transmission, which is advantageous in drone scenarios, as it is more energy-efficient than the Orthogonal Frequency Division Multiplexing (OFDM) technique.

This paper aims to contribute to:

- The analysis of CPC and APC techniques applied to UAVs when the drone's LoS with the base station is restricted. The proposed method reduces the number of unsuccessfully transmitted blocks when the drone experiences fading due to obstacles and barriers. Furthermore, as the transmission/reception system works in the physical layer, and the number of calculated DFTs is the same as the mechanism adopted in terrestrial communications, CPC and APC techniques could be used in real-time scenarios;
- The design of equalization parameters to process transmitted signals;
- The comparison of linear and non-linear equalization schemes where CPC and APC are applied to independent, correlated, and equal channels in UAV settings;
- The closed form equations for the design of equalization parameters, the BER, the PER, outages, as well as throughput in the physical layer;
- The use of signal processing methods to cope with a variety of channel types: independent, correlated, and equal;

The remaining paper is organized as follows: Section II presents the system model. It discusses channels, Markov chain implementation and introduces the theoretical design of the linear and non-linear equalization for CPC and APC usability. Section III explains the system metrics related to performance derived from the simulation. The results of the performance evaluation are presented in Section IV, along with an explanation of them. Finally, Section V concludes this paper.

II. SYSTEM MODEL

The experiment simulates a drone trajectory with constant speed, where obstructions are added in the middle of the path forcing the drone to change direction towards a restrictive communication condition. This circumstance, typically, compromises the link between the UAV and the base station resulting in an unreliable connection. The base station is located at a fixed position (x_b, y_b, z_b) as illustrated in figure 1.

First, we characterize the communication connection between the UAV and the base station. We employ three distinct kinds of complex band channels, denoted by the terms uncorrelated, equal, and correlated to transmit blocks $\{X_k; k = 0, 1, \ldots, N-1\}$ in the frequency domain. Next, we detail the power probability applied to the channel to simulate the obstacles in the scenario. Finally, we deduce the mathematical formulation related to the equalization design and the techniques utilized to change the re-transmissions model.

Considering the channels encountered by wireless devices, uncorrelated channels (independent) perform better. They create a completely new channel after the coherence time and because of that there is a better chance to send the packet successfully than a correlated channel or even the same channel, mainly if the channel is compromised. Although, the channel may remain the same in some instances in the UAV scenarios, using uncorrelated channels between the retransmission attempts might improve performance as we see in wireless communication.

In the proposed experiment, when the system detects a sudden decrease in power at the receiver, it immediately retransmits the block and combines the energy of the lost block with the energy of the re-transmitted one, therefore applying a packet diversity strategy.

For UAVs, the worst-case scenario is duplicating the energy related to the block even though we might have a rejected block. However, the successive retransmissions may contribute to decreases in the effective PER. Additionally, the system can send feedback about changes in the available power to the transmitter to increase the power between retransmission attempts. This last feature improves the goodput rates by reducing the number of retransmission attempts.

A. THE COMMUNICATION LINKS

In the system, the propagation channel that interconnects the terrestrial BSs and UAVs is the linear, multi-path continuous-time complex baseband (tap) channel. Equation (1) calculates the frequency response of the specific channel:

$$H_k(f) = \sum_{l=1}^{L} \zeta_l \exp(-j2f\pi\tau_l) \tag{1}$$

where f is the frequency band and ζ_l^L and τ_l^L are the multipath ray's l_{th} attenuation and the propagation delay, respectively. The system adopts the Rician model in which one of the multipath rays is not susceptible to any loss, and other independent rays can be characterized using Gaussian random variables with a zero mean and a variance of (σ^2_{NLoS}) identically distributed. Without loss of generality, the distance of both devices can be calculated using the 3D Euclidean distance $||d_{bs} - d_{uav}||_2$ equation.

The Independent (IC), Correlated (CC), and Equal (EC) channels' characteristics employed between retransmission attempts in the simulation depend on the multipath factor α. As a result, by including this factor in equation (1), just as we did in equation (9), we may examine the total influence on channels adopted in the point-to-point link.

$$H_k^R(f) = \sum_{i=1}^{N_{rays}} \alpha_i(\tau) + \zeta_{l,d} \exp(-j2f\pi\tau_l) \tag{2}$$

N_{rays} is the amount of multipath components in the simulation. In the IC experiment, all channels use independent slots for each retransmission attempt. Equation (3) describes the IC α parameters.

$$\sum_{i=R} \alpha_i(\tau) \neq \sum_{i=R+1} \alpha_i(\tau) \tag{3}$$

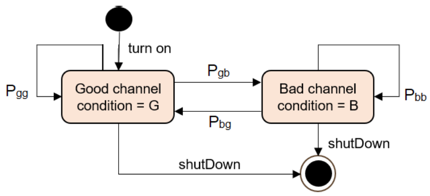

FIGURE 2. Markov chain for channel probability.

Following the same notation, we characterize the correlated channels by applying the equation: (4):

$$\sum_{i=R} \alpha_i(\tau) = \sum_{i=R+1} \alpha_i(t)\phi + \epsilon \tag{4}$$

where ϕ represents the channel correlation between slots and $(1 - \phi^2)(\alpha_i^2)$ provides the variance of the correlated channel and ϵ is the error from the Gaussian model. In EC scenarios, channels use the same multipath configuration for each retransmission attempt as equation (5) depicts.

$$\sum_{i=R} \alpha_i(\tau) = \sum_{i=R+1} \alpha_i(\tau) \tag{5}$$

The results of the retransmission summation depend on the characteristics of the channel throughout each retransmission attempt and the channel characteristics (e.g independent, correlated, and equal) depend on the multipath factor.

B. MARKOV CHAINS FOR CHANNEL PROBABILITY

Using discrete Markov Chain Probability, it is possible to add some randomness in the channel power during the simulation emulating obstacles in the environment. Therefore, we create two different states in the channel that we specify as good and bad, which are G and B, respectively. Equation (6) presents the transition probability. Equations (7) and (8) present the good and bad state probabilities, correspondingly. Figure 2 illustrates the state transition diagram that represents the Markov chain for the channel condition. When the simulation begins, a random variable determines the channel probability for both the initial states and the subsequent transitions to those states.

$$\mathbf{U} = \begin{bmatrix} P_{gg} & P_{gb} \\ P_{bg} & P_{bb} \end{bmatrix}. \tag{6}$$

$$P_G = P_{gg} + P_{bg} \tag{7}$$

$$P_B = P_{bb} + P_{gb} \tag{8}$$

We define the Urban factor *Urb* variable as the percentage of blockage experienced by the UAV that means NLOS connections (in a bad state) during the simulation.

