A SELF- ITINERANT INTELLIGENT AERIAL RADIO ARCHITECTURE (SIIARA)

FOR COVERAGE AND CAPACITY ENHANCEMENT

A thesis submitted to the
School of Business and Social Sciences,
Department of Business Development and Technology
Aarhus University

In the partial fulfillment of requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2017

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DANSK RESUME

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ENGLISH ABSTRACT

In the past few years, the field of telecommunication has seen a massive growth in the number of mobile subscribers. People nowadays are having a constant reliance on their smartphones and other smart portable devices. This widespread adoption of mobile phones might have severe implications on the service and management ability of the Network Service Providers (NSPs) in the near future. A significant growth in mobile data has been observed at live events, where the subscribers use their phones more often than usual. Large user groups appearing at temporary events of carnivals, festivals, etc., demand high data rates for capturing photos and videos and uploading right away. Under such circumstances, the existing ground infrastructure and the state of the art technologies might fail to function in the devised way. Servicing a large number of crowds, particularly in motion can lead to poor coverage and connectivity to the users, posing a challenge to the NSPs, necessary to combat. Therefore, in this context, the mobility management of users and load balancing in the Heterogeneous Networks (HetNets) needs to be engineered appropriately. The purpose of carrying this research work is to improve the condition of congested base stations during mass user accumulations/ movements and to fulfill the user satisfaction requirements in terms of coverage and capacity deliverables by the network.

In this thesis, firstly, the problem of Place Time Capacity (PTC), characterized by the network overloading occurring at the mass social events, is identified. Further, this Ph.D. research work addresses the PTC challenge through a novel solution based on incorporating intelligence and self-adaptive features into small drones. The study focusses on proposing and examining an alternate solution of utilizing small Unmanned Aerial Vehicles (UAVs) in HetNets to offload the ground base stations, overloaded due to heavy user data emanating during the temporary events. Swarms of ad-hoc networks comprising of small aerial devices mounted with radio equipment can be effectively deployed above the ground to serve the capacity and coverage-hungry crowds. A suitable building block architecture of Hovering Ad-Hoc Network (HANET), a novel approach of utilizing aerial drones into the formation of Aerial-Heterogeneous Network (Aerial-HetNet) and, an extended holistic architecture of Self-Itinerant Intelligent Aerial Architecture (SIIARA), are proposed in this thesis work. The study also presents the need for deploying Aerial Radio Architectures (ARA) alongwith their features, advantages, and functionalities.

In this thesis, we have focused on the *Radio Network Analysis* and *Backhaul Network Analysis*, to validate the usage of the above mentioned aerial architectures. The examination of our proposed ARA has been performed on International Telecommunication Union – Radiocommunication Sector (ITU-R), Urban Macro scenarios. The integration of SIIARA with the ground infrastructure to serve the PTC-generating ground users has been investigated in this work, and the results

show that such a deployment outperforms the existing proposed state-of-the-art solutions and yield enhancement in the cellular coverage and capacity of the network. This study proposes and evaluates an alternate platform of using commercially available drones in delivering ad-hoc cellular services and support the existing infrastructure in extending and improving the connectivity to the moving ground users. An added dimension of presenting business case scenarios in utilizing ARA have also been explored in this work.

Lastly, this research work concludes the complete research work and provides the directions for future research work that can be carried out in this field.

DANSK SUMMARY

I de seneste år har telekommunikationsområdet oplevet en massiv vækst i antallet af mobilabonnenter. Folk har i dag en konstant afhængighed af deres smarte telefoner og andre smarte bærbare enheder. Denne udbredte vedtagelse af mobiltelefoner kan have alvorlige konsekvenser for netværkstjenesteudbyderens (NSP'er) service og ledelsesevne i den nærmeste fremtid. En betydelig vækst i mobildata er blevet observeret ved live events, hvor abonnenterne bruger deres telefoner oftere end normalt. Store brugergrupper, der optræder på midlertidige begivenheder af karnevaler, festivaler mv., Kræver høje datahastigheder for at indhente billeder og videoer og uploade med det samme. Under sådanne omstændigheder kan den eksisterende grundinfrastruktur og de nyeste teknologier ikke fungere på den udtænkte måde. At servicere et stort antal skarer, især i bevægelse, kan føre til dårlig dækning og tilslutning til brugerne, hvilket udgør en udfordring for NSP'erne, der er nødvendige for at bekæmpe. Derfor skal mobilitetsstyring af brugere og belastningsbalancering i Heterogene Networks (HetNets) i denne sammenhæng tilpasses hensigtsmæssigt. Formålet med at gennemføre dette forskningsarbejde er at forbedre tilstanden af overbelastede basestationer under massebrugerakkumuleringer / -bevægelser og at opfylde kravene til brugertilfredshed med hensyn til dækning og kapacitetsleverancer af netværket.

I denne afhandling identificeres først problemet med Place Time Capacity (PTC), der er karakteriseret ved overbelastningen af netværket, der forekommer ved de massale sociale arrangementer. Yderligere, denne Ph.D. Forskningsarbejde henvender sig til PTC-udfordringen gennem en ny løsning baseret på at integrere intelligens og selvtilpasningsfunktioner i små droner. Undersøgelsen fokuserer på at foreslå og undersøge en alternativ løsning af udnyttelse af små ubemandede luftfartøjer (UAV) i HetNets for at aflæse jordbasestationerne, der er overbelastet på grund af tunge brugerdata, der stammer fra de midlertidige begivenheder. Sværmer af ad hoc-netværk bestående af små antenneanordninger monteret med radioudstyr kan effektivt udnyttes over jorden for at betjene kapaciteten og dækningssøgende folkemængder. En passende byggepladearkitektur af Hovering Ad-Hoc Network (HANET), en ny tilgang til at udnytte luftdroner i dannelsen af Aerial-Heterogene Network (Aerial-HetNet) og en udvidet holistisk arkitektur af selvrørende Intelligent Aerial Architecture (SIIARA), Foreslås i dette speciale arbejde. Undersøgelsen viser også behovet for at implementere Aerial Radio Architectures (ARA) alongwith deres egenskaber, fordele og funktionaliteter.

I denne afhandling har vi fokuseret på Radio Network Analysis and Backhaul Network Analysis for at validere brugen af ovennævnte antennearkitekturer. Undersøgelsen af vores foreslåede ARA er blevet udført på International Telecommunications Union - Radiocommunications Sector (ITU-R), Urban Macro scenarier. Integrationen af SIIARA med den grundinfrastruktur, der tjener de PTC-

genererende jordbrugere, er blevet undersøgt i dette arbejde, og resultaterne viser, at en sådan udbygning overgår de eksisterende foreslåede state-of-the-art løsninger og udbytteforbedringer i den cellulære dækning Og netværkets kapacitet. Denne undersøgelse foreslår og evaluerer en alternativ platform for at bruge kommercielt tilgængelige droner til at levere ad hoc-celletjenester og understøtte den eksisterende infrastruktur til at udvide og forbedre forbindelsen til de bevægende jordbrugere. En yderligere dimension af at præsentere forretningsscenarier i udnyttelsen af ARA er også blevet udforsket i dette arbejde.

Endelig afsluttes dette forskningsarbejde det komplette forskningsarbejde og giver anvisningerne for fremtidige forskningsarbejde, der kan udføres på dette område.

ACKNOWLEDGEMENTS

Undertaking this Ph.D. has been a life-changing journey and experience for me, and it would not have been possible without support and guidance received from many people in my life. To begin with, I would like to thank the Almighty God for giving me courage, patience, and endeavour to keep me going for this journey of Ph.D.

Firstly, I would like to thank a great personality and my Supervisor, Prof. Dr. Ramjee Prasad, who is responsible for conceiving the platform of the GISFI-PhD program for Indian students, to pursue their Ph.D studies at Aalborg University and Aarhus University. Throughout these years, he has been inspiring and motivating through his supreme supervisory role. He has not only been a great mentor to me but also as a fatherly figure, to whom I have looked upon through my thick and thin times.

I would like to thank my former Supervisor at Aalborg University, Professor Troels. B. Sorensen. It has been an honor to work with him. I whole-heartedly appreciate contributions of his time, ideas, and suggestions in making my Ph.D research work technically inventive and productive. He has been very supportive of my work and has always encouraged me to perform better. I am thankful to him for helping me in every aspect of my research work, be it academically or any form of support in the Ph.D. study process.

Further, I am thankful to Dr. Ashok Chandra and Dr. Sandip Inamdar, with a dream of shaping the Indian engineering faculty, for giving me an opportunity to work with them. They have encouraged a teacher like me to have an international research exposure and to become a skilled technician in my work field.

My special thanks to my colleague, Dr. Ambuj Kumar, whose immense technical knowledge has helped me to make my research work valuable, interesting, and innovative. Without his superior guidance, advice, and suggestions, it would have been nearly impossible for me to finish my Ph.D. research work in time.

My special thanks to Mrs Jyoti Prasad, who took care of us during our stay at Aalborg. She has been a motherly figure to us, encouraging and motivating to follow our dreams. I am also thankful to Dr. Mrs Neeli Prasad for mentoring us and guiding us through the path of our PhD studies.

Furthermore, I am extremely grateful to my family and friends, who have supported me throughout. I would like to thank my parents, Mrs. Shobha Lala, and Mr. Raj Kumar Lala, my sister, Mrs Jyoti Lala Wadhwa and my brother-in-law, Mr. Nishant Wadhwa, for having a persistent belief in me, encouraging me to follow my dreams and supporting me on all the decisions made by me. I would like to thank my dear husband Mr. Karan Mehta for his constant support, for loving me and standing by me through all my needs. My sincere thanks to my parents-in-law, Mrs. Usha Mehta, and Mr. Prakash Mehta for their support in my studies.

I thank my dear friends, Mehak, Priya, Garima, Akanksha, Lalit, and Preeti, who were always beside me and motivated me throughout.

Lastly, I would like to thank all my school and college teachers, who have inculcated knowledge in me and are responsible for my academic and social upbringing.

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ACRONYMS	***ABBREVIATIONS***
A2A	Air To Air
A2G	Air To Ground
ABS	Aerial Base Stations
APN	Active Probing Network
APT	Amoebic Place Time Response
Aerial-Hetnet	Aerial-Heterogeneous Network
AH	Aerial-Hetnet
ASA	Aerial Sub-Architecture
AoE	Area of Event
AP	Asset Provider
ARPU	Average Revenue Per User
B2B	Business to Business
B2C	Business to Customer
BH	Busy Hour
BM	Business Model
BS	Base Station
BSH	Base Station Hub
CAPEX	Capital Expenditure
CBR	Capacity Based Ranking
CMU	Control And Maneuvering Unit
CN	Core Network
COW	Cells On Wheels
COLTS	Cells On Light Trucks
CP	Connectivity Provider
CRE	Cell Range Extension
DAS	Distributed Antenna System
DBR	Distance Based Ranking
DDBAA	Distributed Dynamic Backhauling For The Aerial Architecture
DL	Downlink
DSC	Drone Small Cells
ENodeB	Evolved Node B
EPC	Evolved Packet Core
FON	Fiber Optic Network
FSO	Free Space Optics
G2G	Ground To Ground

GAVH	Gateway Aerial Vehicle Of HANET
GBR	Group Based Ranking
GPS	Global Positioning System
HANET	Hovering Ad-Hoc Network
HSM	HANET Serving Member
HRM	HANET Relay Member
HBS	HANET Base Station Subsystem
HRS	HANET Relay Subsystem
HSPA	Highspeed Packet Access
HGBS	HANET Gateway Base Station
HetNet	Heterogeneous Network
HN	Heterodox Network
IC	Integrated Circuit
IMT	International Mobile Telecommunications
IMU	Inertial Measurement Unit
IRB	Intelligent Rank Based
ISA	Intelligent Sub-Architecture
ISP	Internet Service Provider
LAP	Low Altitude Platform
LOS	Line Of Sight
LOT	Length Of Tolerance
LTE	Long Term Evolution
M2MC	Member To Member Communication
M2UC	Member To User Communication
M2bsc	Member To Base Station Communication
MBS	Mobile Base Station
MCP	Maneuverable And Controllable Platform
MIMO	Multiple Input Multiple Output
MM	Mobility Management
MMW	Millimeter Wave
MMWC	Millimeter Wave Communication
MVNO	Mobile Virtual Network Operator
MWCN	Mobile Wireless Communication Network
NIU	Network Intelligence Unit
NSP	Network Service Provider
NLOS	Non Line Of Sight
OPEX	Operational Expenditure
OLOS	Obstructed Line Of Sight
PSP	Partner Service Provider
PTC	Place Time Capacity

PTCo	Place Time Coverage
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RAN	Radio Access Network
RF	Radio Frequency
RRM	Radio Resource Management
RSSI	Received Signal Strength Indicator
RU	Radio Unit
SCIDAS	Self-Configurable Intelligent Distributed Antenna System
SIIARA	Self-Itinerant Intelligent Aerial Radio Architecture
SINR	Signal to Noise Ratio
SBS	Small Base Station
SMU	Smart Master Unit
SRU	Smart Remote Unit
SUAV	Small Unmanned Aerial Vehicle
TMCN	Terrestrial Mobile Communication Networks
TV	Television
UAV	Unmanned Aerial Vehicle
UMa	Urban Macro
UE	User Equipment
WCDMA	Wideband Code Division Multiple Access
WCN	Wireless Communication Network
WIAIP	Wireless Itinerant Aerial Infrastructure Provider

CHAPTER 1. INTRODUCTION

This is an introductory chapter and explains the background, motivation, and challenges, burgeoning to this research work. This chapter identifies the research problem, scope, and objectives of performing this research work. We briefly describe the proposed solution and explain its utility features in this chapter. Lastly, the chapter gives an outline of the thesis with an overview of the individual chapters and associated scientific contributions in terms of the paper publications.

1.1. PRELIMINARIES

It is important to study and inspect the network problems and related challenges, before proposing the required solutions to address them. This section gives the background, discussing the source of problems that we have targeted to solve. We further put across the motivation behind the study of this research work, considering all the possible problems and associated challenges.

1.1.1. BACKGROUND

Last decade has seen an incredible growth in the mobile data access (for the internet, intranet peer to peer file exchange and, data streaming, etc.) subscriber base [1]. The internet penetration in the developed economies is seen more in comparison to the developing ones [2]. Over the past few years, the rise in internet user base has been significantly observed in populated countries like India, China, etc. This traffic avalanche majorly owes to the affordability of the smartphones, innovative content and low tariff service offerings from the competing Network Service Providers (NSPs). Reports suggest, that by the end of 2022 there will be 8.9 billion mobile subscriptions, with most of the subscriptions to be registered on WCDMA/HSPA, LTE and 5G networks [3]. The number of mobile broadband subscriptions has grown by around 220 million in the fourth quarter of 2016 to reach around 4.3 billion, reflecting a year-on-year increase of around 25 percent [4]. This growing smartphone adoption and the growing user data traffic will drive the service demands even more in the near future.

Providing a good network access to the users at hotspot locations has always been a notable challenge to the NSPs. Public gatherings and events are potentially packed with a huge number of mobile subscribers, that are observed to use their mobile phones more than usual. Real-time picture/video capturing, sharing, and uploading on the social media websites and excessive usage of other mobile phone applications are majorly responsible for keeping the subscribers occupied on their mobile phones. During temporary events like carnivals, festivals, etc., the mass users do not restrict themselves to fixed locations (in terms of mobility), but also travel from one point to the other.

Figure 1.1, shows typical crowd conditions at the election of the new Pope in the year 2005 and 2013 respectively [5]. The distinguishing feature in both the pictures refers to no usage of phones in the picture of the year 2005, whereas, in the year 2013, everyone is using their phones. This shows that with years, people have increasingly started using their mobile phones and tablets at public gathering events.

Figure 1.1 The Mobile Generation [3]

Further, Figure 1.2 depicts a circumstance that triggers the crowd mobility in enormous amount creating substantial subscriber migration. The first picture (a) depicts a famous festival of ‘Ganesh Chaturthi’ in India [6], where we see a huge crowd in celebration with the idol of the God Ganesha. The end of this festival marks submerging the idol into the water after a rally of people in celebration. Another picture (b), depicts a moving people scenario at a carnival in Salvador, Brazil [7]. The mass accumulations and their movements can be easily visualized in these pictures. Such events are pre-planned and are known to be held yearly, comprising the short-lived and random accumulations of people.

This random subscribers’ accumulation and their movements can significantly degrade the network performance by raising uneven capacity demands and can lead to deterioration of the signals in the impacted area [8]. This erratic and uneven capacity demands that are generated at every location and the movement of mass users result in overloading of the ground base stations as they cross their maximum capacity deliverance limit. Such conditions of user congestions, which are phenomenal and prominent in urban areas have been termed as the Place Time Capacity (PTC) [9].

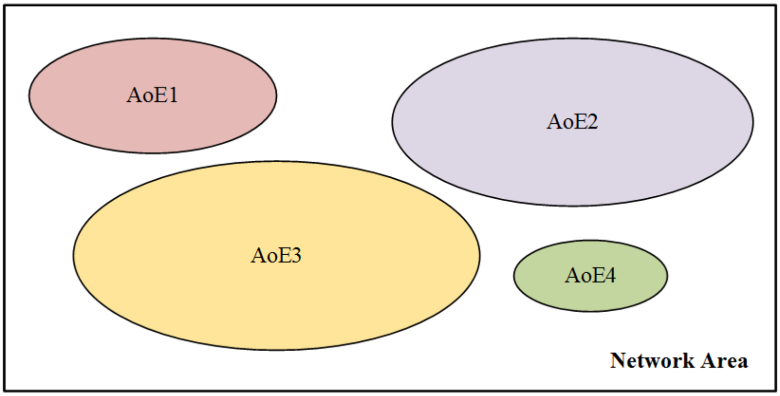
(a) Ganesh Festival in Mumbai [6]

(b) Carnival Salvador, Brazil [7]

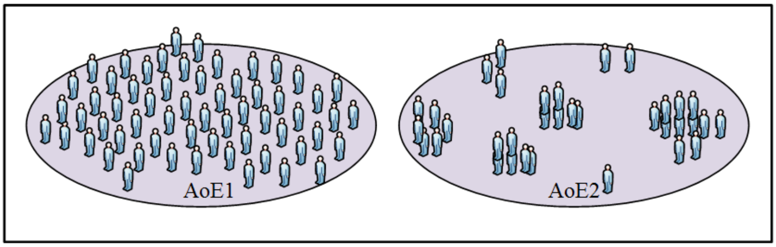
Figure 1.2 Crowded Temporary Events

The area within which the accumulation and movement of mass users take place, we call as the Area of Event (AoE). The AoE can be characterized by the following:

1) Usually packed with a large number of people, attempting to access the cellular network resources simultaneously.
2) There can be more than one AoEs created within a geographical region, representing multiple PTC scenarios of varying user group sizes and diverse areas of AoEs (see Figure 1.3(a)).
3) No fixed user distribution pattern can be observed. The users can follow random, scattered, and uneven distributions (see Figure 1.3(b)).