Figure 3 depicts an example of sudden power changes in the receiver due to obstructions while using independent channels. There are four distance intervals where the power decreases abruptly i.e., 0-4m, 6-14m, 18-26m, and 32-33m. The power variation simulates objects in the trajectory according to the probability the Markov chains define. Before and after these periods, power changes according to the corresponding path loss in the distance between the drones and the base station.

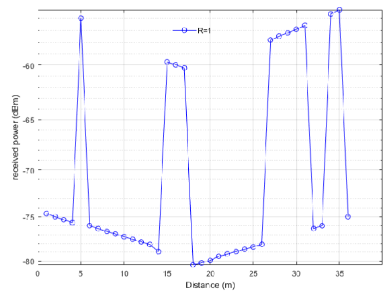

FIGURE 3. Received power changes due to obstructions in the scenario over time.

The frequency domain channel with all the elements is presented in equation:

$$H_k^R(f) = P_{state} \sum_{i=1}^{N_{rays}} \alpha_i(\tau) + \zeta_{l,d} \exp(-j2f\pi\tau_l) \tag{9}$$

where P_{state} is the good or bad channel probability defined by the Markov chain (depending on the LoS or NLoS connection avalability), α is the multipath factor that specifies the channel type between the retransmission attempts.

C. EQUALIZATION AND PACKET COMBINING

Figure 4 depicts the receiver's block diagram, including linear and non linear IB-DFE equalization blocks, and both CPC and APC techniques. When a block is not successfully received, the system tries to recover the packet using a five-step solution as the following describes:

1) The receiver attempts to recover data employing IB-DFE;
2) The receiver instantly requests retransmission;
3) The receiver notifies the transmitter about the power needed to retransmit the block (APC);
4) The receiver combines the energy of the defective block with its retransmitted block (linear scheme);
5) The transmitter increases the transmission power for the next packet (CPC and APC).

In Single Carrier Block Transmission Schemes (SC-FDE), the Fast Fourier Transform (FFT), and the Inverse Fast-Fourier Transform (IFFT) data block conversions $x_n; n = 0, 1, \ldots, N-1$ are done on the receiver side which reduces signal processing in the transmitter. This makes it an option for uplink transmissions. After the decision block, the equalization minimizes the ISI impact related to

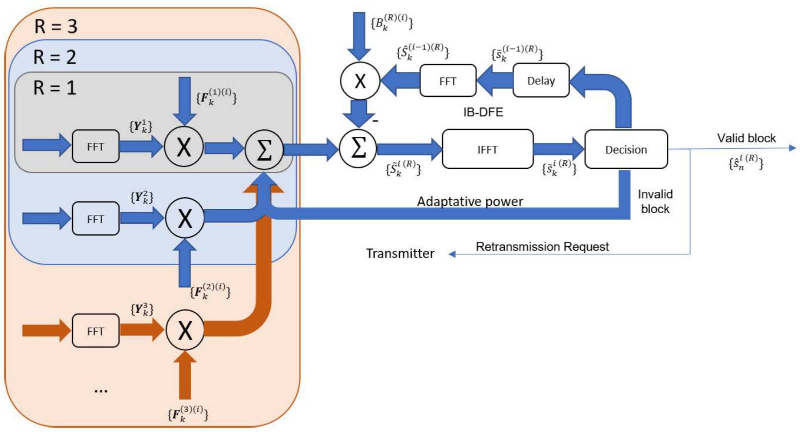

FIGURE 4. Detailed blocks reception with the combining technique.

the delay spread in the transmitted symbols using linear or nonlinear schemes. With linear packet combining, if the transmitted block is still invalid after the equalization procedure, we keep the energy ϕ_k associated with the rejected block in the receiver's memory and immediately add the energy of that block to the energy of the retransmitted one.

In CPC and APC, in addition to the features that linear packet combining provides, the receiver also sends power information from the previous valid received packet as feedback to the transmitter to adjust the power of the next retransmission. The end result reduces the number of necessary retransmissions, increases goodput rates, and the transmitted power may be optimized. Power information is potentially available in Negative Acknowledgment (NACK) packets in the transmitter.

In these simulations, the analysis of retransmission procedures takes place at the physical layer.

The system design begins with the frequency response of the receiver signal after each retransmission without obtaining any adjustment according to equation (10):

$$Y^R_{(k,d)} = H^R_{(k,d)} X^R_k + N \tag{10}$$

where X^R_k is the Discrete Fourier Transform (DFT) of the transmitted signal x^R_k, R is the retransmission attempt, and $N \sim \mathcal{CN}(0, \sigma^2_k)$ is the noise in the channel, while k is an available frequency in the bandwidth.

Our strategy uses the energy received by the successfully transmitted packets between the UAV and the base station to estimate the energy difference while the UAV passes an obstacle. Equation (11) presents the comparison factor used to estimate the power between retransmissions.

$$\phi^R_k = \frac{\sum_{r=2}^{R} |h_r(\tau)|^2}{\sum_{r=1}^{R-1} |h_r(\tau)|^2} \tag{11}$$

where r is the current transmission attempt and the h_r is the respective channel.

Equation (12) highlights the impact of the adaptation factor ϕ^R_k in the received power after each retransmission attempt:

$$Y^{R+1}_{(k,d)} = H^R_{(k,d)} \phi^R_k X^R_k + N \tag{12}$$

The total number of transmitted packets P is defined as $R + 1$. In the three mechanisms (linear, CPC, and APC), the first transmission attempt configures $\phi^1_k = 1$, which indicates that the reception power after retransmission will alter according to the comparison factor that the combiner block estimates in order to improve the reception quality [27].

The matrix multiplication for the reception illustrated in (12) for one frequency $k = 1$ implies that the factor ϕ^1_k is a diagonal matrix and where the main diagonal contains the retransmission comparison factor $diag(|\phi^1_1|^2), \ldots, |\phi^R_1|^2)$.

1) LINEAR EQUALIZATION

By default, SC-FDE employs linear frequency domain equalization to process the symbols available on the receiver side. Equation (13) defines the output samples of the linear FDE block after R retransmission attempts.

$$\hat{X}^{(R)}_k = \sum_{r=1}^{R} F^R_k Y^R_{(k,d)} \tag{13}$$

where the parameter $F^{(i,R)}_k$ represents the feedforward coefficient in both linear and non linear equalization, and $Y^R_{(k,d)}$ represents the received power in equation (10). The system employs the Mean Square Error (MSE) from (15) to estimate the received symbol as follows:

$$MSE = \frac{1}{N_2} \sum_{i=1}^{N-1} E[|\hat{X}^{(R)}_k - X^{(R)}_k|^2] \tag{14}$$

$$= E[|F_1{}^T Y_1^R - X_1^R|^2] \quad (15)$$

Next, we utilize the Lagrangian multiplier to generalize the F_k parameter by minimizing the MSE for each k during the retransmission attempt as in (16):

$$F_k{}^{(i)} = \frac{H^R_{(k,d)}(\phi_k^R)}{(H_k)^2(\phi_k^R)^2(1-\rho^{2(i-1)}) + \frac{(\sigma_N)^2}{(\sigma_s)^2}} \quad (16)$$

where $\rho = \mathrm{E}[X_k{}^{(i-1)}X_k^*]/E[|X_k|^2]$ is the correlation factor between the previously estimated symbol and the current iteration and $(\sigma_N)^2/(\sigma_s)^2$ is the reciprocal of the SNR.

2) NON-LINEAR EQUALIZATION

In non-linear equalization, the system tries to estimate the symbol recursively according to feedback estimation. Two elements define the IB-DFE design, the F_k parameter which is analogous to the linear case and the feedback parameter B_k. After each retransmission, IB-DFE estimates the received symbol in each iteration reducing the ISI and improving the overall system performance in the process.

Equation (17) depicts the detected symbol after IB-DFE according to the received signal using hard decision symbol estimates.

$$\hat{X}_k^{(R)} = \sum_{r=1}^{R}\sum_{i=1}^{I} F_k^{(i,R)}Y_k^R - B_k^{(i,R)}\hat{X}_k^{(i-1)(R)} \quad (17)$$

Non-linear equalizers use feedforward (F_k) and feedback (B_k) parameters to estimate the ISI interference of the detected symbol $\hat{X}_k$ and subtract it in the next iteration of the equalization.

With the help of the MSE criterion and Lagrangian multipliers, it is feasible to estimate the new values for Fk and Bk, assuming that the transmission of one frequency is k.

We define the MSE in each IB-DFE iteration as:

$$MSE = E[|F_1{}^T Y_1^R - B_1\bar{X}_1^R - X_1^R|^2] \quad (18)$$

The F_k parameter is the same in equation (16) Next, we estimate the equation for B_k:

$$B_k{}^{(i)} = F_k{}^R H^R_{(k,d)}\phi_k^R \quad (19)$$

where ϕ_k^R is the adaptation factor. Analyzing the F_k matrix size in equation (16), it is clear that the matrix order increases according to the number of retransmissions ($R \times R$), which is not computationally practical. Authors from [28], and [29] demonstrate that it is possible to reduce the matrix order from $R \times R$ to $C \times C$ where $C \ll R$ by associating the matrix $[IA - BD]$ with its inverse MM^{-1} in both ways $M^{-1}M$. The result of the proposed matrix is $D^{-1}B(I + AD^{-1}B)^{-1}$. Equation (20) depicts the method in (16):

$$F_k^{(R)} = \sqrt{\phi_k^{*(R)}}\left(\frac{\sigma_N^2}{\sigma_X^2} + H^{T(R)}_{(k,d)}\phi_k^R H^{*(R)}_{(k,d)}\right)^{-1} \quad (20)$$

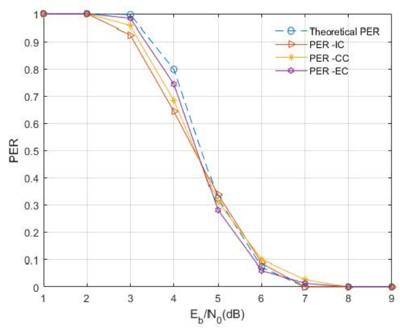

FIGURE 5. PER estimation based on BER results for all channels, R = 1.

III. SYSTEM METRICS

Using the MSE equation from (15), we derive the BER formula for each retransmission using fitting techniques.

$$TheoreticalBER_R = Q(MSE^{-\frac{1}{2}R}) \quad (21)$$

Next, we deduce the PER for each retransmission attempt using fitting techniques for all channels as figure 5 illustrates:

$$TheoreticalPER_R = 1 - (1 - BER_R)^N \quad (22)$$

where N is the FFT size.

When the minimum required SNR is unachievable due to drone distance or the diffraction effects of the obstacles, we immediately ask for retransmissions. The equation for retransmission attempts for the scenario in this paper is:

$$Retr_d = (PER * P_{tot}) - P_{out} \quad (23)$$

where P_{tot} is the total received packets. The linear adaptation system obtains the outage probability P_{out} through estimating the amount of unsuccessful packages after N number of retransmission attempts of the drone's positions in critical locations.

We could keep trying to transmit the blocks until there were no errors. Nevertheless, in practice, if we fail after R attempts, we need to change the transmission parameters (i.e., transmission power, carrier frequency, or the base station, etc.) since the channel is excessively defective. In other words, if the power in the receiver is less than the threshold after summing all the retransmissions, we assume that the block won't be received. Consequently, transmission is suspended.

Therefore, equation (26) defines the P_{out} of the terminal node when P_{thr} is the threshold.

$$P_{ret-total} = \phi_{k_1}Y_1 + \phi_{k_2}Y_2 + \phi_{k_3}Y_3 \ldots . \quad (24)$$

$$= \sum_{r=1}^{R}\phi_{k_r}Y_r \quad (25)$$

$$P_{out} = P_{thr} > P_{ret-total} \quad (26)$$

TABLE 2. Key configuration parameters.

General Parameters	Values
Modulation	QPSK
Equalization Scheme	IB-DFE
DFT-size	N = 1024 symbols
Data lenght	B = 100
Channel Correlation	θ = 0.1-0.8
Realizations non-linear IB-DFE	Iter = 5
Number of rays	L = 16 rays
Distance base-station UAV	d = 10-100
UAV height	H = 10-50
Maximum retransmission attempts	R = 4
Urban factor	Urb = 10% 60% 50%

where Y represents the received power and $P_{ret-total}$ increases or decreases linearly: We could model the increase of power ϕ_k^r in CPC and APC using the power series, but in practice it is not feasible for high values.