(a) Varying sizes of AoE in a Network Area



(b) Uniform and Scattered Accumulations at AoE

Figure 1.3 Types of AoEs

Network problems like PTC, have not been given due attention, but are invoking the service operators to look for alternate solutions in providing better service conditions at events of heavy user accumulations and movements.

1.1.2. CHALLENGES

With the maturity of traditional cellular networks, present Heterogeneous Networks (HetNets) are surpassing the 3G networks to provide high capacity and coverage with guaranteed QoS to the end-user services. Network densification boosts the capacity of the network by providing cell-splitting gains due to re-use of the available spectrum. To cope with the rapid explosion of user data, the mobile network operators have already started to push for denser and heterogeneous deployments of small cells (pico, femto, etc.). However, certain challenges need to be mitigated for an effective HetNet functioning, in particular for the 5G+ future networks, which are promising to offer terabytes per seconds of data rate to its plentiful users. The following points are observed to be the visible concerns:

1) *Wastage of new sites*: Mobility of users characterizes the generation of the PTC phenomenon. Installing fixed small sites at the AoE might improve the capacity handling conditions, but as the accumulations and associated movements are volatile and unpredictable in nature at the temporary events, the additional small sites might be under-utilized at all other times. This, in turn, would result in wastage of the new sites and the allocated radio resources.

2) *Appropriate locations to deploy Pico Base Stations*: It is a difficult task for the NSPs to find the most appropriate locations to place the Pico BSs. The dynamic conditions of the network might not sustainable under the fixed network planning.

3) *Increased CapEx and OpEx*: Service operators are required to perform RF planning to find suitable locations to add small cells. Under PTC circumstances, the mobility pattern of users is unknown, and hence prior deployment at unplanned and random locations of small cells shall be futile. Small cell installation comes with the cost and effort required for site rental and backhauling, creating an unnecessary burden on the Capital Expenses (CapEx) and Operational Expenses (OpEx).

4) *Handover Burden*: Small cells increase the number of handovers taking place. Handoffs must be done at the correct time to maintain the QoE, especially when the users are mobile. The moving users might cross the small cells frequently, resulting in the number of handovers bound to be accentuated. The network might get burdened in performing a large number of handovers simultaneously, during the short time intervals.

5) *Complex Backhauling*: The existing backhaul network might get congested and collapsed with the small cell densification and heavy user traffic. Moreover, providing additional backhaul connections has been a challenging problem with small cell networks.

The key challenge for today’s mobile operators now is to identify and correct the capacity shortfalls of the sporadic and mobility-driven high-traffic scenarios. With LTE in its execution phase in most of the developing countries, telecom operators must consider employing intelligent and strategic ways of additional network infrastructure to serve the space-time varying subscriber base. This thesis focuses on serving the challenges mentioned above and presents suitable combating solutions.

1.1.3. MOTIVATION

As for the challenges described in the previous sub-section, we delve into this research work to propose an alternate, easy, and rapidly deployable network provisioning system through aerial vehicles. The *Unmanned Aerial Vehicles (UAVs)*, aka *Drones*, have always fascinated me for their appropriateness in the future technology and business ecosystems, pertaining to their scopes and usage in a wide variety of applications. A significant amount of attention has been given to the Unmanned Aerial Vehicles (UAVs) research field in the recent past. As the name suggests, the UAVs operate without the humans on board. Endowed with advances and improvements in drone technology, Integrated Circuit (IC) technology, autonomous computing and sensing and, the payload carrying capability, the UAVs of any shape and size are being used in almost every field. The wide variety of drone applications includes disaster recovery, search and rescue operations, surveillance, transportation, agriculture, etc. However, with the advent of technology, in the past two decades, the drones have crowning possibilities for applications into civilian and commercial sectors. These days, drones are being used for ground vehicle traffic control and even for pizza deliveries. This has been possible due to advancements in the fields of electronics, chemistry, material science and robotics that have made UAVs lighter and durable with long-lasting batteries, making it more applicable and economical for their non-conventional usages.

Owing to a UAV’s design and execution inception, some researches are being carried out to elevate the applicability of UAVs in the wireless communications. Attempts are being made to integrate network Base Station (BS) and UAV to form an ‘Airborne BS’, forming a Wireless Communication Network (WCN) in the space. The *Facebook Drone Project* [10] and *Google Loon Project* [11] are some of the examples that are performing research to use High Altitude Platforms (HAPs) in the air to provide connectivity to the ground users. Although the area of aerial BSs seems quite futuristic, the flat and static network dimensioning and the conventional contrarieties that are associated with the traditional Terrestrial WCN remain equipotent.

Given the challenges to the telecom operators and service providers, to meet the high data rate service demands of the massive user base, the level of infrastructure is required to be re-considered. Presently, the service delivery is more concentrated to the localized service areas, with the goal of providing high-quality services through the addition of small cells. The key objective of densifying the network with small cells is to provide required services at densely populated urban areas, especially at the hotspots. A traffic hotspot occurs when a BS experiences significant traffic load beyond its capacity to serve, creating concerns about QoS provisions to its connected users. Small cells, on the other hand, are deployed within the coverage range of macro BSs to provide a localized capacity boost in the traffic hotspots. However, there are issues concerning the network densification through small cells (mentioned in the previous sub-section), and their addition does come with bigger challenges to look upon.

My keen interest into UAVs and their application as airborne BS motivated me to study a concept that uses UAVs as a baseline of a network deployment strategy that may work either in coordination with the ground-based network or, as standalone architecture. Their usability into wireless communications has now become an interesting solution. Small UAVs can overpass the loopholes that exist in the wireless infrastructure and enhance the efficacy of the present cellular networks. RF-enabled small drones are being proposed and tested for their utility in the next generation wireless communications. Aerial Base Stations (ABS) can be a robust solution for improving connectivity and extending the radio coverage to the subscribers on the ground. The idea is to have bases station-mounted drones that can work in coordination with each other to form a spatial WCN. The intention is to have a WCN that is easily and readily deployable for the cases where time-honored WCNs fail to perform, such as, during natural calamities or when there are too many users in a network area (like PTC conditions), etc.

We see the following features characterizing the UAV utilization into WCNs:

1) *Ease of Deployment*: Small UAVs can be ported and deployed as per the need. The UAVs can be transported to the target areas in a truck where they can be made to launch and operate.

2) *Three-dimensional Spatial Coverage:* The UAVs with their maneuverability can easily hover in the 3D space. They can be at Line of Sight (LoS) with any of the ground objects.

3) *Increased Payload Capacity*: Advancements in mechanical engineering and drone technologies are supporting higher payload capacity. Compact and battery efficient structures are creating new scopes for deployment in various applications.

4) *Increased Endurance*: Upgraded light weight aircraft materials, high payload capacity, etc. are improving power consumption in a UAV. Moreover, the alternatives of employing solar chips are encouraging longer flight times.

5) Adaptability: The small UAVs can vary their altitudes, speeds, and orientation as per the requirements of the application.

6) *Cost-Effective:* The cost related to manufacturing, maintenance, and repair is becoming relatively low.

7) *Customizability:* UAVs can be customized and incorporated with multiple advanced sensors as per utility and can be driven by intelligent software algorithms.

8) *Reachability:* Small and low-altitude UAVs are easy and fast to reach the target areas, even where the conventional network services fail to reach.

Owing to the features mentioned above, we have employed the use of small UAVs as an effective platform for providing the cellular network services to the moving crowd users and help the existing ground infrastructure to be offloaded during PTC oriented heavy network congestions. To achieve the purpose, I have been trying to timeline my research so that a drone-based BS can be prototyped and analyzed empirically. However, because of the need for coordination with the right vendor, along with the fact that I was a visiting scholar in Denmark, the prototype model was not feasible to build in the given time bracket. Therefore, I decided to build and investigate the idea of airborne BS on soft-platforms (through simulations).

During my first visit to Aalborg University (AAU) in May 2014, I interacted with a research scholar who was working on solving the similar congestion problem in a WCN that arise due to movement and accumulation of a vast number of users. My first paper contribution [9], was with the same scholar, where we have defined the wobbles of congestions that happen here and there across a WCN through users' capacity in demand expressed as a function of place and time dimensions, and named as the Place Time Capacity (PTC; please see section 2.1.2 for a detailed discussion). The Ph.D. dissertation [8], by the same author, successfully identified and investigated the user dynamics as an ever-growing challenge for present and future WCNs and adduced the need for an intelligent network that is sensitive to the user wobbles. In [9], it was shown that until a WCN is non-responsive to the user dynamics, any network implementation is meaningless, from present to future, and across the generations to come of wireless communications.

I contributed in [9], with an intention to extrapolate the concept of our investigations. The concept of time and place dependent capacity requirements that wobble in a WCN area, ideated me to attribute a well-contemplated aerial architecture to mitigate the consequences of PTC for the network situations requiring smooth, iterative, and configurable deployments that are proportional to place and time-varying capacity demands of the network users.

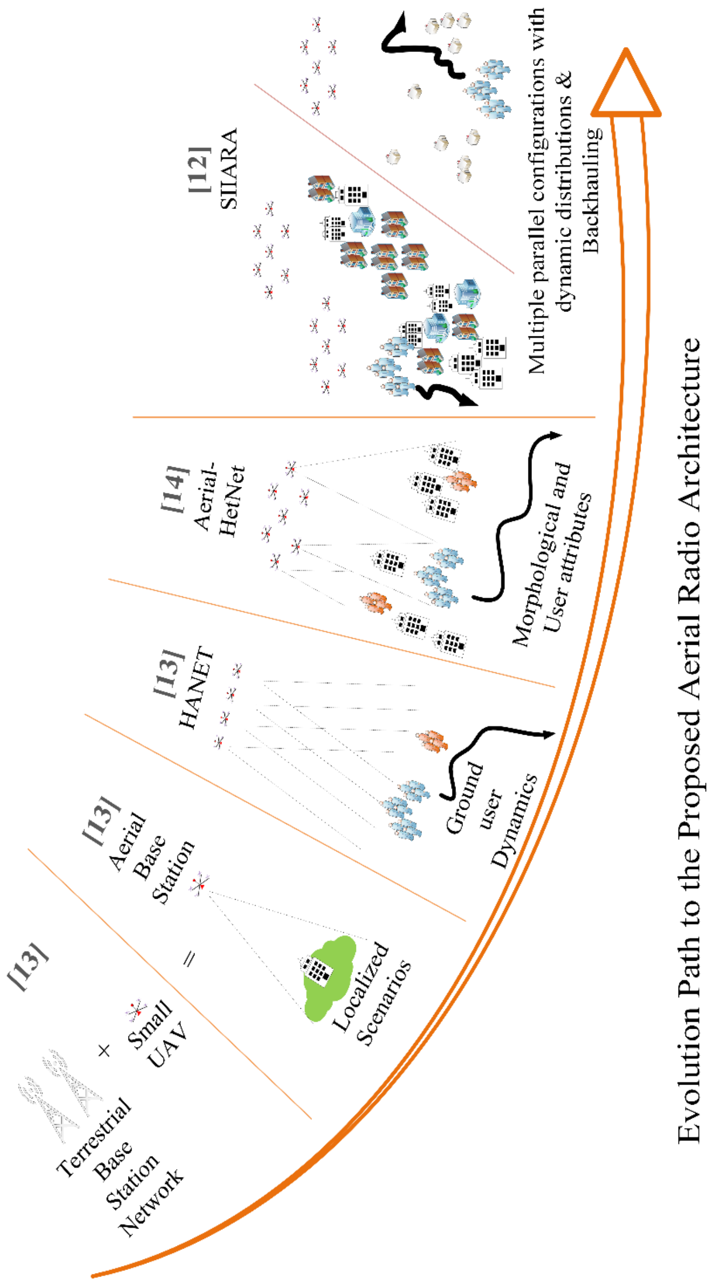


Figure 1.4 The Evolution Path of the Research Work

This architecture is defined in our research as the "*Self-Itinerant Intelligent Aerial Radio Architecture (SIIARA)* [12]", and is a novel concept that has evolved from a single operational entity to a full-fledged airborne WCN. Figure 1.4 above briefly illustrates the evolution stages of the proposed SIIARA, where we see the building block (unit entity) is formed by combining the BS and UAV technologies, defined as a 'Member', which further forms a high-altitude constellation of network above the problematic area, in the form of a "*Hovering Ad-Hoc Network (HANET)* [13]". The HANET then evolves to form an airborne WCN with more intelligence and includes the dynamic backhauling and channel reuse coordination, defined as the *Aerial-Heterogeneous Network (Aerial-HetNet)* [14], which is a novel leap from the conventional terrestrial HetNets. Finally, several Aerial-HetNets, scattered across a pan area, coordinate with each other to form a flexible and expandable itinerant architecture of SIIARA. All these stages are elaborated in detail in Chapter 3 of this thesis.

1.2. PROBLEM DEFINITION

While planning, and dimensioning the network, NSPs target certain user distributions per sub-area that eventually determines the number of sites required and the number of radio channels to be assigned per site. However, under the influence of certain triggers (as discussed in the previous section), the user distributions tend to vary from time to time questioning the original network dimensioning. This pushes the quality of services below the benchmark.

While accumulations of users may become problematic in certain service areas, the motion of the grouped users is a catastrophe to the NSPs. This phenomenon was defined as the Place Time Capacity (PTC) problem in [9] [8]. Deep investigations in solving the PTC problem with ground-based intelligent architecture was presented in [8], wherein the resources were distributed locally based on the accumulations and motions of the users. There were other solutions of pseudo cells, moving cells, COWs (Cells on Wheels) and COLTs (Cells on Light Trucks) that have also been proposed previously. However, all these solutions have the following limitations:

1. *Static Infrastructure*: The ground-based network deployment demands pseudo-permanent infrastructure that reduces the flexibility of the 'accommodative infrastructures' to solve the PTC issue. A lot of resources can be saved if the infrastructure moves along the source of the problem generator.

2. *Indefinite PTC problem*: The solutions for solving PTC accumulation until now have a limitation of offered resources. This means that the infrastructure today can accommodate the extra users up till their resources are available. In [8], although the infrastructure is flexible in terms of resources, still a number of resources available per site cap the network.

The user accumulation is not governed by the available resources or the supporting infrastructure and may proceed indefinitely depending on the type of the trigger. Thus, presently available solutions must be extrapolated in such a way that this indefinite behavior is taken into account.

3. *Reachability*: Currently proposed solutions are limited to serving those areas where the signal power is ample enough to cater the users. However, every corner of the service area cannot be as brightly illuminated with the serving signals as attained near the serving sites, resulting in the formation of weak signal areas and coverage holes. Cell boundaries and edges often witness sparse signal levels. In [9] [8], we have discussed that the PTC phenomenon is majorly observed in the areas where network services are absent than in the areas where the network services are present. Thus, the accumulation of users in and around coverage holes is an adverse condition for both the users and the NSPs. Therefore, the network infrastructure is inadequate to provide services to the accumulations due to its non-reachability.

4. *Expandability*: In concurrence with the indefinite PTC problem, there comes a problem of expanding the presently deployed network infrastructure. As mentioned earlier, the present network architectures are predominantly static in nature and are immune to the network jitters caused due to heavy user accumulations and their mobility in groups. The best possible resolution is to provide COWS/COLTS or new sites, but they have limitations in servicing the PTC conditions (discussed in Section 1.1.1 and Section 2.2.2). Thus, the network lacks in expanding to the time instances of the PTC events.

5. *Cost-Effectiveness*: Many times, where PTC problem occurs regularly at certain locations, the NSPs try to dissipate the problem by installing new sites in the target areas. As a result of this, crowded cities like Delhi and Mumbai (in India), Berlin (Europe), New York (USA), etc. are installed with a lot more sites than actually required to serve the overall subscribers in the cities, which turns out to be a costly affair.

In this thesis, by elucidating intelligent and innovative architectures, we attempt to deal with the challenges and limitations mentioned above in handling and managing the PTC-like situations.

1.3. RESEARCH OBJECTIVES AND CONTRIBUTIONS

The main research goals of this Ph.D. thesis are listed below:

I. To bring into attention and consideration, the network degradation that occurs due to random accumulations and movements of mobile users in groups. We have discussed the problem and analyzed as to why the currently proposed solutions are insufficient to identify and manage the problem.
II. To suggest a solution to service the problem mentioned in (I), discussing the features, advantages, and disadvantages of its deployment.
III. To propose a suitable architecture of "Self-Itinerant Intelligent Aerial Architecture (SIIARA) [12]" supporting the solution (II) to justify its applicability and suitability for the present and future Mobile Wireless Communication Network (MWCN) to solve the problem (I).
IV. To evaluate the proposed solution in a HetNet environment and investigate the impact on the coverage and capacity aspects of the network.
V. To present a business aspect of the proposed architecture and present suitable scenarios with revenue gains.

1.4. THESIS OUTLINE

The Ph.D. thesis is divided into seven chapters. Overviews of the chapters with scientific contributions that constitute the dissertation are summarized as below:

- Chapter 2: *An Overview of the Place Time Capacity Problem* – Chapter 2 is an introductory chapter on elaborating the problem of Place Time Capacity (PTC). This chapter gives a complete overview of PTC and discusses the actual problem with its possible impact on the Heterogenous Networks (HetNets) and what are the drawbacks of NSPs in dealing with such a problem. A PTC evaluation model which has been taken into consideration for evaluating our results is also presented in this chapter. This chapter further gives state of the art (both ground and aerial solutions) to solve network problems and discusses the limitations of the solutions proposed so far in dealing with PTC-like situations.

- Chapter 3: *The Evolution of the proposed Aerial Radio Architecture* – Chapter 3 introduces our proposed solution of the aerial WCN to solve the PTC problem. The chapter begins by discussing the necessities and features that need to be incorporated/inherited from the previous cellular architectures. It then discusses the strategy adopted in handling PTC-like network conditions. This chapter further describes the proposed aerial architectures of SIIARA and its evolution concept of HANET and finally to Aerial-HetNets in detail.

- Chapter 4: *The Radio Network Analysis of the Aerial Radio Architecture* – Chapter 4 presents the first part of the simulation analysis of our proposed aerial architecture. The Radio Analysis of the SIIARA is investigated on an Urban Macro layout specified by ITU-R. This chapter gives the detail on the system model, system assumptions, and specifications. The radio parameters like signal level, SINR, cell range extension, etc. have been examined for cases before and after the PTC creation and HANET deployment (also under the Aerial-HetNet formation). Different use case scenarios were considered, and results were discussed and analyzed.