In this scenario, we calculate the throughput T including only successful package receptions and its basis is PER:

$$T = (1 - PER)bits \tag{27}$$

where $bits$ is the amount of data transmitted over time. In addition, the equation 30 estimates the delay amongst the initial and the final required transmission attempt to attain optimal power in the linear case without power adaptation:

$$delay = 1 + \sum_{r=1}^{R} pTs \tag{28}$$

where p refers to the amount of retransmitted packets required to achieve the optimal power and Ts in the block delay and the cumulative probability distribution (CDF) on the reveived power over the retransmission attempts in the UAV can be written as:

$$Pr(P_{ret-total} < P_{opt-power}) = \sum_{r=1}^{R} P_{(ret-total)(k)} \tag{29}$$

IV. RESULTS AND DISCUSSION

Below we discuss the results of the proposed systems. First, we consider the linear adaptation. Next, we cover the constant adaptation factor ϕ_k^R, followed by a discussion about the outcomes of dynamic adaptation in response to channel fluctuations.

The channels used in the simulation were the continuous-time complex base-band (tap) channels described in section II regarding equal, correlated, and independent properties between the slots. We used the Quadrature Phase Shift Keying (QPSK) modulation scheme as well as SC-FDE with Linear and Non-Linear Equalization (IB-DFE). The results were obtained using Monte Carlo simulations.

We increased values for the SNR at the transmitter during the simulation. The transmission data length was $B = 100$, and R represented the maximum number of transmissions allowed for each block. As UAVs have limited power, we configured the maximum achievable gain as 20 depending on the scenario. The amount of IB-DFE iterations was $Iter = 5$. The Urban Factor refers to the percentage of obstacles per total area configured in the simulations, For the linear equalization Urb = 10%, for the CPC the configured value was 60% and for the APC the value was 50%. The key configuration parameters are described in table 2.

In the linear adaptation system, the energy of the retransmitted packets was added to the receiver to increase the overall power reception. CPC and APC transmission schemes included the linear adaptation feature and extended it using feedback mechanisms to send information to the transmitter about the minimum power required so it could be adjusted before losing more data.

It used the energy from previous successful blocks and channels to establish the ratio gain. Although we generated random obstacles in the simulation, for the sake of simplicity, we assumed that the sudden slow fading loss was the same for all of the channels.

The signal received overtime was estimated using equation (30):

$$y_{uav}(t,p)_r = h(t,p)_r * x(t)_r + n(t)_r \tag{30}$$

where $x(t)_r$ is the transmitted signal. $n(t)_r$ is the noise associated with the retransmission parameter r. $h(t,p)$ represents the channel in the time domain described in equation (1) as a function of the distance between the drone and the base station.

A. LINEAR EQUALIZATION WITHOUT POWER ADAPTATION

In the linear Adaptive transmission, the energy from each retransmission boosted the total reception power. Taking as an example, the figure 6 depicts how the total energy rose after four retransmission attempts across all channels. As a result, we can see that the overall power during fading (between 20 and 24m and 26m) rose four times between the first and final retransmissions (R = 1 and R = 4), respectively.

Figure 7 and Figure 8 depicts the BER and PER vs the normalized SNR Eb/N_0 per retransmission attempt (R) for each channel (IC, CC, EC) respectively. According to the results in BER, independent channels showed the most significant improvements over the course of four retransmission attempts. They recovered very fast after fading. For example, when comparing the first and second retransmissions, the Eb/N_0 improved from roughly 26 dB to 23 dB when the packet loss was 10^{-3}. This gain was related to the uncorrelation between the blocks in the slot and the Rician channel model utilized in the simulation.

Figure 9 shows the retransmission amount (R1, R2, R3, R4) for each channel (IC, CC, EC) during fading, specifically

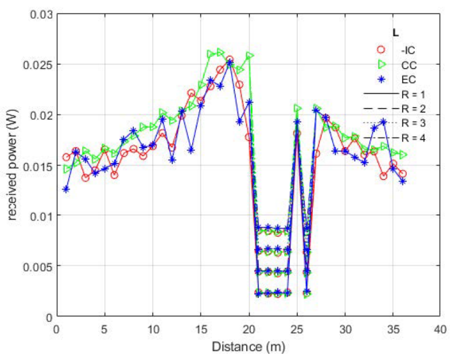

FIGURE 6. **Recovered signal after adaptive packet combining in the second retransmission.**

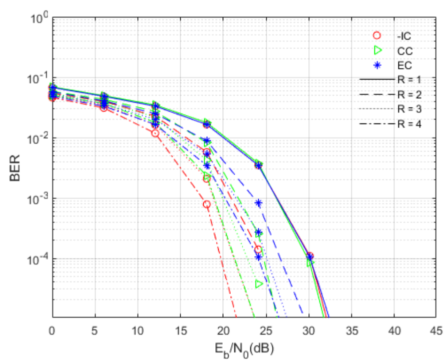

FIGURE 7. **BER - IC, CC, EC channels vs Eb/N_0 over all distances.**

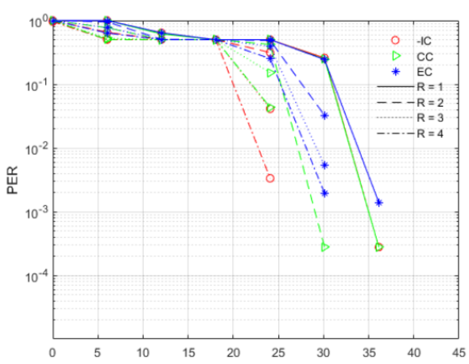

FIGURE 8. **PER - IC, CC, EC channels respectively vs Eb/N_0 over all distances.**

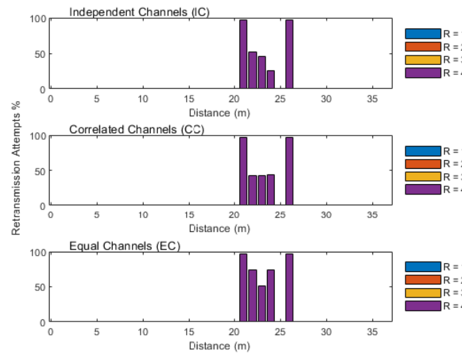

FIGURE 9. **Retransmission attempts % for IC, CC, EC channels during unexpected fading.**

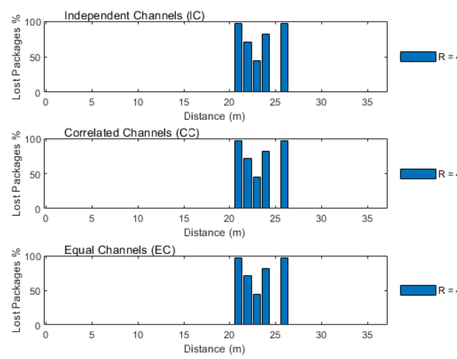

FIGURE 10. **Rejected packets after last retransmission R = 4.**

in the range between 20m and 24m and at 26m. As a result of fading, when the UAV lost packets while passing over obstacles and barriers, the number of retransmissions increased.

As we can see, all of the blocks that were broadcast at a distance of 21m were retransmitted four times in total. The identical thing happens at a distance of 26 meters. The blocks were retransmitted roughly 50% of the time along the other distances. If a block is refused, the algorithm recovers it by adding up all of the retransmission energy it has received. We saw that the performance related to the transmission attempts is similar for each of the channels. Only the correlated channel transmitted fewer packets during retransmission compared to others.

Figure 10 presents the number of rejected packets after the fourth attempt for each channel (IC, CC, EC) during fading. Here, we observed that all channels lost most of the blocks after four retransmissions. This limitation is related to the maximum gain provided by the transmitter and the channel condition in the previous retransmissions.

Figure 11 illustrates delay versus SNR between the first and the transmission and the final transmission required to achieve optimal power for each channel (IC, CC, EC). We see

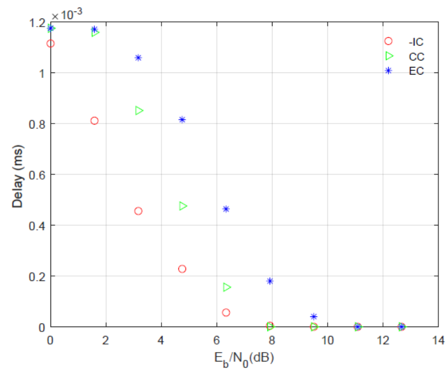

FIGURE 11. Delay between transmitted and received blocks for IC, CC, EC channels R = 4, distance = 50m.

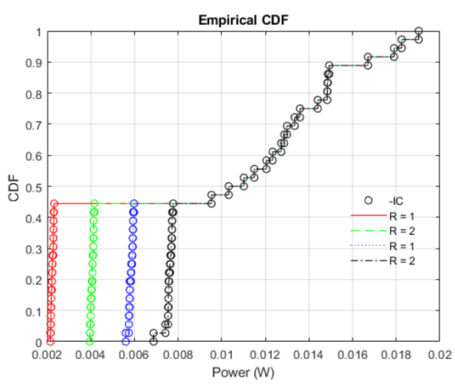

FIGURE 12. CDF received power among retransmissions for IC, CC, EC channels R = 4, distance = 50m.

that the retransmission attempt adds an additional delay to the system for all channels. Also, the delay is reduced as the SNR rises for all channels

Figure 12 demonstrates the CDF versus power for IC channel. When the channel experiences fading, the power is adjusted in each transmission attempt in order for the loss of the signal strength. If no losses occur, the power level remains the same (with no adjustments).

B. NON-LINEAR EQUALIZATION WITH AND WITHOUT CONSTANT POWER ADAPTATION

Figure 13 presents the received power over distance using constant adaptation. In this figure, the fading experienced by the drone is overcome by the retransmission attempt. The number of retransmissions is reduced to only one after the abrupt fading.

Figure 14(a) and 14(b) depict BER results when $Iter = 5$ and ϕ_k^R are 1 and 5. When $\phi_k^R = 1$, it means that the adaptive

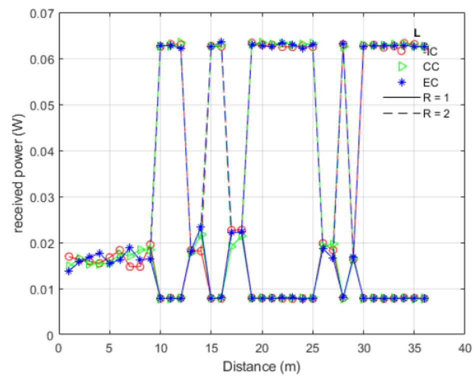

FIGURE 13. Power constant adaptation, $\phi_k^R = 4$. *Iter* = 5.

parameter and fading have the same value. This parameter was used to generate the BER in figure 14(a). In this case, the system relied on the IB-DFE iteration mechanism and the energy summation between blocks to recover from fading.

The first attempt achieved a $BER < 10^{-3}$ when the SNR was between 20 and 25 dB in all channels. In the second transmission, the SNR for all channels improved by at least 3dB. The independent channels improved the most significantly, from approximately 27 to 18 dB. The gain between retransmissions occured because IB-DFE reduced the ISI between the received symbols throughout each iteration, and the unsuccessful energy of blocks was added to the retransmitted ones. On the other hand, the second retransmission achieved a $BER = 10^{-3}$ when the SNR ranged from 3 to 11 dB for all of the channels when ϕ_k^R was five times greater than the fading experienced by the drone.

Figure 15 depicts the PER vs the normalized SNR Eb/N_0 per retransmission attempt (R1, R2) for each channel (IC, CC, EC) when distance = 50m, $Iter = 5$,and ϕ_k^R is 1 in figure 15 (a) and 5 in figure 15 (b).

Figure 16 (a), (b), (c) and (d) show the effects on PER after increasing the Adaptive factor proportionally in each simulation (i.e $\phi_k^R = 1, 2, 4, 10$, respectively). As we increased the power in the system, we saw that the PER results improved for all channels.

When $\phi_k^R > 1$, the number of retransmission attempts necessary were lowered to just one. However, power was squandered since it was raised needlessly in order to adjust the retransmission energy. There were no outages in this situation.