- Chapter 5: *The Backhaul Network Analysis of the Aerial Radio Architecture* – Chapter 5 presents the second part of the simulation analysis of our proposed architecture. The concept of Distributed Dynamic Backhauling in SIIARA is introduced, and analysis on the proposed Intelligent Rank Based (IRB) algorithm was done for specific case scenarios. The system model and simulation assumptions are described in detail. The chapter ends by giving the suitable results and discussion on the analysis and evaluations performed.

- Chapter 6*: The Business Model Perspective to the Aerial Radio Architecture* – Chapter 6 focuses on providing a business perspective to our proposed solution of aerial architecture. An introduction to the need and objective of presenting the business model view is firstly discussed. A brief state-of-the-art follows the introduction in relation to the business model for future generation networks. Lastly, we give different examples where our proposed architecture can be used for business modeling.

- Chapter 7: *The Conclusions and Future Research Paradigms* – The thesis ends with chapter 7 that starts with giving overall conclusions of the research contributions presented in this thesis work. Then, a discussion on the future research paradigms for the proposed work is presented. Firstly, a physical structure of the proposed aerial HANET Member is proposed and discussed. Lastly, we propose a complementary architecture of HANET with Self Configurable Intelligent Distributed Antenna System (SCIDAS) in the name of 'Heterodox Network' to solve the PTC problem.

1.5. LIST OF PUBLICATIONS

- **Journal Publications**

1) **P. L. Mehta** and R. Prasad, "Aerial-Heterogeneous Network: A Case Study Analysis on the Network Performance Under Heavy User Accumulations," Wirel. Pers. Commun., pp. 1–20, May 2017.
2) **P. L. Mehta,** Ambuj Kumar and R. Prasad, "A Pragmatic Business Approach to a Novel Aerial Radio Architecture," Journal of Multi Business Model Innovation and Technology, River Publishers (Submitted).
3) **P. L. Mehta** and R. Prasad, "Distributed Dynamic Backhauling in Aerial Heterogeneous Networks," Wireless Personal Communications (Submitted).

- **Book Chapters**

1) **Purnima Lala Mehta**, Ambuj Kumar, "Heterodox Networks: An innovative and alternate approach to future wireless communications," Book chapter in Role of ICT for Multi-Disciplinary Applications in 2030. River Publishers, 2016.

- **Conference Publications**

1) **P. L. Mehta**, T. B. Sorensen, and R. Prasad, "Distributed Dynamic Backhauling in Self-Itinerant Intelligent Aerial Radio Architecture," Global Wireless Summit, Nov. 2016.
2) **P. L. Mehta**, T. B. Sorensen, and R. Prasad, "SINR based capacity performance analysis of hovering Ad-Hoc network," in 2016 19th International Symposium on Wireless Personal Multimedia Communications (WPMC), 2016, pp. 147–152.
3) **P. L. Mehta**, T. B. Sorensen, and R. Prasad, "A Self-Itinerant Aerial Radio Architecture for Serving Place Time Variant User Accumulations," Wireless World Research Forum (WWRF), Oct 2016.
4) **P. L. Mehta**, T. B. Sorensen, and R. Prasad, "HANET: Millimetre wave based intelligent radio architecture for serving place time capacity issue," Wireless VITAE, 2015 Global Wireless Summit, Dec. 2015.
5) Kumar, A.; **Mehta, P.L.**; Prasad, R., "Place Time Capacity- A novel concept for defining challenges in 5G networks and beyond in India," Global Conference on Wireless Computing and Networking (GCWCN), 2014, IEEE Global Conference, vol., no., pp.278,282, 22-24 Dec. 2014.

The Table 1.1 shown below illustrates the publication contributions with respect to the chapters of this thesis.

Chapter Details	Publications
Chapter 2: ***An Overview of the Place Time Capacity Problem***	[9]
Chapter 3: ***The Evolution of the proposed Aerial Radio Architecture***	[13][12][14]
Chapter 4: ***The Radio Network Analysis of the Aerial Radio Architecture***	[12][15]

Chapter 5: ***The Backhaul Network Analysis of the Aerial Radio Architecture***	[16][19]
Chapter 6: ***The Business Model Perspective to the Aerial Radio Architecture***	[18]
Chapter 7: ***The Conclusions and Future Research Paradigms***	[13][17]

Table 1.1 Paper Contributions in correspondence to the Thesis Chapters

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[13] P. L. Mehta, Sorensen,T.B, and R. Prasad, “HANET: Millimeter wave based intelligent radio architecture for serving place time capacity issue,” in *Wireless VITAE 2015*, Hyderabad,India.

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[15] P. L. Mehta, T. B. Sorensen, and R. Prasad, “SINR based capacity performance analysis of hovering Ad-Hoc network,” in 2016 19th International Symposium on Wireless Personal Multimedia Communications (WPMC), 2016, pp. 147–152.

[16] P. L. Mehta, Sorensen,T.B, and R. Prasad, “Distributed Dynamic Backhauling in Self-Itinerant Intelligent Aerial Radio Architecture,” presented at the Global Wireless Summit 2016.

[17] Purnima Lala Mehta, Ambuj Kumar,” Heterodox networks: An innovative and alternate approach to future wireless communications,” book chapter in Role of ICT for Multi-Disciplinary Applications in 2030. River Publishers, 2016.

[18] P. L. Mehta, Ambuj Kumar, R. Prasad, “A Pragmatic Business Approach to a Novel Aerial Radio Architecture,” Journal of Multi Business Model Innovation and Technology, River Publishers (Submitted).

[19] P. L. Mehta and R. Prasad, “Distributed Dynamic Backhauling in Aerial Heterogeneous Networks,” Wireless Personal Communications (Submitted).

CHAPTER 2. AN OVERVIEW OF THE PLACE TIME CAPACITY PROBLEM

The first chapter highlighted the problem of Place Time Capacity (PTC) and our proposed solution to solve it. This chapter is centred around elaborating the PTC problem and discussing its impact on the existing network dimensioning approaches in context to HetNets. We discuss state of the art in serving the mass accumulation of people and PTC problem and in context to our proposed solution.

2.1. UNDERSTANDING THE PTC PHENOMENON

In this sub-section, we will first attempt to briefly discuss the conventional approach of planning and dimensioning the network. Next, we review the impact of the conventional dimensioning process related to the HetNet environment. Then we discuss how the NSPs today are failing to cope up with the erratic user demands and the impact of PTC on the network revenue.

2.1.1. NETWORK PLANNING AND DIMENSIONING

In cellular networks, the design and planning process plays a crucial role in determining how efficient the deployed network is. The goal is to provide seamless and quality services to all the subscribed users. The Cellular Network Planning and Dimensioning plays a major role in reducing the Capital Expenditure (CapEx) and Operational Expenditure (OpEx).

The network service area is divided into smaller areas called as cells. The heart of a cellular network is the Base Stations (BS) that facilitates communications with the user mobile phones. These BSs are placed in each cell. The available spectrum is distributed among the cells and reused to utilize the spectrum in the most productive manner. Out of several criteria, a network is designed based on the following generic parameters:

1. Coverage – The area to be served by the network (km^2).
2. Capacity – The ability of the network to provide services to the users with the desired level of quality (erlangs/bits).
3. Peak Traffic Demand – The busy hour traffic during which the demand is highest.
4. C/I ratio – The ratio of wanted carrier signal to unwanted interference signals.
5. Cost – The cost of deploying the network.

Coverage and Capacity are the two most important attributes that well define the effectiveness and performance of any network. Coverage estimation calculates the area where the users can communicate with the BS with the goal to provide sufficient signal quality in that service area. Capacity estimation evaluates the number of sites that are needed to carry the anticipated traffic over the estimated coverage area. The goal is to provide sufficient radio resources to the users. Determining the number of sites needed, site locations and Radio Resource Management (RRM) with the available spectrum with minimum cost are the main aspects that are considered by the NSPs. The network operators plan and dimension the network with prior information like population covered by the cell, traffic distribution, geographical area, available bandwidth, etc. There is a cost associated with installing each BS site, and increasing number of cells in the area means additional cost to the NSPs. The revenue generated by the cell is calculated based on the user traffic estimation. Talking specifically about LTE, frequency and bandwidth, coverage and QoS requirement, target services at cell edge, number of subscribers, traffic profile per subscriber, and indoor penetration are included as inputs to the network dimensioning procedure and Maximum Allowed Path Loss (MAPL), cell range, number of sites and sectors and eNodeB configuration are included as output [1]. The coverage and capacity design estimate the number of sites needed for the target area (refer Figure 2.1).

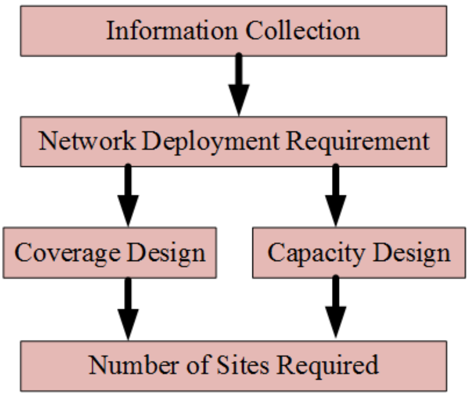


Figure 2.1 LTE Network Dimensioning Procedure [1]

Further, Network Optimization is a necessary task to configure the network in a way that with the available radio resources, the minimum number of sites with maximum user traffic servicing is obtained under dynamic network conditions.

2.1.2. THE PLACE TIME CAPACITY (PTC) PHENOMENON

We have introduced the problem of Place Time Event [9], which in context to network capacity that has been termed as Place Time Capacity (PTC). At crowded events, the users cause spiky demands and experience data traffic volumes greater than the regular days [3]. There are too many users trying to access the radio resources at the same time, resulting in connection failures and low internet connectivity. The subscribers experience lower speeds while accessing their mobile services. Each cell is allocated a certain amount of frequency channels to service the estimated users. The migration of users from different cell areas to a concentrated service area creates an overloading situation for the BSs. The number of users in a BS’s service area increases beyond the maximum serving capacity of the BS. In such conditions, the traffic demand exceeds the traffic supply by the BSs, but only for limited amount of time. As the crowd travels, other BSs become congested. This volatile and transitory phenomenon of congestion occurring at the BSs, due to the irregular and heavy user traffic demands is called as the Place Time Capacity (PTC) problem [1]. More the number of subscribers more is the capacity demand and more the intermittent travel behavior the subscribers show, and hence more is the coverage and capacity demand.

Figure 2.2 illustrates the PTC problem. The diagram shows three base station towers with their coverage footprints. The grouped users are depicted to be moving from the coverage area of Base Station-1 to Base Station-2 and finally to Base Station-3. The PTC is generated due to the high-capacity demand of the moving users at a time (T) and position (P) of the travel. As shown in this figure, at (T1, P1) and (T2, P2) the groups users travel through the coverage region of Base Station-1, at (T3, P3), (T4, P4) and (T5, P5) the users travel through coverage region of Base Station-2 and lastly at (T6, P6) and (T7, P7) the users travel in the coverage region of Base Station-3. Consequently, the subscriber creates the need for the capacity, throughout the path it traverses and generates the Place Time Capacity (PTC) problem [2].

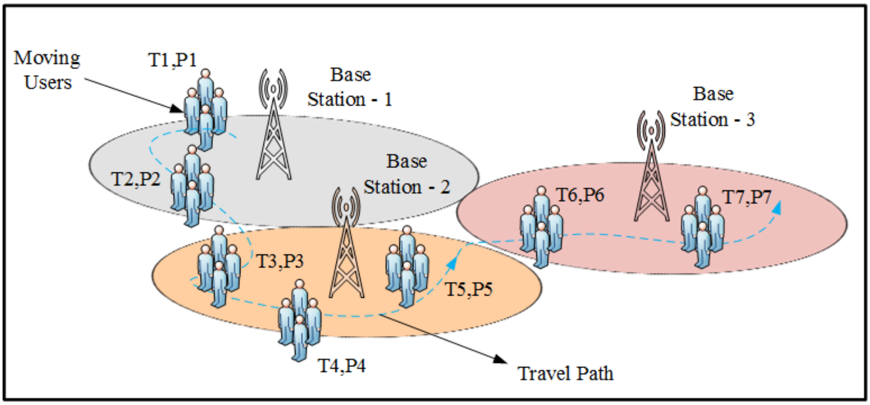


Figure 2.2 The Place Time Capacity Problem

2.1.3. THE PTC PROBLEM IN HETNETS

To service the exponential growth of subscribers, small cell networks are becoming popular. The Heterogeneous small cell networks (HetNets) are typically composed of multiple Radio Access Technologies (RATs) that are comprised of Macro Base Stations (MBS) with high transmit power and large cell radius and Small Base Stations (SBS) with low transmit power and small cell radius [3]. The main idea of state-of-the-art Heterogeneous network architecture is that the macro base stations fulfill the coverage requirements and the small cells (pico, femto cells) fulfill the capacity needs of the network.

Apart from the tasks mentioned in the previous section, Mobility Management (MM) is another central facet to be managed by the NSPs. However, deployment of HetNets introduces some challenges and handling MM is one of them. The PTC causing users in the network are not static in their movements but are dynamic. The users cross one cell area to the other while moving, creating the need for Handover (HO). The deployment of small cells increases the complexity of MM in HetNets leading to less reliable handover execution in HetNets. There are numerous cells within HetNets, and with user mobility, the quality of signal fluctuates resulting in handover failures [4] [5]. The LTE technology supports a high degree of mobility of users and can exacerbate the HO burden due to a large number of people moving together in groups. We see the group mobility patterns of mass users occurring at temporary events of carnivals, festivals, and random accumulations at events like marathons, public gatherings, sports events, etc. Mass moving users make the handover management in HetNets even more complex. Figure 2.3 below illustrates this problem in a HetNet environment consisting of the Macro cell (in pink), Micro cell (in purple) and Pico cells (in green). We show a group of users crossing the cell boundaries of multiple cells while moving, arising the need for multiple handovers at a given instant of time.

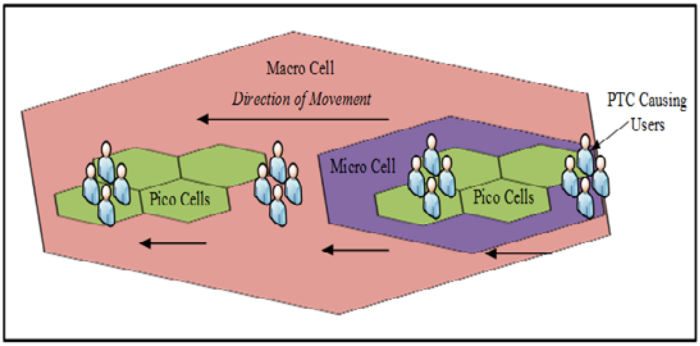


Figure 2.3 Handovers taken by a Group of Mobile Users

Load Balancing in HetNets is another aspect of dealing with under mass moving subscribers. A sufficient number of users must associate with the respective macro cells or small cells depending on the highest received power. More fixed small cells will make it difficult for the balanced loading amongst the different cells in the area. Moving users will complicate the load balancing and burden the network with frequent user associations resulting in poor connectivity to the user while in motion.

Although, the NSPs configure the BSs to cater the high capacity demands, known as the Busy Hour (BH) traffic. However, under the extreme influx of users, there are no radio resources left with the BS to service the extra users converging into its service area. Moreover, as the number of subscribers within a geographical region remains the same, there are other BSs with low load conditions due to the migration of users from its cell area. This creates and imbalance in load in the entire network region. Such phenomenon can frequently be observed in populated countries like India and China and metropolitan cities like Delhi (India), Shanghai and Beijing (China), New York and Chicago (USA), Berlin (Europe), etc. where the number of people per sq. meter are quite high. Future mobile communications are required to accommodate well the scores of moving users with varying QoS requirements and demanding seamless mobility [6].

Therefore, we postulate that the future 5G HetNets need a dynamic network infrastructure to consider the aspects mentioned above of the network problems.

2.1.4. SHORTFALLS OF THE NETWORK OPERATORS

As mentioned in Section 2.1.1, the NSPs plan and configure the network as per the maximum traffic generated in the area, which in turn is proportional to the estimated number of users. The main problem lies with the fact that NSPs do not consider the huge spiky demands concentrated to a specific region of the network. As the accumulations and their movements have no specific travel patterns, NSPs fail to prepare the network for the uneven and untimely heavy data demands. The AoE can change from one place to the other and can be created at different times, hence the PTC denomination.

Densifying the AoE with small cells might not be an appropriate solution (as discussed in Section 1.1.1). Moreover, adding more bandwidth to the entire network to deal with the extra traffic will be quite an expensive solution. Usage of radio resources has their own limitations. The NSPs are lacking the adoption of congestion control mechanisms to deal with the unprecedented rise in heavy traffic leading to unavailability of radio channels and congested backhaul links.

The NSPs must consider the 'high data demands on the move' while configuring the network. The need today is to deploy need-based user-centric service delivery that adequately provides high data rate services and fulfill the QoS requirement while on the move. As the wireless devices are evolving, the strategies and solutions must also evolve to accommodate the dynamic conditions of the underlying network.

2.1.5. EVALUATING THE PLACE TIME CAPACITY

In this sub-section, we will attempt to discuss how a simple PTC model is taken into consideration for evaluating our results.

Following are the parameters considered:

1. The capacity demand per user in bps (B).
2. The length of time the user was active (T_{tot}).
3. The length of time the user was static (T_{static}).
4. The length of time the user was in motion (T_{mov}).
5. The distance traveled by the user during T_{mov}, as one set of observations.
6. A total number of users with individual parameters mentioned above.

Further, following are the assumptions taken into account:

- All the users in a cluster are assumed to have same throughput demand (1 mbps, 2 mbps, and 4 mbps…etc.).

- The below formulation is used to evaluate the PTC at the AoE:

$$\overrightarrow{PTC_u} = \sum_{k=1}^{K} B \int_{T_{mov_{ku}}^{-}}^{T_{mov_{ku}}^{+}} \overrightarrow{v_{ku}}(t_{mov_{ku}})\, dt + \sum_{z_u=1}^{Z_u} \widehat{p_{z_u}}(\tilde{t}_{z_u}) B T_{static_{z_u}} \tag{2.1}$$

where,

- $\overrightarrow{PTC_u}$ is the PTC generated by the uth user, and the accent (or arrow) indicates that it is a vector entity.
- $T_{mov_{ku}^{-}}$ and $T_{mov_{ku}^{+}}$ are the beginning and end time instances (stamps) of the $T_{mov_{ku}}$ duration; the suffix '*u*' represents the time values of the uth user, and '*k*' represents the kth duration of all 'K' quantum of movements.
- $\overrightarrow{v_{ku}}$ is the velocity with which the uth user is moving in the area at the kth duration of itinerancy. Also, $\overrightarrow{v_{ku}}$ is the function of $t_{mov_{ku}}$ which is kth the time of movement for the uth user.
- Z_u is the number of times the uth user has taken a pause in the movement, with z_u being the variable for Z_u.

- $\hat{p}_{z_u}$ is the unit position vector, expressed in the location coordinate values, indicating the location of the uth user where it has taken zthhalt in the movement, $\hat{p}_{z_u}$ is the function $\tilde{t}_{z_u}$which is the time stamp of the zth halt duration and the marker of$\tilde{t}_{z_u}$can be placed at any instance in the duration. As an example, if the user 12 makes a 7th halt during 14:07 to 14:31, then $\tilde{t}_{7_{12}}$ can be any marker between 14:07 to 14:31 as decided by the system. In present investigation, the beginning time stamp is considered. Hence for our case, $\tilde{t}_{7_{12}}$ = 14:07.
- $T_{static_{z_u}}$is the duration of the uth user for the zthhalt. In the case discussed above, $T_{static_{7_{12}}}$= 24 minutes.

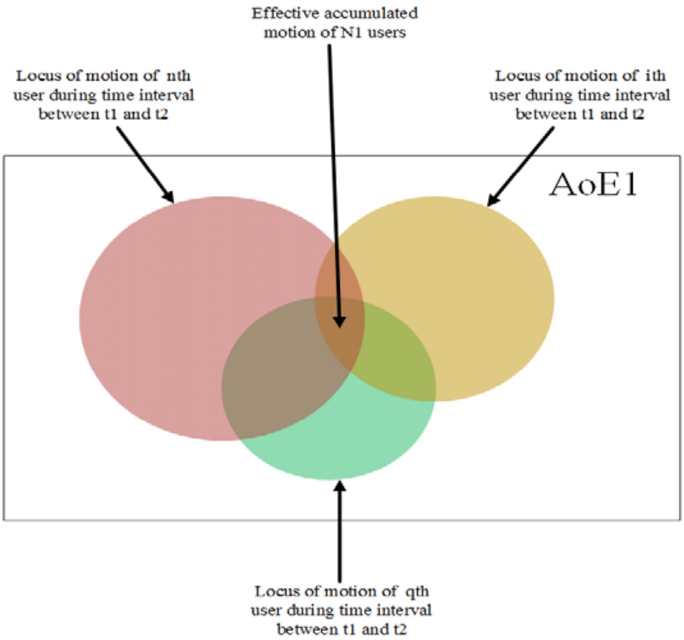
It is quite clear from equation 2.1 that the first term on the right-hand side represents the place iterations and the second term represents the time iterations.

For a total of N users in the AoE, the severity of PTC can be identified with the number of users that coincide collectively at popular locations. Due to this reason, the quantities mentioned in the equation 2.1 are vectors and the position vector $\hat{p}_{z_u}$is introduced in purpose to make the second term vector. This is because, the magnitude of the PTC quantities may be the same, however with every new position, the PTC value is different and adds up to the total PTC.

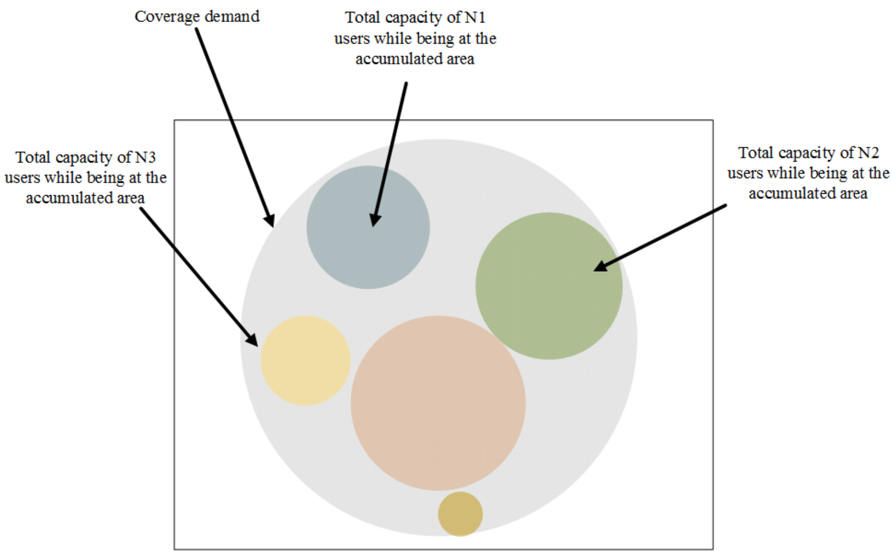
Figures 2.4 and 2.5 of Venn diagrams below represent the above discussion and illustrates the effective accumulation of the users in motion at a particular AoE. Each set represents the locus of the nth, ith and qth user between time intervals t_1 and t_2. The users within the AoE do not have specific patterns of movement. The size of each set represents the degree of freedom of movement of the users. The union represents the effective accumulation for a given time duration that results in the generation of PTC phenomenon.

Figure 2.4 illustrates the formation of multiple and concurrent user clusters at AoE. The user clusters can have varying capacity demands owing to different sizes within the AoE. The span of these clusters in the same vicinity show the coverage demand at the AoE.

Figure 2.5, illustrate how we evaluate PTC based on the total PTC demand. The spatial separation between user clusters may affect the network dimensioning for our proposed architecture in Chapter 3. We also include the concept of Place-Time Coverage (PTCo) in terms of simultaneous accumulation of clusters at different locations which may inflate the BS demand (discussed in next chapter).



(a) Effective accumulation of the users



(b) Coverage and Capacity demand at AoE

Figure 2.4 Crowded Events

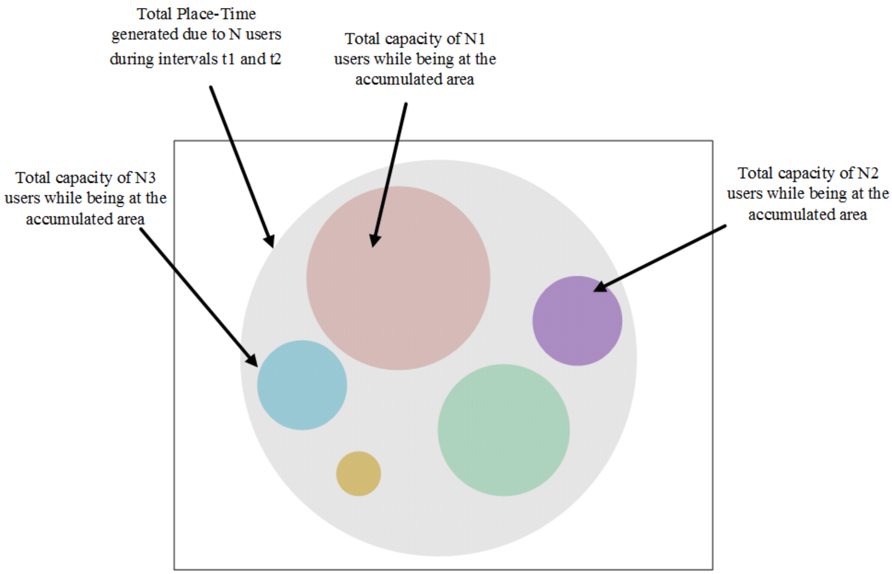


Figure 2.5 Total PTC Demand

2.1.6. IMPACT OF PTC ON THE NETWORK HEALTH AND REVENUE

These days, the revenues coming from mobile subscriptions are decreasing, and on the other hand, the subscriber growth and demand and usage are increasing. The NSPs are under constant pressure to meet the heavy user demands and still have a decent gain in the revenues. Since the deployment of 4G LTE architecture, there has been a revenue shift from voice services to data services (broadband, video i.e. multimedia applications).

The revenue is directly proportional to the amount of traffic generated. More and more operators are now deploying HetNets. However, network densification for the future networks, might not lead to densification of the users in context to the PTC scenarios. The point to note here is that adding small cells does not necessarily mean an increase in the capacity handling and revenues. Under PTC conditions, the number of users in the geographical region remains the same, which means the heavy data rate demands arise from localized regions in the network and the rest of the network is pretty much non-unutilized. Lack of quality service provisioning in the AoE will affect the revenue generation as the accessibility to the radio channels is limited, leaving many users with no radio resource allocation. Furthermore, there is a loss of revenue from the other sites not falling in the AoE due to the absence of the majority of the users that have migrated to the AoE region.

2.2. BRIDGING THE GAP

Before presenting our solution, in this subsection, we will describe the solutions that were proposed previously to serve the PTC problem. We shall also discuss our proposed solution of UAVs with argumentation on why it might be suitable to serve the PTC congestion problem.

2.2.1. CONVOLVING APPROACHES

The dissertation [7], corresponding to its confabulatory investigations on the Place Time Capacity and Coverage (PTC^2) and its implication on network dimensioning, proposes an architecture entitled "Active Probing Feedback Based Self-Configurable Distributed Antenna System" (or SCIDAS in short), that configures according to the Place-Time convolved behavior of the Mobile Wireless Communication Network (MWCN). The SCIDAS architecture has a Cloud Radio Access Network (C-RAN) based modular architecture. Each module, termed as SCICELL, has two components, SCIDAS Node (or SCIN) and SCIDAS Wireless Access (or SCIWAN). In SCIN, there exists intelligent module, along with the network core that works in coordination to disseminate the resources distinctively among the remote sites through Remote Radio Heads (RRHs) via the Optical Fiber Network (OFN) in the area.

Therefore, unlike the conventional MWCN architecture, the SCIDAS architecture can manipulate the resources distribution according to its "wish." The distribution is iterative, meaning that the resources can be re-distributed and redirected to RRHs of different sites within the network, at various time stamps. The Active Probing Module (APM), which is collocated with the RRHs at each network site, allows SCIDAS to sense the environmental variabilities and send it over the same OFN. This to-and-fro communication of the core with the individual RRHs at all network site locations enables the SCIDAS architecture to instruct individual RRHs to behave as per APM's observations. Thus, the distribution of network resources (or channels) among the network sites can be densified or rarefied according to the PTC^2 wobbling across the area.

The dissertation is a unique work on its own, incorporating the Place Time variances in the network architecture. Although once deployed, the SCIDAS can be a major boon to the PTC^2 and resource managements, however, smearing of the SCIDAS architecture at "each and every" corner of the network area is a time taking and a complex task. Moreover, the SCIDAS architecture is evolved over the conventional network paradigm of the static infrastructure of the radio access network, which huddles the "fine tuning" in architectural iterative configurability and resource allocations. Hence, future scopes of SCIDAS architecture may seek for the need of assistive, collaborative, and complementary sub/architectural solutions that can either coexist or work in solitary to perform defined tasks.

The last point is valid for any network architecture; however, it is mentioned here with a purpose to have a scope of accommodating other architectures that can work as complementary or stand-alone along with SCIDAS or contemporary architectures.

2.2.2. THE UAV AS A SOLUTION

There has been a growing interest in using small UAVs in the field of wireless communications due to progress in sensor technology, in-flight controls, 3D cameras, GPS radios and low-cost design of drones. We propose a disparate way of exploiting the UAVs in following the moving users and providing the cellular services with the required Quality of Service (QoS) under the dynamically varying network conditions of the PTC phenomenon. The UAVs seem to be an apt choice for handling and managing PTC congestion due to the following main features:

1) *Mobility*: The users that cause the PTC phenomenon are moving with no regular patterns and speeds. Fixed Base Stations (BS) cannot follow the moving users to give the best possible connectivity. The UAVs, mobile in nature can follow and adapt to the travel patterns of the ground users.
2) *Reduced Handovers*: Placing fixed small cells will increase the burden on the number of handovers that take place. With UAVs above the users at all times, the number of handovers per user will reduce preventing the load of handover processing on the network.
3) *Line of Sight (LoS) Communication*: The small UAVs are close to the ground enabling LoS communication with the ground users. The link between a UAV and a UE suffers much less shadowing than Non-Line of Sight (NLoS) ground relays [8].
4) *Enhanced Signal Quality*: The LoS and mobility feature combinedly brings UAVs close to the users thereby improving the Signal to Noise Ratio (SINR) to the moving users.
5) *Increased data rates*: Sharing the user traffic with the ground base stations can result in efficient use of the available resources and enhance data rates to the users.
6) *Deployment at Multiple Terrains:* The UAVs can be the most practical and convenient solution for deployment at multiple terrains, for example, near water bodies, rugged terrains, mountainous areas, etc.
7) *Adaptability*: The drone BS can adapt to their altitudes and transmit powers as per the need at the ground areas to cover.
8) *Intelligence*: Imbibing intelligent algorithms to operate under varying network conditions can make the network respond faster and better.
9) *Cost*: The one-time cost in manufacturing the drones prevents the cost of adding fixed small cells, and the drone can be re-used at different places and times.

The small UAV cells will aid in offloading the users from the macro cells just as the small cells perform in the HetNets. It will not only increase the overall capacity but significantly enhances the experience of both macro and UAV cell users. The users benefit with better data rates through the traffic splitting between macro cells and UAV cells. Thereupon, expanding user data demand with varying positions bring about the need for innovative, intelligent, and self-deployable mobile infrastructure to serve the coverage and capacity ineffectual areas in future wireless networks.

2.3. TRENDING STATE-OF-THE-ART

To mitigate the sporadic and unprecedented traffic demand of the users, we present the state-of-the-art solutions proposed and investigated until now, in this sub-section.

2.3.1. GROUND DRIVEN SOLUTIONS

Matt Richtel in his article on 'Inauguration crowd will test Cellphone Networks' in The New York Times [9], January 2009, endorsed on the novel concept of Verizon Wireless for deploying the ‘Cells On Wheels (COWs)’ and ‘Cells On Light Trucks (COLTs)’[10] (see Figure 2.6). The main idea of such a mobile deployment was to serve a huge crowd gathering at the event of Presidential inauguration (when) in the United States. The report also mentions that the largest telecom operators in the United States have been asking its subscribers to limit their phone calls and to delay sending photos in light of network congestion at sports events, huge gatherings, concerts, etc.

Figure 2.6 Cell On Wheel (COW) [10]

A concept of 911- network on wheels (911-NOW) has been proposed by Bell Labs to drive the coverage and capacity need for disaster recovery operations emphasizing the deficiencies aroused during Hurricane Katrina and Rita where the communication infrastructure was damaged [11]. The mobile wireless network infrastructure schemed by them is a cost-efficient auto-configurable network that can be deployed promptly as a single-cell solution for localized communication as and when needed. The 911-NOW proposed can be mounted on fire trucks, boats, unmanned drones to provide capacity and coverage on demand in real time. The 911-NOW vision has been urged for disaster relief situations only.

Another remediation solution of ‘Moving small cell’ was proposed in [12] to offload moving and unpredictable congesting traffic efficiently. They have deployed small cells on the top of public transportation and performed investigations at crowded streets. They claim that the data rate of each user in the coverage area will be improved due to the LoS communications.

Such transportable cell solutions (like COWs, COLTs, 911-NOW, moving cells,etc.) are however insufficient in serving the needs of the mass moving users. The events where we observe huge crowds are often debarred with vehicles. Even if deployed to follow the users, such solutions cannot penetrate the crowd and will be able to give connectivity to a limited extent only. The users follow different and unpredictive trajectories which make the usage of moving cells purposeless due to their limited mobility capability.

Some private mobile networks that are portable have also been into literature. For instance, [13] a portable LTE network that can reach several hundred meters to deliver IP connectivity efficiently during emergencies, events have been demonstrated. Alcatel-Lucent and Bell Lab's lightradio™[14] has provided an alternative to the existing base stations that can be ported and deployed easily at high-density hotspots adding sufficient capacity intelligently, efficiently and at a lower cost. However, the lightradio™ lacks the ability to sense the network and physical environment around it and needs to be placed/ fixed manually as and when the need arises. However, these portable devices cannot autonomously operate and follow the moving users. These statically placed devices need manual intervention for their portability and make it an ineffectual solution under dynamic PTC circumstances.

2.3.2. AERIAL DRIVEN SOLUTIONS

The advent of technology has brought drones to the civilian applications. Wireless Communications involving UAVs have seen a significant surge in the research field for a wide variety of applications. The High-Altitude Platforms (HAPs) have been into the study for over a decade and now being researched for providing broadband access to the users. The Project Loon launched by the Google in June 2013 [15], is developing high-altitude balloons to provide internet access to the rural and remote areas with the speeds of 4G-LTE. The balloons will be placed in stratosphere forming an aerial wireless network with the aim of covering billions of people. Facebook with its tagline 'Connecting the World from the Sky,' are testing its Drone project, named Aquila [16] since March 2014, to provide global internet access to the unconnected areas. This solar-powered drone will be able to fly without landing for three months at a time by using a laser to beam data to a base station on the ground.

On the other hand, leveraging the use of small and low-altitude UAVs are paving their way into enhancing the existing wireless infrastructure. With the features mentioned in Section 1.1.1, the UAVs are proposed to be deployed where either the terrestrial infrastructure is absent or fails to perform its required tasks during catastrophe events. A major amount of work in the literature have proposed UAVs to operate as well-developed BTS sites in the air to provide the emergency cellular services when the ground base stations are damaged. In the case of natural calamities and disaster events, UAV deployment can augment the existing ground infrastructure and provide services to the affected ground users. Less number of Low Altitude Platforms (LAPs) are needed in comparison to the ground base stations to cover the desired area [17]. Researchers have lately investigated different aspects of using UAV solutions under such circumstances.

Some funded projects have been carrying out research in making Low Altitude Platforms (LAPs), a part of the future wireless communications. The project ABSOLUTE [18], have been experimenting Aerial Base Stations with Opportunistic Links for Unexpected & Temporary Events (ABSOLUTE). The main goal of the project was to provide a high-capacity IP mobile data network with low latency and massive coverage suitable for many forms of multimedia delivery including public safety and mass events [19]. Their work include investigating the performance of 4G LTE-WiFi multimode base stations deployed on airborne platforms, study the impact of platform elevation and mobility on the cell coverage and channel capacity [20], proposing a statistical propagation model for predicting the air-to-ground path loss between a low altitude platform and a terrestrial terminal [21], and providing a mathematical model capable of predicting the optimum altitude of a LAP based on the statistical parameters of a given urban environment [22]. They have also studied the effect of the temperature, bandwidth, and scheduling discipline on the system capacity and coverage in different public safety scenarios [23]. Further, they have demonstrated an Aerial-Terrestrial Hybrid architecture for wide-area radio coverage suggesting regulations, design, and implementation of aerial base stations for public safety scenarios [24]. Another project called AVIGLE [25] has been working in building dynamical ad-hoc on-demand radio networks to provide additional mobile radio communication capabilities in situations with insufficient cell coverage[26]. They have performed coverage analysis for cellular networks for UAV altitudes up to 500m based on aerial Received Signal Strength Indicator (RSSI) measurements

[27]. Further, they have evaluated the performance of Relay-UAVs to extend the operational range and performed experimental analysis of our Role-Based Connectivity Management to maintain reliable communication in UAV swarms [28].