C. NON-LINEAR EQUALIZATION WITH POWER ADAPTATION

Previous results employed a constant ϕ_k^R across all retransmission attempts. With the help of APC, we demonstrate the effect of channel power variations across a range of distances in this section. As shown in equation (6),

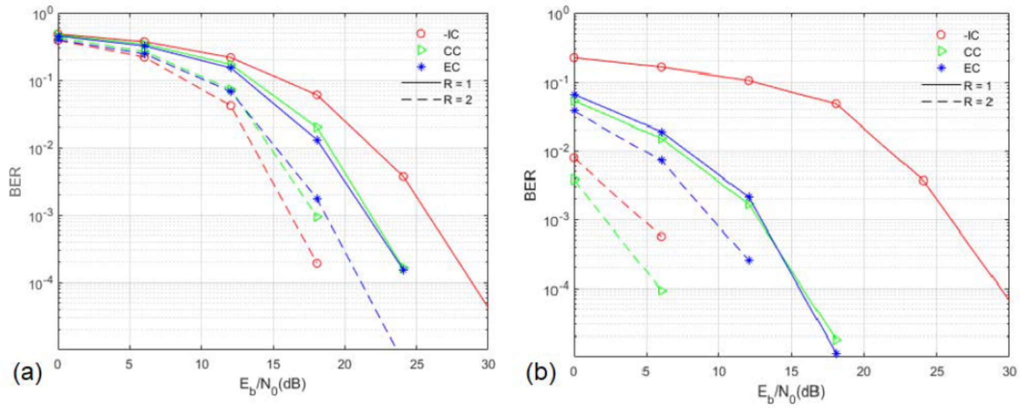

FIGURE 14. BER parameter for each retransmission attempt: distance = 50m, $Iter$ = 5, (a): ϕ_k^R = 1, (b): ϕ_k^R = 5.

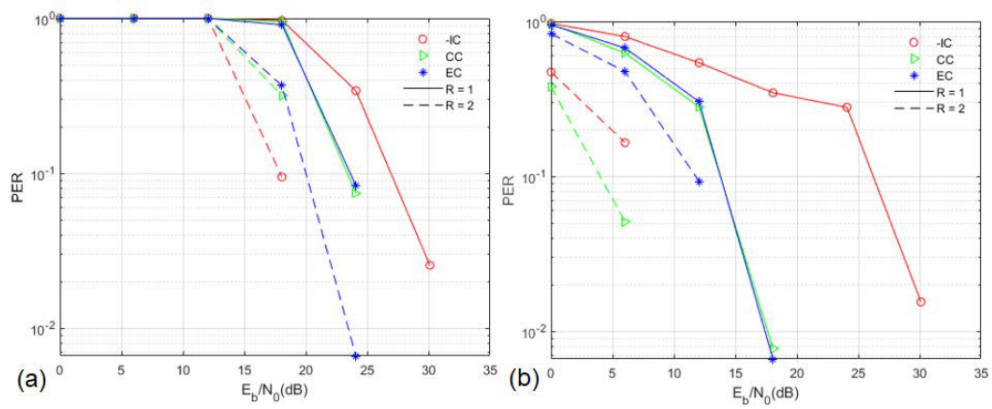

FIGURE 15. PER parameters for each retransmission attempt: distance = 50m, $Iter$ = 5, (a): ϕ_k^R = 1, (b): ϕ_k^R = 5.

the variable ϕ_k^R is computed in real-time and changed in response to the decreasing power in the channel. Its value is updated to assure effective transmission based on prior experience.

For instance, using $10 - 3$W channel power, the drone effectively sent packets during previous fading circumstances. In order to replicate this successful experience, we adjusted our system such that it could provide the necessary power using the channel parameter. The values previously estimated in the receiver are sent back to the transmitter throughout NACK packets. After receiving NACK information, the transmitter adjusts the power to ensure the subsequent successful transmission. In this way, it was possible to optimize power usage until we achieved the maximum power available for communication in the UAV and reduced the number of retransmissions required.

Figure 17 depicts power over distance using the channel adaptation technique. While a usual telecommunication system requires B = K blocks to recover from attenuation of K. In this figure, we see that only one retransmission is needed to overcome fading for all channels used. In UAV scenarios, power is a constraint; consequently, such mechanisms are helpful to recover from packet loss. They are power efficient as they adapt the required power according to the environment using the information available in the NACK and retransmission packets.

Figure 18 presents the results related to BER when $Iter = 5$. We can achieve a $BER = 10^{-4}$ when SNR was approximately 25dB.

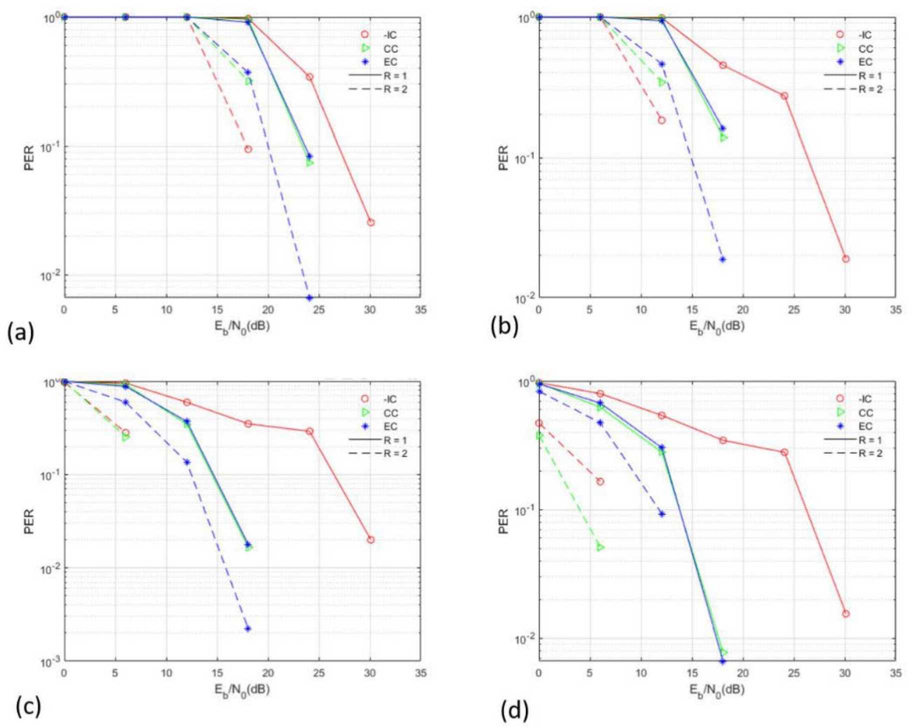

FIGURE 16. Recovered signal after adaptive packet combining in the retransmissions attempts.

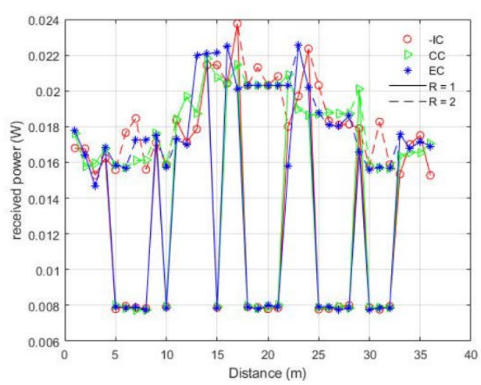

FIGURE 17. Power adaptation for all channels (IC, CC, EC), *Iter* = 5.