There are some other projects like AIRBEAM [29], ANCHOR [30], SMAVNET II [31], etc. that have been performing research on the similar lines in exploiting the small UAVs into wireless communications.

Recent work considering small UAVs have looked at a variety of aspects of performing research to complement the ground base stations. From optimization of coverage through altitudes, transmit power, coverage area to acting as relays, operating into ad-hoc networks, etc., research is being carried out. Authors in [32], have investigated the optimized placing of the UAVs through brute force search in a scenario of lost infrastructure and achieved improvements in the throughput coverage and fifth percentile capacity of the network. A concept of ‘drone-cells’ [33] was contemplated to provide a quick deployment opportunity as aerial base stations for unexpected and temporary events. The authors have formulated an equivalent quadratically-constrained mixed-integer non-linear optimization problem and proposed a computationally efficient numerical solution to solve the 3-D placement problem efficiently in serving the maximum number of users with the minimum required area. Another aspect of obtaining maximum coverage region was also presented. In [34], the optimal altitude of ‘Drone Small Cells (DSCs)’ leading to a maximum ground coverage and minimum required transmitting power has been derived. In [35], a dynamic algorithm is proposed for adapting the position of the Aerial Base Station (ABS) to support minimum power consumption by minimizing the total path loss of the ground subscribers.

Small unmanned-aerial-vehicles (SUAVs) operating as wireless relays for assisting the cellular network performance during local traffic imbalances and emergency operations was proposed in [36]. Their simulation results show that trough-to-peak throughput improvements can be achieved for users in poor coverage zones. To enhance spectral and link connectivity a multi-source cooperative communication system using multiple small relay UAVs was studied in [37]. Feng et al. have compared the advantages of airborne relaying to the conventional peer-to-peer mobile relays under three channel types, Line-of-sight (LoS), Obstructed LoS (OLoS), and Non-LoS (NLoS) [8].

Some papers have laid emphasis on using multiple UAVs forming ad-hoc networks and working in cooperation for several applications [38]. Wireless ad-hoc networks are composed of devices communicating without any predetermined infrastructure [39]. Through ad-hoc networks of small UAVs, a larger area can be served. In [40], authors have proposed a drone formation algorithm that determines the 3D geographic location of each drone in an ad-hoc drone network used for building instant network infrastructure. In [41], 3D locations of the UAVs are determined using circle packing theory, to maximize the total coverage area and coverage lifetime of the UAVs. A novel approach for optimally deploying UAVs to provide wireless to service ground users while minimizing the overall UAV transmit power needed to satisfy the users' data rate was proposed in [42]. A resource allocation optimization algorithm to minimize mean packet transmission delay in a 3D cellular network with multi-layer UAVs has been suggested in [43]. For managing the radio resources, a game theory based power-efficient Radio Resource Management (RRM) of the Aerial LTE uplink and downlink was presented in [44].

Further, UAV deployments have been suggested to provide services at hotspots and areas with distributed user density. In [45], the authors have simulated multiple UAVs equipped with enodeB and UE technology to provide cellular services on the ground to the heavy crowds leading to the cell overload. The authors proposed a combination of traffic and analytical interference model to evaluate the downlink case of system configurations. They observed an increase in total system capacity by 40 Mbps using four aerial relays. To complement the macrocell infrastructure, small cells mounted on UAVs were proposed to provide additional capacity to the areas of high user equipment (UE) traffic in [46]. An algorithm based on cluster analysis was suggested to calculate the suitable UAV locations with prior knowledge of UE coordinates. On comparison with the pico cell deployment, they have demonstrated that airborne access points significantly provide improved received signal strength. In [47], a neural-based cost function approach is formulated to solve the problem of UAV assignment over geographical areas subject to high traffic demands based on the user demands. Through their study, they have demonstrated that multiple UAVs can not only provide long-range connectivity but also better load balancing in a HetNet environment. Their proposed approach yielded improvements in fifth percentile spectral efficiency up to 38% and reduced delays up to 37.5% compared with the ground-based network. Kalintari et al. [48], proposed an optimization problem based on particle swarm optimization to estimate the number of drone-BSs and their 3D placements based on user traffic requirements. Their paper made certain implications through their approach such as (i) the number of drone-BSs in an area is proportional to the user density in that area, (ii) drone-BSs can decreases its altitude in a dense area to reduce interference to the users that are not served by it and increase its altitude to cover a large area in a low-density region. The authors have further proposed the concept of 'multi-tier drone-cell' networks to enhance connectivity whenever, wherever, and however needed to serve the hard-to-predict the spatiotemporal distribution of the traffic [49]. Another paper [50], examined a placement algorithm of (UAV)-mounted Mobile Base Stations (MBSs) wherein the MBSs are placed sequentially, starting from the perimeter of the area boundary in an inward spiral manner until all users are covered. A comparison with other benchmark algorithms was made by them and observed their proposed algorithm perform better in terms of minimum number of MBSs required.

2.4. CONCLUSIONS

In this chapter, we have elaborated the problem of Place Time Capacity (PTC) congestion arising due to random and unprecedented subscriber accumulations at various locations in the AoE. We started with presenting the conventional network dimensioning process and discussed the impact of PTC on the existing network dimensioning in context to HetNets. Through Section 2.1, we concluded that the conventional network planning and dimensioning do not converge to solving the PTC problem. This has compelled us to propose a non-conventional approach to using UAVs to dissolve the PTC oriented overload conditions mentioned in Chapter 1. In relation to solving the PTC problem, we have mentioned the State-of-the-Art in context to the current approaches and discussed their limitations. Lastly, we have given a brief description of the State-of-the-Art in context to the UAV solutions. While discussion Section 2.3, we could find that UAVs can be utilized as a new paradigm in dimensioning the network, where a swarm of small UAVs can collectively coordinate with each other to form a new layer of network architecture to mitigate the PTC problem. The upcoming chapters of this thesis shall present and investigate the new and innovative paradigm of forming holistic network architecture namely Self-Itinerant Intelligent Aerial Radio Architecture (SIIARA).

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CHAPTER 3. THE EVOLUTION OF THE PROPOSED AERIAL RADIO ARCHITECTURE

Our work [1], has introduced this issue of Place-Time Event, which has been described in terms of network capacity as the Place Time Capacity (PTC) problem. This work elaborated in [2], the Place-Time Event was also extended to coverage investigation and was termed as Place Time Coverage (PTCo). Collectively, the Place-Time Event for the Mobile Wireless Communication Networks (MWCN) was defined and introduced in [2] as ”PTC^2” (Place Time Coverage & Capacity). We have also discussed the state-of-the-art in relation to solving the PTC challenge. As we believe that both the PTC and PTCo are the repercussions of the random user accumulation and group mobility, we observe that not much work has been done in investigating the network dimensioning in solving the PTC^2 problem until proposed solution in [2]. In [2], the author had proposed a ground-based intelligent network architecture of ’Self-Configurable Intelligent Distributed Antenna System (SCIDAS),' as an attempt to solve the problem of PTC^2. However, as mentioned earlier, the ground-based networks are static forms of network dimensioning and have less flexibility to accommodate the abrupt accumulations. Hence, we believe that a more flexible and adjustable architecture to be able to serve the sporadic PTC^2 problem in a more effective way. We have proposed aerial radio architecture to serve the PTC problem that can either work as a standalone or as a complementary architecture to SCIDAS. The possibility of latter has already been investigated as ’Heterodox Network’ in [3] and will be further discussed in Chapter 7 of this thesis.

This chapter will introduce and describe the standalone aspect of our proposed aerial architecture of Self-Itinerant Intelligent Radio Architecture (SIIARA) [4]. The chapter will also discuss the stages of its evolution including HANET and Aerial-HetNets and their working paradigms to solve the PTC problem.

3.1. NECESSITIES OF THE EVOLVING ARCHITECTURE

The Aerial Radio Architecture (ARA) is required to possess the features of the conventional network systems, as well as some additional features and intelligence to work as standalone network architecture. Following are some features and functions that must be by default imbibed in the ARA to serve the cellular users and function as a complete cellular network provisioning system.

1) *Inheritance*: The proposed architecture shall inherit the following features of the existing architectures;

a. *Cellular Layout*: Any cellular serving network is distributed over land areas called ’Cells,' and each cell is served by at least one fixed-location transceiver, known as a cell site or base station [5]. The area over which the signal strength from the BS lies above a threshold value is referred to as the coverage area of a BS or a cell footprint. To improve the network capacity and spectral efficiency, a technique of *frequency reuse* is used wherein; the available frequency channels are reused in the network system [6].

b. *HetNet*: In Heterogeneous Networks, cells of different sizes and transmit powers are used, referred to as macro-, micro-, pico- and femto-cells [7]. The coordination between macro cells and small cells (pico,femto), has a positive impact on the performance of the cellular radio network, and consequently on the overall user experience [8].

c. *Backhauling*: It is a property of the telecommunications networks to provide a connection from a user associated with one BS to the user associated with another BS. This is possible only if there is a communication pipe through which the user data flow can be performed. This is known as the backhauling pipe of the network. The connection between the BS and the rest of the world begins with a backhaul link to the core of the Internet Service Provider's (ISP) network [9].

d. *Network Hierarchy*: There are different network entities involved in a telecommunication network to work together in providing cellular services to its subscribers. In a cellular network, the user is connected to a BS, the BSs are connected to the Switching Centre, and a number of switching centres are connected to the Core Network (CN).

2) *Polymorphism*: A variety of technologies, cell sizes, transmit powers and network architectures that can configure it with rapid changes in customer demands and mobilities. An architecture that is flexible enough to accommodate the user patterns in terms of variable demands, locations, and individual/group mobilities and to jail break the limitations of the static infrastructure.

3) *Encapsulation*: The novel architecture is supposed to function intelligently to solve the PTC problem. Being a smart entity, it is important that all the function of a deployment shall remain ‘personal’ to that approach. Therefore, unlike the traditional approach, where resource planning is

ubiquitous in nature, the novel architecture must respond to the specific 'location demand,' and therefore the solutions remain "encapsulated" to latent to the external parallel solutions. This is also an add-on feature for the security of the system.

4) *Compatibility*: The architecture is required to supports backward compatibility with older technologies and architectures. A seamless user experience requires interoperability with the previous telecom standards with the addition of new generation of services and devices in the network.

3.2. HANET: FOUNDATION OF THE EVOLVING ARCHITECTURE

From this section, we will introduce and describe in detail our proposed Aerial Radio Architecture. We start with describing the strategy to solve the problem and then describe the foundation of evolution, HANET. We will cover the HANET features, architecture, and its communication links in this sub-section.

3.2.1. STRATEGY TO SOLVE THE PROBLEM

The problem of PTC considered in this thesis work is mobility oriented. Hence, a solution that is mobility-driven will be well-suited to address the problem. The strategy proposed through this study work is giving a 'moving' solution that follows the 'moving' problem, which is why we consider flying aerial radio nodes as our proposed solution. However, to be able to succeed in following, it is important to know the cause of the problem which is the moving user behavior. Following are some points that characterize the PTC problem w.r.t. the changing mobility behavior of the users within the AoE.

1. *Moving/Accumulation Pattern*: The AoE can be a small or large geographic area depending on the live event happening. However, the users within the AoE can follow different patterns of movement. The users can be distributed in scattered manner, uniform manner or can form clusters/groups with spaces between any two adjacent groups.
2. *Direction*: The users can move either in a single direction representing a carnival along a street or can wander in different directions on occasions of festivals, etc.
3. *Volume*: The number of users in groups may be varying, where one cluster can have 10 users in it, another cluster has 50 users in it and so on.
4. *Capacity demand*: The users might have different service agreements with their respective NSPs and might have varying data rate requirements.

3.2.2. THE HANET ARCHITECTURE

The foundation of the evolution of the SIIARA was built with the introduction of Hovering Ad-Hoc Network (HANET). The SIIARA is the holistic and extended version of the HANET. To have a better understanding of the SIIARA, we will first describe HANET and its operating architecture in detail in this sub-section.

3.2.2.1 The Conception of HANET

To identify and solve the problem of PTC, the requirement is to build a team of multiple UAVs, so that the entire AoE is well covered. This team of small UAVs are proposed to create an ad-hoc network in the air. We define HANET as *a team of self-itinerant, intelligent, and adaptive hovering radios to serve the dynamic traffic need of moving subscriber hotspots by optimally positioning themselves at the Area of Event (AoE)* [10]. The AoE has already been discussed in detail in Chapter 1.

Previously two types of ad-hoc networks, namely Mobile Ad-hoc Networks (MANETs) and Flying Ad-Hoc Networks (FANETs), have been standardized. However, our proposed ad-hoc network differs from above mentioned ad-hoc networks, for acquiring a different set of features and applications. In Table 3.1, we differentiate the HANETs from other classes of ad-hoc networks.

Parameter	**MANETs**	**FANETs**	**HANETs**
Node Mobility	Low	Very high	*Low*
Mobility Model	Random	Regular (predeterminedpaths)	*Nomadic (mobilityfollows*
Node Density	Low	Very low	*Low*
Topology Change	Slow	Fast	*Quasi-constant*
Radio Propagation (node altitude)	Close to ground,	High above ground, LOS	*Both above and close to ground*
Mobility type	Quasi-Stationary, ground	Flying	*Hovering (ground &flying)*
Inter-member distance	Short	Long	*Shorter*
Communication Band	On-demand,	Unlicensed/ Cellular	*IMT and Millimeter-wave*
Application type	Specific user scenario	Multi-UAV applications	*PTC load dispersion*

Table 3.1 Difference between MANET, FANET and HANET [10][11]

Through this table, we can see that HANET possesses its own features and applications that are different to what have been standardized before. The Members of the HANET team are close to the ground, have LOS with its neighboring Members, hovering with low mobility, and following no fixed topology in the air. This class of ad-hoc network has its specific application of functioning as a BS and to provide network services to the ground users as and when required.

3.2.2.2 The Communication Links

A team of UAVs attempting to work together in cooperation and coordination requires communication links to send/receive information among themselves and from other entities of the network system. The major entities involved in a PTC-like scenario, handled by the HANET are the ground users, ground BS and the multiple Members of the HANET team. Broadly two categories of communication are defined, (i) Intra-Network/Intra-HANET Communication corresponding to communication between the Members, users and HGBSs belong to only on HANET, and, (ii) Inter-Network/ Inter-HANET Communication corresponding to the communication between the Members, users and HGBSs belonging to separate HANET systems (discussed in Section 3.3.1). The latter will be further discussed in the next section.

The intra-network communication in the HANET architecture has the following types of communication links:

1) *Member to User Communication (M2UC) Link*: This link corresponds to the Air to Ground (A2G) type communication with one of the sender/receiver is in the air at a certain altitude from the ground. In this case, the Member is in the 3D space attempting to communicate with the users on the ground. The information transfer takes place at the IMT frequencies with the purpose of delivering the cellular services. We have further proposed this link be connected to the Millimeter Wave (MMW) based devices, that are proposed to be operative in the future 5G+ communication networks [11].

2) *Member to Member Communication (M2MC) Link*: This link corresponds to the Air to Air (A2A) type of communication with both sender and receivers in the 3D space. Here, the Members of the HANET are needed to communicate with each other with the aim of handling and managing the PTC situation. The information transfer will include the user data and control information necessary to be communicated to the Members like placement coordinates, battery updates, etc. We propose the operating frequency channels to be working in the 60 GHz millimetre wave band.

3) *Member to Ground BS Communication (M2BSC) Link*: This type communication link is again A2G type of communication link. The Member and ground BS communicate with each other through this type of link. The user data needs to be backhauled. As the HANET does not carry its own backhauling system, the offloaded data is required to reach the core network through the ground BSs. This type communication is also proposed to take place through 60 GHz millimetre wave channels.

The Figure 3.1 below illustrates the respective links between the entities of the network system.

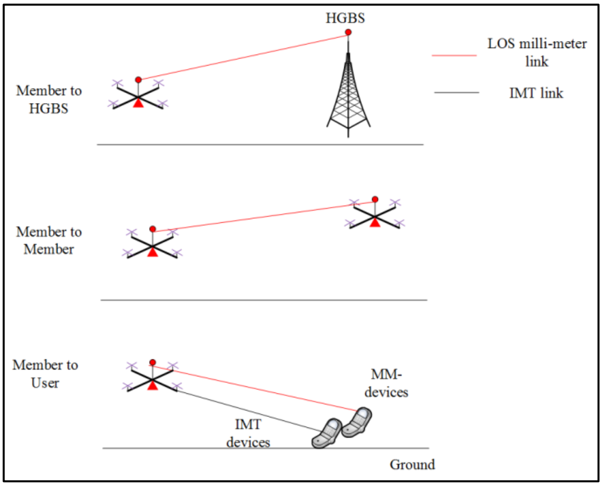

Figure 3.1 Communication Links of an HANET Member [10]

3.2.2.3 The Adoption of Millimeter Waves in Aerial Radio Architecture

In the previous section, we have proposed the M2MC and M2BSC to operate in the separate layer of 60 GHz Millimeter Wave Communication (MMWC).

Following are some advantages of using 60 GHz MMW channels for communication.[12][13][14];

a) Multi-Gbps data-rate is carrying capability supporting extremely high-speed subscriber applications like video streaming.
b) Unlicensed frequency band (in some countries but currently in India), hence no cost in acquiring additional spectrum. The 60 GHz band has more bandwidth available than all the other unlicensed bands.
c) Minimal interference with the IMT frequency bands (below 6 GHz).

d) The line of Sight (LoS) connectivity between the Members due to short range communication and hence encouraging directional links to compensate for the heavy path loss.

In the previous section, we have proposed the M2MC and M2BSC to operate in the separate layer of 60 GHz Millimeter Wave Communication (MMWC). The use of millimeter wave technology into cellular network field is still in an amateur phase. Moreover, the employment of MMW frequencies in aerial networks is a green field of research. In one the research work performed by Facebook [15], have investigated point-to-point MMW radio link to serve as a connection between a ground station and their project of solar-powered UAV, 'Aquila' [16]. However, their research is in a growing phase and some scientific and engineering challenges to be resolved before actual deployment.

In one of the recent works, authors have examined the use of MMW spatial-division multiple access and demonstrate its advantage in improving the cellular network capacity because of its abundant frequency spectrum resource [17]. They have proposed the use of MMW in high data rate urgent or ad-hoc UAV cellular network communications and discussed the aspects of channel modeling and propagation characteristics.

The exploration and investigation of 60 GHz MMW communications into aerial cellular networks is a new research field, and through our research work, we take this opportunity to use the 60 GHz MMW channels into our analysis of communications amongst the HANET Members and their communication with the ground base stations. Our proposed architecture envisages the use of 60 GHz MMW channels for the wireless backhauling of the cellular network data also.

Further, millimeter wave technology is propositioned to perform viable communications as MMW radio access channels between a BS and the users [18] [19]. The millimeter wave communication is undoubtedly serving its way into 5G and beyond cellular communications.

3.2.2.4 The Operating Architecture

As defined earlier in this chapter, a Hovering Ad-hoc Network (HANET) is a network of aerial radio Members that operate in collaboration and coordination to serve the PTC situations at the AoE. Such aerial Members form an ad-hoc network at a certain altitude from the ground and aid in providing the cellular services to the users latched to the Members. Figure 3.2 depicts a conventional network architecture of a single HANET [10], where an AoE with accumulated PTC causing users are depicted. The users are shown to be scattered, clustered and more in number than what a BS can serve. Two ground base stations BS1 and BS2 falling within the AoE region are shown to be overloaded. The HANET Members are placed in the air, with altitude much more than the height of the overloaded BSs. The Members are shown to be linked. However, not all Members are connected to each other. The Members can perform two roles based on their locations in the AoE, namely HANET Serving Members (HSM) and HANET Relay Members (HRM). As the names suggest the former are responsible for delivering services to the users associated with them and the latter are needed for relaying the data to the nearest, unloaded BS. The unloaded BS in this architecture is called as the HANET Gateway Base Station (HGBS), which is responsible for transferring the received data from the HRMs to the backbone network for backhauling. There can be more than one HGBS used to process the user data. A Member is capable of being a part of either HSM or HRM or both.

Separate subsystems other than conventional Base Station Subsystem (BSS) (involving the overloaded Base Stations BS1 & BS2) are also defined in this architecture. The HANET Base Station Subsystem (HBS) includes the HSMs, and the HANET Relay Subsystem (HRS) contains the HRMs and HGBSs.

This figure also depicts the communication links mentioned above. The omni-directional links for the M2MC and M2BSC operating in the 60 GHz band are shown in the illustration below.

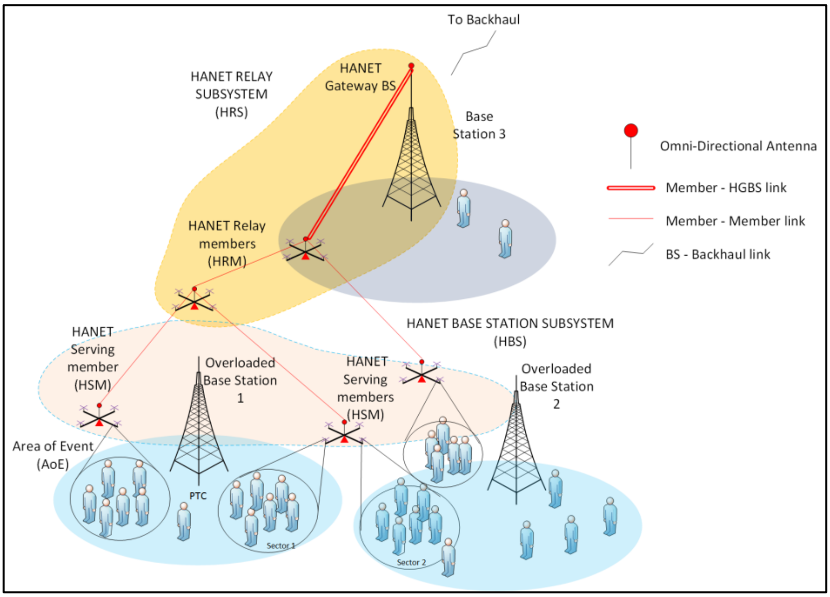

Figure 3.2 HANET Architecture [10]

3.3. AERIAL- HETEROGENEOUS NETWORKS – A NOVEL APPROACH IN UTILIZING SMALL UAVS

We have discussed the Heterogeneous networks in Chapter 2. Here we will introduce a novel and innovative way of adopting the small UAVs to form an Aerial-Heterogeneous network (Aerial-HetNet) [15] in the air. The Aerial-HetNets are different from the ground HetNets with the radio base stations integrated into small UAVs and operating from a much higher height than the ground base station. Similar to the HetNets, the Aerial-HetNet is suggested to be a collective arrangement of Macro, Micro, and Pico Members (cells), having different cell sizes and transmit powers. Hence, Aerial HetNet refers to an alternate cellular network delivering an aerial architecture that conforms to the specifications of a HetNet, but the radio nodes here are aerial, hence the term ‘Aerial-HetNet.'

The HANET can be well utilized to employ into the formation of Aerial-HetNet. A Member can be placed at different altitudes in the 3D spatial domain. The altitude will determine the footprint of the aerial cell on the ground; more is the altitude, larger is the ground footprint. As depicted in Figure 3.3, a Member can be placed at low, medium, and higher altitudes to form cell footprints on the ground representing Macro, Micro, and Pico Aerial Cells.

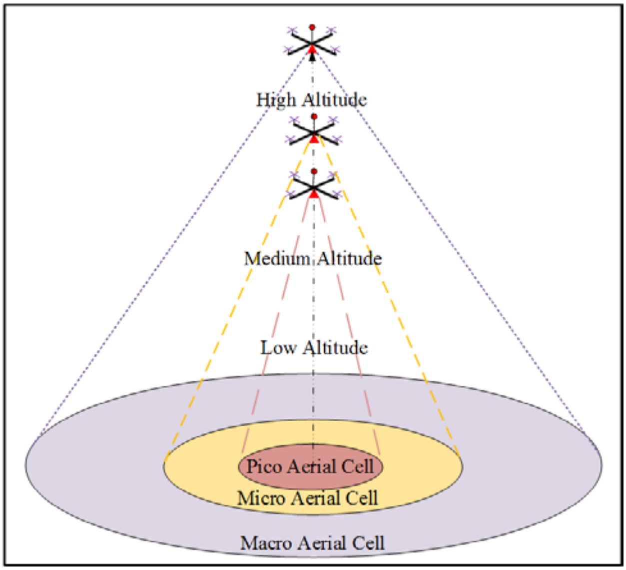

Figure 3.3 Cell Footprints of a Variable Altitude Member

The Aerial-HetNet can be combined with the ground HetNet to form a Hybrid Aerial-Terrestrial Heterogeneous Network. This hybrid network can be put into operation during PTC conditions and under catastrophe events. The whole idea owes to the surfacing of dynamic and need-based network conditions, wherein the fixed ground base stations are not sufficient or fail to perform their assigned tasks.

Figure 3.4 below, illustrates the concept of Hybrid Aerial-Terrestrial Heterogeneous Network consisting of two layers of UAV altitudes. The HANET Serving Members (HSMs) can adjust their heights and be configured as Micro HSMs and Pico HSMs. These Micro and Pico HSMs can place themselves and operate alongside the terrestrial Macro Base Station. The HSMs form multiple layers in the air owing to different heights from the ground. As seen in Figure 3-4, the placement of HSMs into two layers of Layer 1 and Layer 2. The placement in the space must ensure not to have overlapping and interfering cell footprints on the ground among themselves and with other ground MBSs, micro and pico cells (if present). Optimizations can be performed to obtain optimal values of altitudes to give coverage ranges as desired.

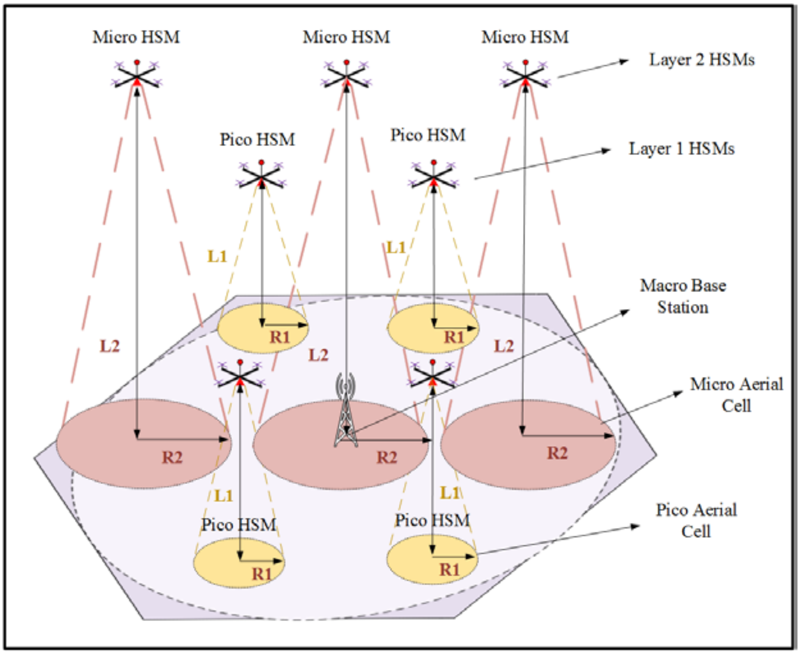

Figure 3.4 Hybrid Aerial-Terrestrial Heterogeneous Network [15]

3.4. SELF-ITINERANT INTELLIGENT RADIO ARCHITECTURE

So far, we have discussed our strategy in handling the PTC situations and the evolution of the SIIARA through the description of HANET. We will introduce SIIARA as an extension to HANET in this sub-section. Here, we aim to discuss our proposed aerial architecture of SIIARA in an exhaustive way.

3.4.1. THE CONCEPTUAL EXTENSION

In the previous sub-section, we have discussed HANET, which is the foundation of our proposed architecture of SIIARA in [4]. Here in this section, we will discuss SIIARA in detail.

A network can go through multiple problems at a time; a similar situation can arise when there can be scenarios when PTC has occurred at multiple places but at the same time. This means that in a single geographical region, more than once we can find accumulations/moving users giving rise to the creation of more than one AoEs, separated by distance. Because of this, we need multiple HANET systems operating simultaneously but at different locations. These geographically spaced HANET systems, working to offload the ground BSs, can be connected to each to communicate with one another. It is not necessary that each Member of the HANET communicate with each Member of the neighboring HANET system. The communication between multiple HANET systems is called as the Inter-Network/Inter-HANET Communication (as mentioned in Section 3.2.2.2). This type of communication will ensure the connectivity between the users that are associated with multiple HANET systems within a large geographical area. The Inter-HANET communication further corresponds to the backhauling in the traditional communication networks. We propose the use of Gateway Aerial Vehicle of HANET (GAVH) (to be discussed in next sub-section) as the link between co-HANETs. The ground BSs could also be chosen to link multiple HANET systems, but that would unnecessarily impose a burden of extra resources. The HANETs are mobile in nature and would require changing links of communication quite frequently. Fixed BSs might not be an appropriate solution, as acquiring/releasing links with multiple ground BSs to make two HANET systems connected will turn out to be a complex and time-consuming procedure.

Further, the movement of the multiple user groups and with various HANETs following them, we propose the process of Distributed Dynamic Backhauling of the Aerial Architecture (DDBAA) (described in Chapter 5), and this feature led us to propose the Self Itinerant Intelligent Aerial Radio Architecture (SIIARA) [4]. The SIIARA inherits features of the HANET and has been suggested to comprise of the additional functionalities that are mentioned in our work in [4] and are elaborated below:

1) *Alternate and Flexible Backhauling*: The aerial Members are responsible for offloading the users from the overloaded terrestrial macro base stations. Eventually, this data is required to be backhauled to the backbone network through the unloaded base stations. To perform this functionality, the Members are required to maintain sufficient backhaul link capacities to accommodate the additional traffic load generated due to PTC. This will require no intervention of the ground base stations to backhaul the

offloaded user data. The gateway BS (HGBS) are only needed for the data transfer.

2) *Intelligent and Adaptive*: The motion dynamics of the ground users play a major role for the Members to deliver services in an efficient manner. An intelligent and adaptive mobility management is required to make decisions on certain factors, for example, the position and height control from the ground (in all three dimensions), roles to be played by the Members (HSM/HRM/GAVH), load sharing, addition/deletion of the Members with minimal disruption in the network, etc.

3) *Interference Management*: The Members and the ground BS work together to serve all the users present in the AoE. The Members must ensure minimal interference among themselves and with the ground BSs that fall in the footprint of the Members. Decisions on frequency planning, antenna tilt optimization and power control can be used to reduce interference between the co-cells, which require intelligence to play a part in the adaptation and control according to the network circumstances. To keep interference in limits, strategies to use minimum Members must also be employed. MMWC between Members and with ground BS ensures minimal interference to the LTE bands.

4) *Radio Resource Management*: The spectrum available with the NSPs is always scarce and buying additional spectrum incurs a huge cost. It is crucial for the Members to manage and optimize the allocated radio resource blocks to them. The Members share the resources with the ground BS and reuse to serve users based on their locations, QoS and service requirements, etc. The decision-making will again make use of intelligence for optimized allocation of available radio resources in the AoE.

3.4.2. THE OPERATING ARCHITECTURE

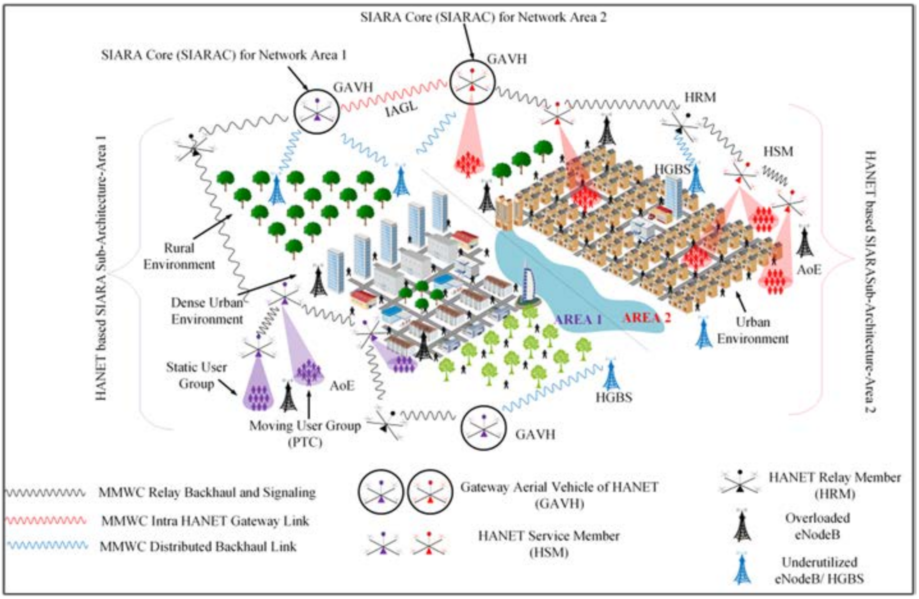

Figure 3.5 Self-Itinerant Intelligent Aerial Radio Architecture [4]

The SIIARA comprises of two independent layers of LTE-A network provisioning to the users namely: The Members and the Terrestrial eNodeBs. The SIIARA is formed of multiple HANETs operating over a large geographical area, linked together with the goal of providing cellular services at the crowded and congested areas. Figure 3.5 illustrates a typical SIIARA, comprising of multiple HANET systems in a large geographical region working in different network environments of Dense-Urban, Urban, and Rural. The entire region is built with two sub-architectures, namely *HANET based SIIARA sub-architecture 1* and *HANET based SIIARA sub-architecture 2*. The former represents the Dense Urban, and Rural environments and the latter represents the Urban environment. The PTC is shown to be generated by the static and moving user groups, creating multiple AoEs. The terrestrial eNodeBs are categorized into two types, first are the overloaded eNodeBs that are overloaded due to PTC generation and the second are the eNodeBs that are underutilized due to temporary user drifts from its serving area towards the AoE region (named as HGBS).

The most distinguishing feature added to the SIIARA is another role played by the aerial Members apart from HSM and HRM. As shown in the figure, this role is of Gateway Aerial Vehicle of HANET (GAVH) that acts as a gateway between any two different HANET systems for mutual communication. The major responsibility of GAVHs in the SIIARA are to manage communication between the neighboring

HANET systems that are operating to serve the scattered clusters of users during mega events like carnivals, or religious/social festivals (namely Tomatina Festival, Spain; Ganesh Chaturthi, India). The GAVH can also communicate with HGBSs to relay the user data for inter-network data exchange for the backhauling of the offloaded data (as shown in the figure above).

The SIIARA supports three types of MMWC links, namely:

1) *MMW Relay Backhaul and Signaling Link*: This link is established between the Members (HSM or HRM) and is the same as *Member to Member Communication (M2MC) Link* mentioned in the description of HANET. This link is accountable for relaying user data (backhauling) and the control information (signaling) between the members for maneuvering control and optimal positioning of each member, health statuses, etc.

2) *MMW Inter-HANET Gateway Link*: This link is used for inter-HANET communication between the two HANET systems. The exchange of information (data and control both) between two isolated HANETs takes place through this link.

3) *MMW Distributed Backhaul Link*: As the SIIARA is deployed to serve the high data rates to the mass user accumulations, a single backhaul relay link from HANET to a chosen HGBS may congest the backhauling from the HGBS to the core network. The Members are proposed to split and bifurcate the backhaul packets between multiple terrestrial eNodeBs i.e. multiple HGBS. This data can be eventually combined and converted to user information. This process has been termed as Distributed Dynamic Backhauling and will be discussed in detail in Chapter 5.

3.5. CONCLUSIONS

Our proposed solution, the aerial radio architecture of HANET and SIIARA were addressed in this chapter. We have discussed the HANET first, described its features, architecture, and communication links. We have then introduced a novel and innovative concept of Aerial-HetNet in this chapter, which is a combination of variable altitude aerial Members. The Aerial-HetNet can be combined with the terrestrial network to form Hybrid Aerial-Terrestrial Heterogeneous Network that can be put into operation for heavy user accumulation scenarios and in providing services at the disaster situations where few or none of the ground networks are working. Lastly, we discuss the main architecture of SIIARA, the HANET being the foundation of the SIIARA. Multiple HANETs operating to serve multiple PTC scenarios in a large geographical region forms the SIIARA. For solving the PTC, the aerial Members involved in SIIARA are required to play various functionalities and roles, which are dependent on their locations in the network area. The additional features of SIIARA were also discussed in this chapter.