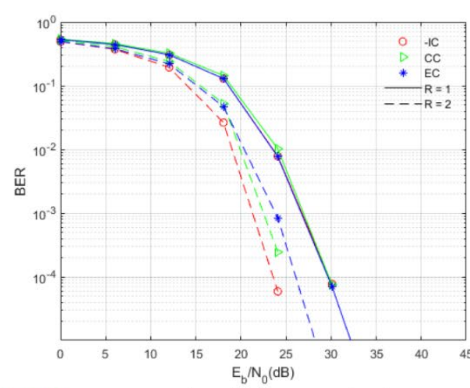

FIGURE 18. BER - IC, CC, EC channels using power adaptation, *Iter* = 5.

The corresponding results related to the retransmission amounts required to send a block successfully in CPC were seen in APC. It was possible to reduce the blocks retransmistted to only one or two depending on the interference and noise levels experienced by the drone. There were no outages and the drone used optimal adaptive communication power according to the changes in the environment.

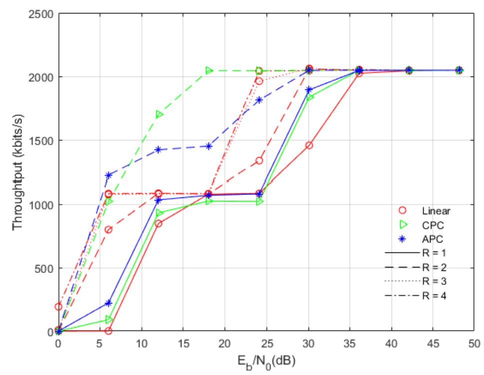

FIGURE 19. **Throughput for independent channel using Linear: *Iter* = 1, $\phi_k^R = 1$, CPC: *Iter* = 5, $\phi_k^R = 6$, and APC: *Iter* = 5 methods.**

The figure 19 highlights the achieved throughput using linear, CPC and APC techniques. According to the figure we see that the overall throughput rises when using CPC and APC with lower retransmission amounts resulting in an improvement in the system's reliability.

The validation of the results is based in the random environment obstruction not only in the small fading parameter.

V. CONCLUSION

Fading channels affect the overall transmitted information in the UAV A2G links, resulting in disconnection and restricting drones' ability to operate in LoS scenarios. We demonstrate that utilizing a linear adaptation to retransmit packets when the drone undergoes fading might boost the chances of successful packet reception. For instance, after four retransmission attempts, the overall power during the fading increased four times. The results for non-linear equalization with constant adaptation - CPC for BER and PER are satisfying. It is possible to reduce the number of transmissions to only one, but the power optimization is inadequate. With channel adaptation APC, on the other hand, there is no power dissipation, and the number of retransmissions per block stays at one. Additionally, Independent channels also provide considerable advantages over SNR ranges and retransmission attempts, as previously mentioned, this means that correct adjustment of the coherence time by the communication system might increase the results of our system. Finally, APC is an alternative to improve communication when the drone is confronted with natural and human-made obstacles and obstructions.

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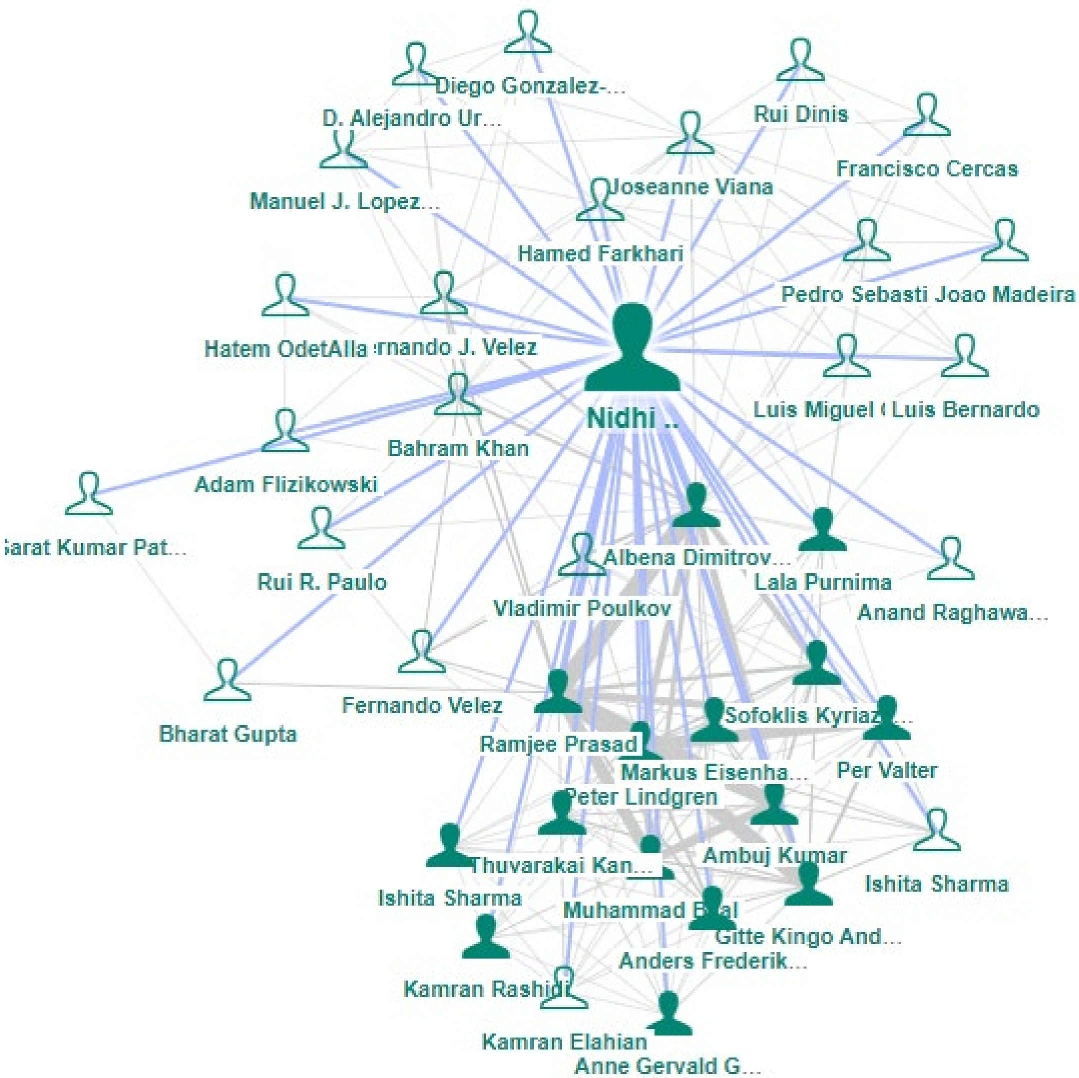
B Appendix B Co-Author Statements