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CHAPTER 4. THE RADIO NETWORK ANALYSIS OF THE AERIAL RADIO ARCHITECTURE

This chapter describes the investigations and evaluation of the ’Radio’ part to handle PTC scenarios through our proposed model of SIIARA. The Radio part has been further evaluated into three categories. The first one is the analysis of the Signal to Interference plus Noise Ratio (SINR) at the user locations under PTC conditions and their improvement upon the deployment of the HANET [1]. The second evaluation considers one of the important aspects of HetNets, which is the Cell Range Extension (CRE) [2] when applied to HANET. The third evaluation considers the HANET structured into an Aerial-HetNet [3] and its analysis under different case studies. The sections in this chapter will present the system model and assumptions, followed by the simulation results for all the three categories of radio investigations.

4.1. SYSTEM MODEL

This section will outline the system model along with the assumptions that are taken into investigating the radio analysis. We will first discuss the global assumptions, common to all the Radio Analysis categories or else discussed otherwise. Then we will discuss the simulation and technical assumptions along with the simulation parameters considered pertaining to the evaluation of our aerial radio architecture.

4.1.1. GLOBAL ASSUMPTIONS

For our simulations, a set of assumptions and formulations prevalent to both the analysis will be described in this section.

A. General Assumptions

1) The Members have inbuilt LTE-A and MMWC radios for being able to provide required cellular services to the ground users.
2) The Members are capable of following the moving ground users at the AoE. This means that each Member is able to avoid obstacles, adjust the moving speeds and hover as per moving user’s patterns.
3) The Members have idealized (single) sector radiation from antennas (so that the beam is defined only by the elevation height).
4) There is orthogonal resource allocation between the Members to have minimal interference.
5) The aerial network to be evaluated in an Urban Environment.

B. Spectrum Partition

We incorporate the total system bandwidth of 20 MHz (LTE-A), which needs to be shared between the BSs and Members. The Members are deployed above the AoE and to provide cellular services to the accumulated users and are made to follow in the moving direction of the users. Only the BSs that are falling in the AoE region are severely affected by the accumulations. The Members will serve the extra users in the AoE that are not being served by the MBSs due to overloading. We have suggested the total system bandwidth of 20 MHz be partitioned between the affected BSs and the Members within the AoE. We prevent to have additional spectrum coming from the Members, as it will append a huge cost to the aerial network deployment. We propose 15 MHz of the bandwidth be allocated to the MBSs, and the remaining 5 MHz is assigned to the Members following the traditional frequency reuse factor of 1 (as illustrated in Figure 4.1). This partition might lead to less interference between the two layers of sites. The MBSs shall regain their shared spectrum after falling out of the AoE region and continue to operate as prior to the occurrence of the accumulation within its coverage region.

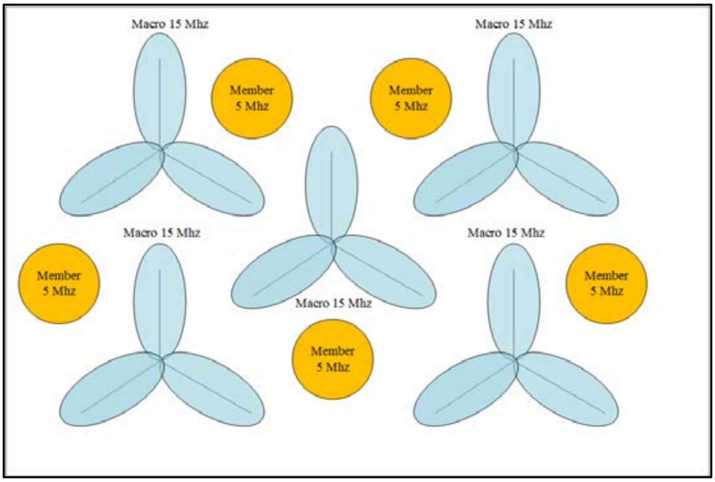

Figure 4.1 Spectrum split between Macro BS and Member

C. Spectral Efficiency and Capacity Calculations

Our simulation analysis considers an interference limited network in which the thermal noise power at a receiver is assumed to be negligible when compared to the interference power. The SINR formulation derived in [2], at an arbitrary UE 'n^{th}' position is given by the following equation,

$$SINR = \frac{P(d_{ns})}{\sum_{i \in N, i \neq s} I(d_{ni})} \quad (4.1)$$

where $P(d_{ns})$ is the average signal power received by UE 'n' at a distance of d_{ns} from its serving site s, and the denominator gives the total interference power I_{ni} from all the N sites in the network area, except the serving site s, d_{ni} is the distance of the UE n from the i^{th} site and P_n is the noise power. We further map the SINR received at each UE position using the *Shannon Capacity* formula to calculate the estimated throughput per user TP_{UE} under the *Fair Resource Sharing* scheme and is expressed as,

$$TP_{UE} = \frac{B\log_2(1 + SINR)}{N_{UE}} \quad (4.2)$$

where B is the channel bandwidth, and N_{UE} are the number of UEs falling in the coverage region of the respective sites. The *Fair Resource Sharing* method is the simplest method of all and guarantees fairness among the users by allocating equal resources to all the UEs. An increase in the number of UEs in the cellular footprint of a site directly impacts the individual UE throughput that can be achieved.

D. Number of Member Requirement

The number of Members that are required to cover the AoE is calculated as per the total capacity requirement of the extra UEs influx in the AoE. We calculate the initial number of Members N_{Member}, each having a capacity to deliver a throughput of TP_{Member}, to be placed above the AoE region based on the group throughput demand $TP_{group}$of the additional number of UEs N_{UE} at the AoE (equation (4.5)). The throughput delivered by each member is the product of downlink spectral efficiency SE (bits/s/Hz/cell), channel bandwidth B (Hz) and a number of sectors N_s per member site (equation (4.3)). The group throughput is calculated by multiplying the additional user influx N_{UE} with the throughput requirement of each user TP_{UE} (equation 4.4)).

$$TP_{Member} = SE \times B \times N_s \quad (4.3)$$

$$TP_{group} = N_{UE} \times TP_{UE} \quad (4.4)$$

$$N_{Member} = \frac{TP_{group}}{TP_{Member}} \quad (4.5)$$

4.2. SINR ANALYSIS

This section will discuss the simulation and technical assumptions for the radio part investigation. The simulation assumptions will briefly describe the network layout, and environment that we have chosen to evaluate our aerial architecture and the technical assumptions shall consider the radio aspect of the simulation.

4.2.1. SIMULATION ASSUMPTIONS

For the investigation of our proposed architecture model, we have selected a simulation platform under ITU M.2135-1 recommendation in evaluating the IMT-Advanced radio interface technologies [4]. We have selected the interference-limited Urban Macro (UMa) cell scenario that focuses on large cells and continuous coverage. The typical building heights are over four floors and are assumed to be spread across the network area uniformly. The Macro Base Stations (MBSs) are located on the rooftops of the buildings. The building width (W_b) and the average height of the building (H_b) have been taken into consideration for evaluation of the path loss. The A2G propagation model parameters have been chosen for the Dense Urban scenario and are further described in the next sub-section. The MBSs follow the regular hexagonal cellular layout as per the ITU-R guidelines for IMT-A.

4.2.2. TECHNICAL ASSUMPTIONS

To perform a radio simulation involving aerial Members and ground BS and users, certain technical aspects are required to be considered. Here, we will describe the formulations used in determining the radio characteristics of the network.

A. Propagation Channels

We will discuss the different propagation channels used to determine the signal path loss from the transmitter to receiver entities involving the Members, BSs and UEs.

1) Member to User/BS Propagation Channel

This type of channel falls under the M2UC and M2BSC channels, forming an A2G type of radio link. The physical land morphology on the ground plays a significant role in the propagation characteristics of the radio signals transmitted from the air in case of aerial radio networks. The radio signals transmitted from a Member travels initially through the free space until encountered with the physical environment (trees, buildings, water bodies, etc.) and experience signal deterioration due to the occurrence of scattering, reflection, and diffraction (see Figure 4.2).

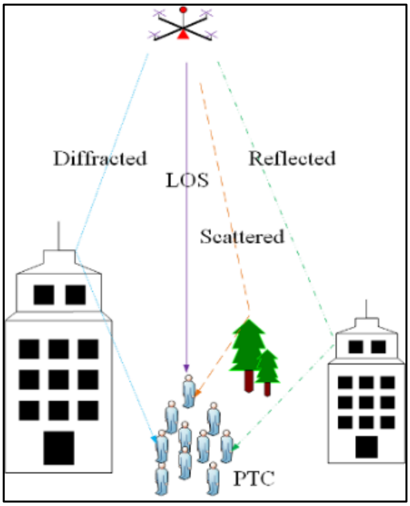

Figure 4.2 Signal Deterioration from Member to ground [1]

For our simulations, we have used the free space path loss *FSPL(dB)* (equation (4.6)) with an additional path loss of η_{MU} (equation (4.7)), accounting for the shadowing and penetration losses in between the Member and a user in the urban environment.

$$FSPL(dB) = 20\log_{10} D + 20\log_{10} f - 27.55 \tag{4.6}$$

$$PL(dB) = FSPL(dB) + \eta_{MU} \tag{4.7}$$

where *PL(dB)* is the total path loss, f is the center frequency of MHz, D is the distance between the ground user and member in meters. In our simulations, we simplify the A2G propagation model by using a constant factor η_{MU}, to incorporate the additional losses.

2) Member to Member Propagation Channel

This type of channel falls under the M2MC channel, forming an A2A type of radio link. We have used the short range and high bandwidth of 60 GHz MMWC for the communication between the Members. We considered the free space path loss calculation as described above and presented in equation (4.6), however in this case an additional path loss component η_{MM}, is included to account for atmospheric absorption caused by oxygen and water vapor molecules between two Members. This is because the high-frequency millimetre waves suffer greater attenuation in the air [5].

$$PL(dB) = FSPL(dB) + \eta_{MM} \tag{4.8}$$

3) Macro BS to User Propagation Channel

This type of channel forms the traditional Ground to Ground (G2G) radio link between the BS and its user. To determine the path loss for the LTE Macro BS to UE radio access channels we consider the ITU-R NLOS Path Loss Models for Urban Macro Cell environment as described in the previous section [4]. The path loss *PL* is formulated as,

$$PL = 161.04 - 7.1 \log_{10} W_b + 7.5 \log_{10} H_b \left(24.37 - 3.7 \left(\frac{H_b}{H_{BS}}\right)^2\right) \log_{10} H_{BS} + \left(43.42 - 3.1 \log_{10} H_{BS}\right)\left(\log_{10} d - 3\right) + 20 \log_{10} f - \left(3.2\left(\log_{10}(11.75 H_{UE})\right)^2 - 4.97\right) \tag{4.9}$$

where W_b and H_b are the widths and the average height of a building in the environment respectively, f is the centre frequency (GHz), d is the link distance (m), H_{BS} and H_{UE} are the antenna heights of the MBS and UE respectively.

B. Capacity Calculations

To evaluate the network throughput, we incorporate the modified alpha-Shannon capacity formulation [6]. Our simulation considers 2x2 MIMO transmission modes and 64 QAM as the modulation technique. The formulation to estimate the link throughput considers two fitting parameters, the bandwidth efficiency factor α, and the maximum target SNR efficiency factor ω. The capacity equation is given as,

$$C = \alpha * B * N_L \log_2\left(1 + \omega * \frac{N_R}{N_L} * 10^{\frac{SNR_{dB}}{10}}\right) \tag{4.10}$$

$$N_L = \min\{N_T, N_R\}$$

$$\alpha = ACLR * \eta_{cp} * \eta_{pilot} * \eta_{L1/L2}$$

$$\omega = 1 - \frac{M-1}{10^{\frac{SNR_{dB}}{10}}}$$

where, B is the system bandwidth (20 MHz), N_T is the number of transmit antennas, N_R is the number of receiver antennas, both equal to 2, SNR_{dB} is the signal-to-noise ratio in dB, *ACLR* (0.9) is the transmission performance measurement for wideband networks, η_{cp} (0.93), η_{pilot} (0.9) and $\eta_{L1/L2}$ (0.715) are the CP, pilot and Layer1/Layer2 overhead respectively, and M is the modulation technique type.

4.2.3. SIMULATION PARAMETERS

The minimum capacity requirement for each user in the SINR analysis has been taken to be 2 Mbps. Only the extra users that are not being served by the MBSs (due to overloading) in the AoE will be served by the Members. A maximum distance of 220 m has been considered between the Members to be able to communicate in the 60 GHz MMWC channel (calculations are done as per above-mentioned equations and link budget).

The remaining simulation parameters for the SINR Analysis are illustrated in the Table below.

Parameter	Value
Simulation Area	2000x2000 m^2
Propagation Environment	Urban Macro
Transmit Power Fixed BS/HANET	49/30 dBm
Simulation Frequency (f)	2 GHz
System Bandwidth LTE/MMWC	20/100 MHz
Antenna Gain BS/HANET/UE	17/10/0 dBi
Antenna Height BS/UE	25 /1.5 m
Antenna Configuration	2x2 MIMO
Modulation technique	64 QAM
Average DL Spectral Efficiency (SE)	2.2 /3 bps/Hz/cell
UE Receiver Sensitivity	-102.9 dB
Member Altitude	190 m
Cell Range Offset	7 dB
UE distribution	PPP (λ= 175 per km^2)
PTC user distribution	PPP (λ= 278 per km^2)
Inter-Site Distance (LTE)	500 m
Maximum Inter Member Distance (MMWC)	220 m
Building Height/Width	20/20 m
η_{MM}/η_{MU}	8/21 dB

Table 4.1 Simulation Parameters for the SINR Analysis [1]

4.2.4. RESULTS

The UMa network model (as described in section 4.2.1) with 22 UMa sites with randomly distributed UEs (according to PPP) are presented in Figure 4.3. The green dots represent the ground UEs. The Coverage and SINR plots of the UMa sites, which are depicted in Figures 4.4 and 4.5 respectively.

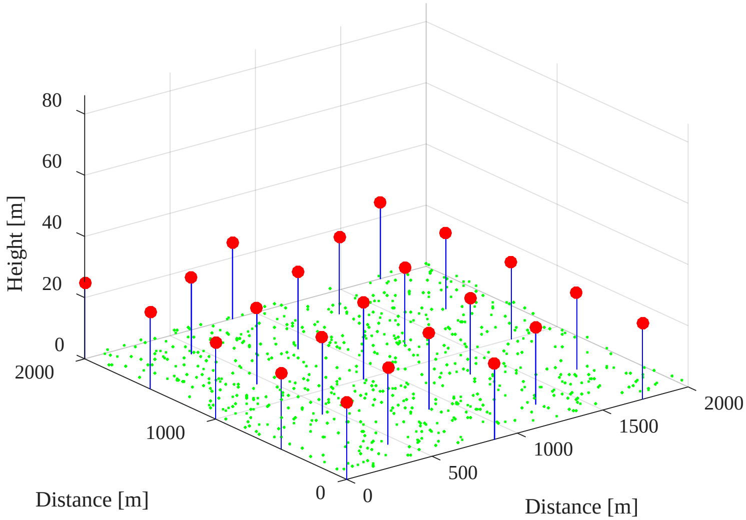

Figure 4.3 Urban Macro Network Model [1]

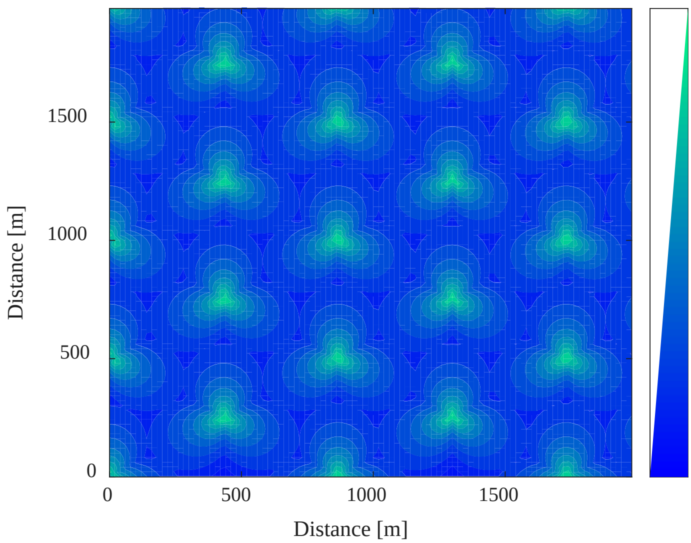

Figure 4.4 Coverage Plot of UMa Network Model [1]

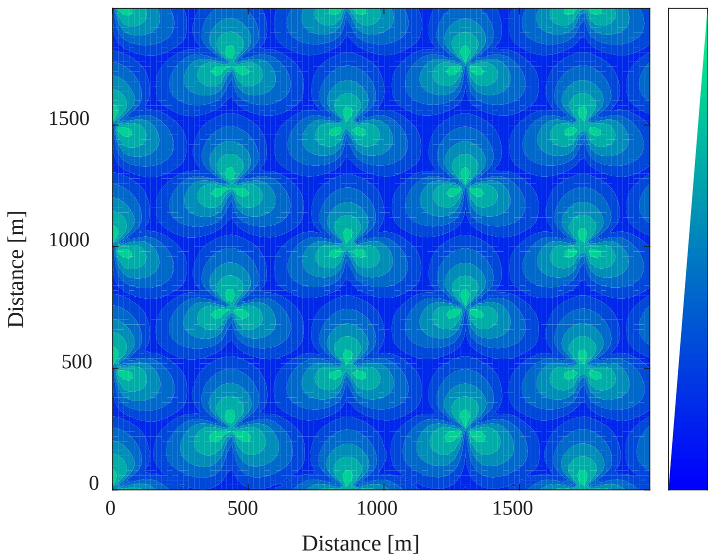

Figure 4.5 SINR Plot of UMa Network Model [1]