The purpose of this section is to document the required co-author statements for the articles used in this dissertation. The statements are presented in the same sequence as introduced in the dissertation:



INSTITUT FOR FORRETNINGSUDVIKLING OG TEKNOLOGI
AARHUS UNIVERSITET

Evolving Architecture and Emerging Technologies for Beyond 5G and 6G Networks

Declaration of co-authorship*

Full name of the PhD student: NIDHI

This declaration concerns the following article/manuscript:

Title:	6G Enabling Technologies: New Dimensions to Wireless Communication
Authors:	Nidhi; Albena Mihovska

The article/manuscript is: ~~Published~~ ☐ ~~Accepted~~ ☐ ~~Submitted~~ ☐ In preparation [✓

If published, state full reference: IEEE Communications Surveys & Tutorials.Submitted

Has the article/manuscript previously been used in other PhD or doctoral dissertations?
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B. Major contribution
C. Equal contribution
D. Minor contribution
E. Not relevant

Element	Extent (A-E)
1. Formulation/identification of the scientific problem	B
2. Planning of the experiments/methodology design and development	A
3. Involvement in the experimental work/clinical studies/data collection	B
4. Interpretation of the results	B
5. Writing of the first draft of the manuscript	B
6. Finalization of the manuscript and submission	B

Signatures of the co-authors

Date	Name	Signature
16/08/22	Albena Mihovska	(A. Mihovska)

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Signature of the PhD student

*As per policy the co-author statement will be published with the dissertation.

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Trends in Standardization Towards 6G

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
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Declaration of co-authorship*

Full name of the PhD student: NIDHI

This declaration concerns the following article/manuscript:

Title:	Trends in Standardization Towards 6G
Authors:	Nidhi; Bahram Khan; Albena Mihovska; Ramjee Prasad; Fernando J. Velez

The article/manuscript is: Published ✓ ~~Accepted~~ ☐ ~~Submitted~~ ☐ ~~In preparation~~ ☐

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4. Interpretation of the results	C
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6. Finalization of the manuscript and submission	C

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	Albena Mihovska	
	Ramjee Prasad	
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6G Enabling Technologies: New Dimensions to Wireless Communication

Declaration of co-authorship*

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4. Interpretation of the results	B
5. Writing of the first draft of the manuscript	B
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Overview of 5G New Radio and Carrier Aggregation: 5G and Beyond Networks

AARHUS BSS SCHOOL OF BUSINESS AND SOCIAL SCIENCES
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Declaration of co-authorship*

Full name of the PhD student: NIDHI

This declaration concerns the following article/manuscript:

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4. Interpretation of the results	B
5. Writing of the first draft of the manuscript	A
6. Finalization of the manuscript and submission	C

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Survey on Resilient 5G Second Phase RAN Architectures and Functional Splits

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Authors:	Bahram Khan;Nidhi; Hatem OdetAlla; Adam Flizikowski; Albena Mihovska; Jean-Frédéric Wagen; Fernando J. Velez

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Spectrum Sharing and Dynamic Spectrum Management Techniques in 5G and Beyond Networks: A Survey

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Declaration of co-authorship*

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6. Finalization of the manuscript and submission	B

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Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management

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Title:	Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management
Authors:	Nidhi, Albena Mihovska

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Nidhi and A. Mihovska, "Small Cell Deployment Challenges in Ultradense Networks: Architecture and Resource Management," 2020 12th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP), 2020, pp. 1-6, doi: 10.1109/CSNDSP49049.2020.9249560.

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Authors:	Nidhi; Bahram Khan; Albena Mihovska; Vladimir Poulkov; Ramjee Prasad; Fernando J. Velez

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4. Interpretation of the results	B
5. Writing the first draft of the manuscript	A
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	Bahram Khan	[signature]
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	Ramjee Prasad	[signature]
	Fernando J Velez	Fernando José da Silva Velez

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Nidhi, Aug 15, 2022 Nidhi

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Business Opportunities for Beyond 5G and 6G Networks

Declaration of co-authorship*

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This declaration concerns the following article/manuscript:

Title:	Business Opportunities for Beyond 5G and 6G Networks
Authors:	Nidhi; Albena Mihovska; Ambuj Kumar; Ramjee Prasad

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3. Involvement in the experimental work/clinical studies/data collection	B
4. Interpretation of the results	B
5. Writing of the first draft of the manuscript	A
6. Finalization of the manuscript and submission	B

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INSTITUT FOR FORRETNINGSUDVIKLING OG TEKNOLOGI
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Overview of Network Slicing: Business and Standards Perspective for Beyond 5G Networks

SCHOOL OF BUSINESS AND SOCIAL SCIENCES
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Nidhi, Aug 24, 2022 [signature]

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Cost Revenue Trade-off for the 5G NR Small Cell Network in the Sub-6 GHz Operating Band

Declaration of co-authorship*

Full name of the PhD student: NIDHI

This declaration concerns the following article/manuscript:

Title:	Cost Revenue Trade-off for the 5G NR Small Cell Network in the Sub-6 GHz Operating Band
Authors:	Bahram Khan;Nidhi; Rui R Paulo; Albena Mihovska; Fernando J. Velez

The article/manuscript is: ~~Published~~ ☐ ~~Accepted~~ ☐ Submitted ✓ ~~In preparation~~ ☐

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B. Major contribution
C. Equal contribution
D. Minor contribution
E. Not relevant

Element	Extent (A-E)
1. Formulation/identification of the scientific problem	D
2. Planning of the experiments/methodology design and development	D
3. Involvement in the experimental work/clinical studies/data collection	D
4. Interpretation of the results	D
5. Writing of the first draft of the manuscript	D
6. Finalization of the manuscript and submission	D

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MOOC on "Ultra-dense Networks for 5G and its Evolution": Challenges and Lessons Learned

SCHOOL OF BUSINESS AND SOCIAL SCIENCES
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Declaration of co-authorship*

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