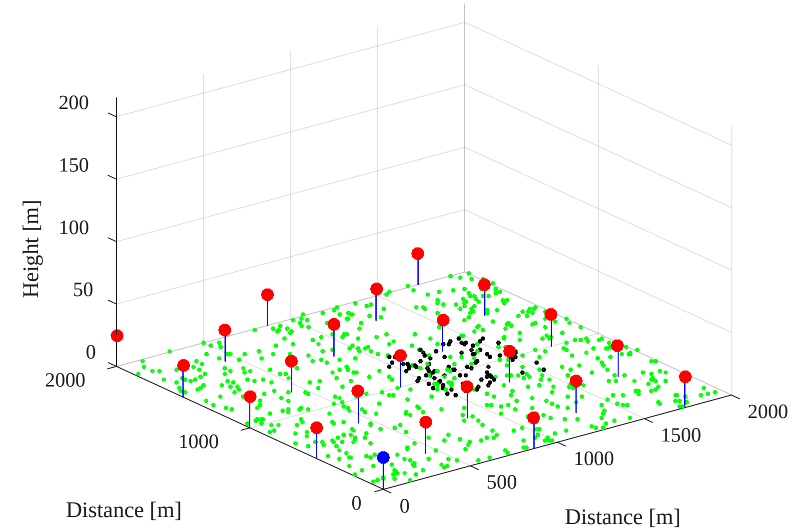

Figure 4.6 UMa model with PTC [1]

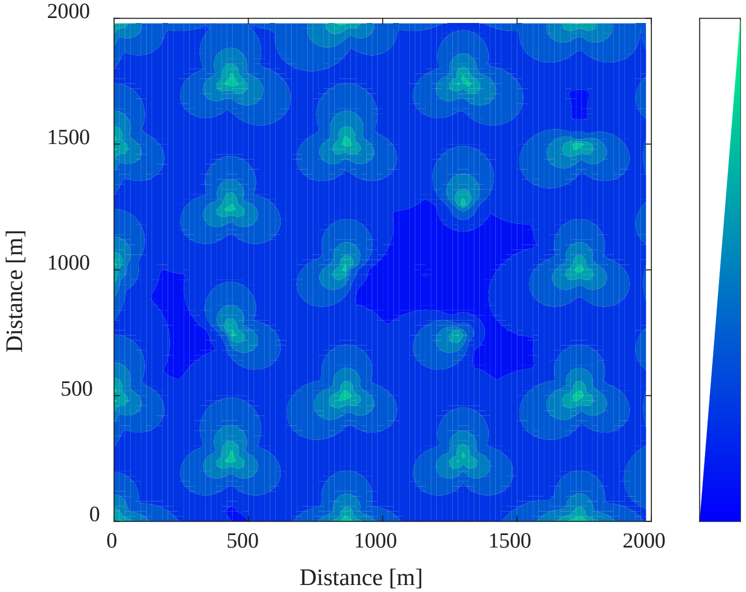

Figure 4.7 Coverage Plot after PTC generation [1]

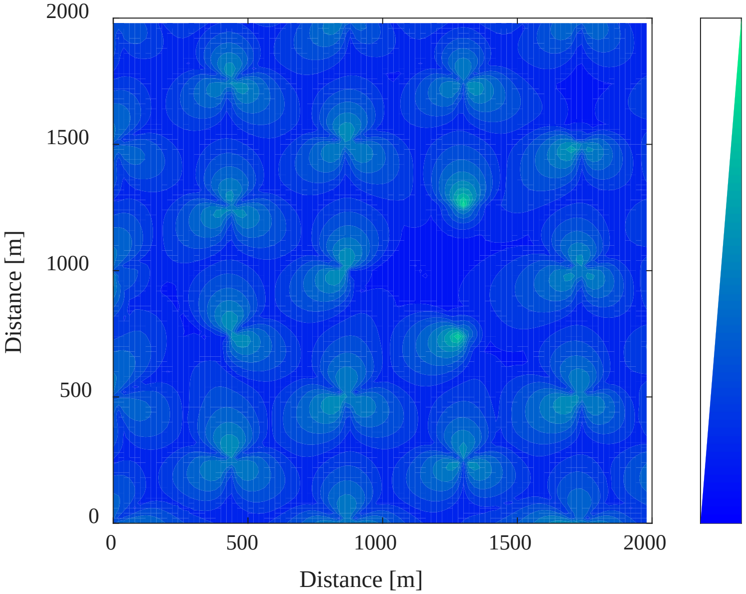

Figure 4.8 SINR Plot after PTC generation [1]

The PTC formation at the AoE, with accumulated UEs (in black), are shown in Figure 4.6. The accumulation of users at a specific region of the network area degrades the coverage and SINR levels in the AoE and can be clearly seen in Figures 4.7 and 4.8 respectively. We can observe that the range of SINR values have now deteriorated to below 0 dB at the AoE region only. The Coverage levels are also observed to be deteriorated with about 20 dB drop.

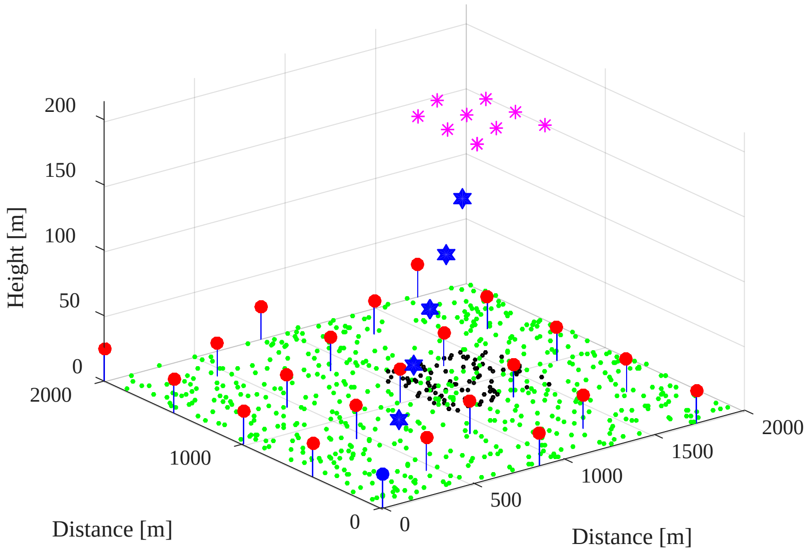

Figure 4.9 PTC handled by HANET team [1]

The deployment of HANET Members (HSMs in magenta) above the AoE is shown in Figure 4.9. The blue stars correspond to the HRMs forming a relay chain to the HGBS (blue UMa in the corner) to relay the user data. The association of the users of the respective serving sites after incorporating the cell range offset is illustrated in Figure 4.10. The colored users represent the association with the respective sites following the same color.

After the deployment of HSMs above the AoE, we can clearly observe an improvement in the Coverage and SINR levels. As depicted in Figures 4.11, the coverage levels now lie between -80 dB to -60 dB at the AoE region that was beyond -100 dB in Figure 4.7 without the HANET implementation. The SINR levels have also improved with minimum values around -4 dB which earlier was around -10 dB (Figure 4.12).

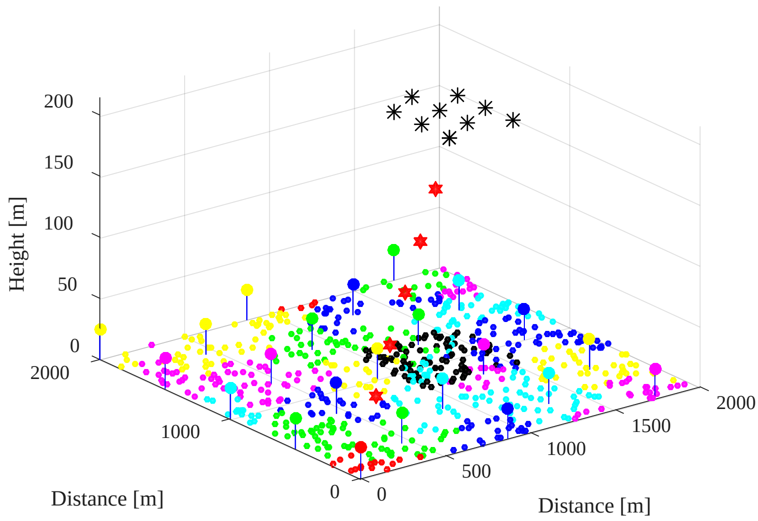

Figure 4.10 User association with respective sites [1]

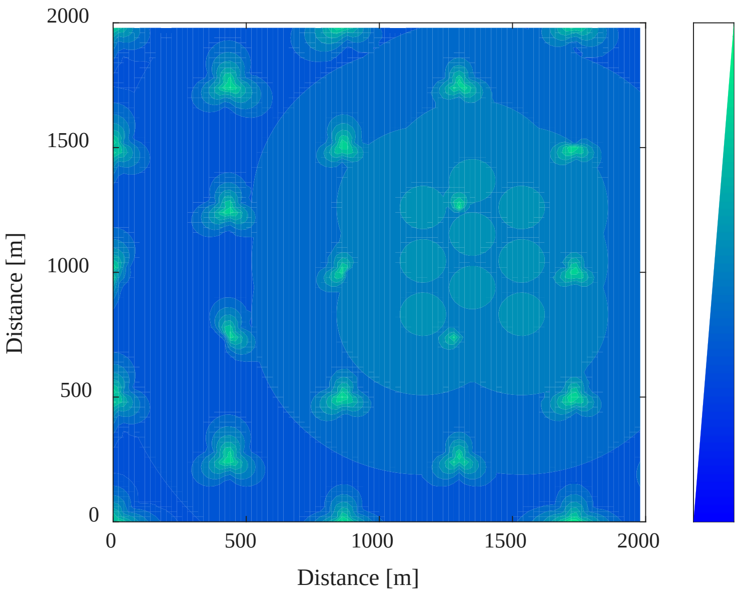

Figure 4.11 Coverage plot after HANET deployment [1]

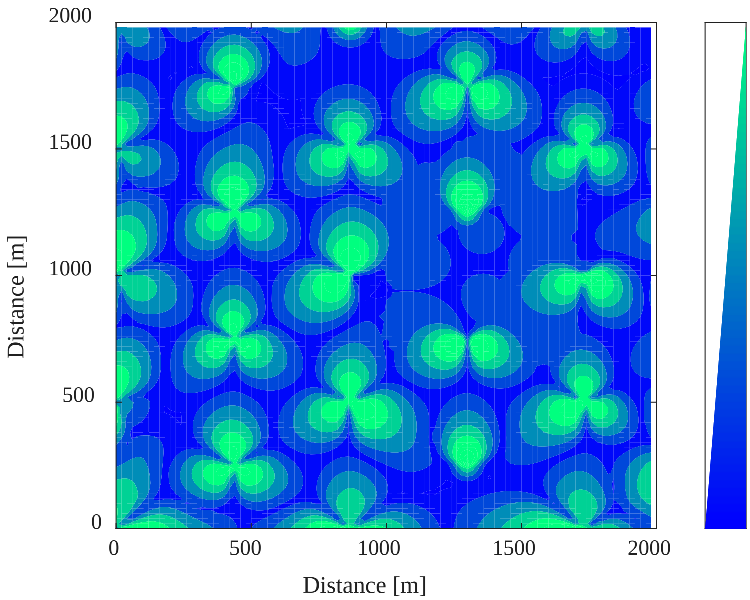

Figure 4.12 SINR plot after HANET deployment[1]

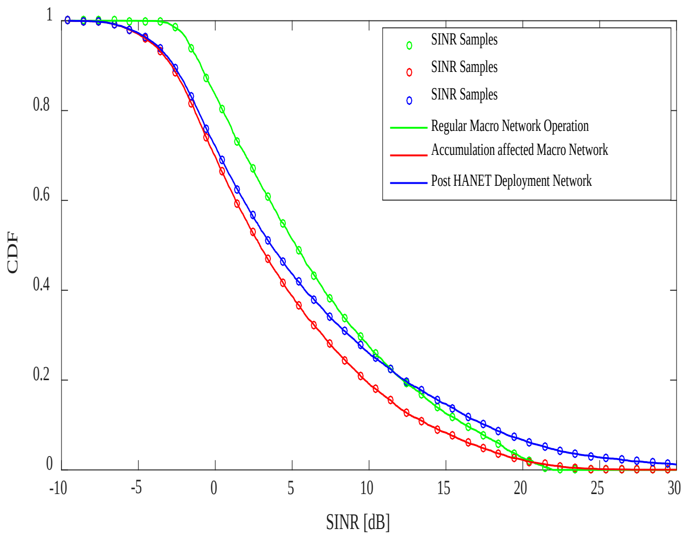

Figure 4.13 CCDF plot of SINR samples [1]

Finally, we compare the obtained SINR results using the Complementary Cumulative Distribution Function (CCDF) plots. We compare the SINR sample values for three simulated AoE case scenarios, namely, (i) Case I: Urban Macro operation only (legend color green), (ii) Case II: Urban Macro network under PTC problem (legend color red), and, (iii) Case III: Urban Macro network with HANET deployment at the AoE (legend color blue). The curve representing scenario Case II is significantly lower than that the curve is representing Case I, under the effect of significant user accumulations thereby affecting the user SINRs. Further, the curve representing vase III initially falls between Case I and Case II, however, dominates in the later portion. This is because the Members were deployed with the target of serving the group users that were severely impacted due to PTC problem. The scattered individual users at the edges of the cells and the boundaries of the AoE were not covered, as the deployment of the HANET team is not optimized in terms of their positions and locations. Covering every edge user will result in deploying more number of Member sites. Due to this reason, not much improvement in the SINR is seen for the users with allowed value of SINRs. However, for the users that are close in the distance to either of the associated sites (Members or Macros), experience a significant improvement in their SINR values from Case II and eventually better SINRs from regular operation of scenario Case I due to the additional Member site deployment.

4.3. CELL RANGE EXTENSION ANALYSIS

Heterogeneous networks (HetNets) are composed of multiple cellular sites of different cell types and configurations. The network expansion of the existing network is performed by densifying the network with small pico cells. The high-power Macro cells offload the user traffic to low power small pico cells to expand the capacity of the network. In our case, we employ the low power, low altitude aerial radio Members functioning as flying pico cells to offload the extra load in the network. As PTC-driven situations are high user service scenarios, it is important that enough users be served by the Members and aid in offloading the Macro sites. We perform the Member cell enlargement by adding a cell range extension bias to attain a sufficient number of users with the Members. Hence, Cell Range Extension (CRE) plays an important role in performing the required user association with the available serving sites [7].

4.3.1. SIMULATION ASSUMPTIONS

The CRE simulation analysis is also evaluated on the Urban Macro (UMa) network model as per guidelines are given in ITU M.2135-1 report for evaluating IMT-A case scenario [4]. We perform the downlink evaluation of the CRE analysis with SIIARA implementation on 3D Urban Macro for three cases, (i) Macro only, (ii) Macro with PTC and, (iii) Macro with PTC and SIIARA implementation. In the first case, we create 3D UMa network with Macro sites each having three sectors distributed with an Inter-site distance of 500 m. The number of active users as given by ITU-R guidelines is 30 for each site. In the second case, we generate a PTC causing user accumulation with the network users drifting towards a specific region (AoE) in the network representing carnival/parade like situation. The Macro sites are falling in the region of AoE and are shown to be overloaded due to the influx of extra users at the AoE. Finally, we execute the working of SIIARA by placing Members above the AoE region and observing the improvement in throughput achieved by the users over the first and second cases. We evaluate the performance of the cellular network performance after SIIARA implementation in assistance to Macro network over variable PTC user distributions and cell range expansions. The influence of different values of CRE bias on the user throughputs will be made to find the optimal throughputs, and the results will be shown in the next section.

4.3.2. TECHNICAL ASSUMPTIONS

A. Member to User/BS Propagation Channel

In the previous sub-section, for the SINR Analysis, we had employed the Free Space Path Loss model. However, it is the simplest model for evaluating the signal path loss. As the serving sites are flying in the air, it would be more appropriate to consider a propagation model that calculates the path loss considering the aerial characteristics of the signal transfer. The signal propagation characteristics of aerial radio networks differ from the terrestrial radio channels with a probability of having Line of Sight (LoS) at most of the times. Hence, in the current analysis, we utilize the Air to Ground propagation channel for the Dense Urban environment as derived in [8] and [9], which have been modeled based on the environment specific parameters for radio propagation as defined by ITU [10]. The total path loss calculation includes free space path loss and an additional path loss occurred due to multipath fading as the signal reaches the urban environment. This model considers mean value (expectation) of the path loss. Hence, η for both LOS and NLOS refers to the mean value of the excessive path loss. The Air to Ground path loss accounts for the LOS probability and is given by,

$$PL_{avg} = \frac{A}{1+a\ exp\left(-b\left[arctan\left(\frac{H}{R}\right)-a\right]\right)} + 10\ log\left(H^2+\boldsymbol{R}^2\right) + B \tag{4.11}$$

where, $A=\eta_{LOS}-\eta_{NLOS}$

$$B=20\ log\ f+20\ log\left(\frac{4\pi}{c}\right)+\eta_{NLOS}$$

This channel model utilizes two constants, *a* and *b*, their values are dependent on the environment was chosen. The probability of LOS depends on the height *H* of the member from the ground level and the horizontal distance R between the member and the ground user (cell radius). The centre frequency is given by f (Hz), and c corresponds to the speed of light ($3x10^8$ m/s). Here, η refers to the mean values of the excessive path loss for LOS (η_{LOS}) and NLOS (η_{NLOS}) connectivity in dB. The distance between HANET member and ground user D is related to H and R as $\sqrt{H^2+R^2}$ (depicted in Figure 4.14 below).

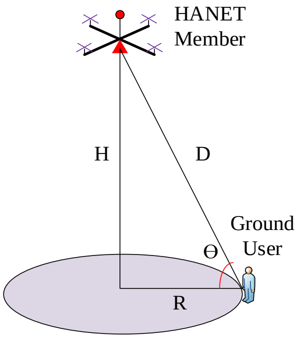

Figure 4.15 Cell Footprint of a Member [2]

B. CRE Calculations

We obtain the Member Cell Range Expansion by a procedure in which each user performs cell selection depending on CRE bias τ, and downlink receive power (P_r) as follows,

$$P_r\_apparent = P_r\_actual + bias \qquad (4.12)$$

$$Serving\ Cell = argmax\ \{RSRP + bias\} \qquad (4.13)$$

One of the drawbacks of incorporating positive CRE is that the users along the cell range expanded boundaries of the associated HANET cells still accept the received power from the Macro cell which is higher than the power received from the HANET cell. These users belonging to the CRE zone might be susceptible to high interference from Macro cells due to co-channel operation leading to severe downlink inter-cell interference (ICI). To avoid this interference, the total spectrum available of 20 MHz (100 RBs) is partitioned as 15MHz (75 RBs) for the Macro cells and 5 MHz (25 RBs) for the SIIARA members (as described previously). Such a spectrum partition will help to have entirely different resource block allocation to the users belonging to two distinct layers of sites and hence result in lower interference in the network. This spectrum partition is performed only with the

Macro sites covered in the AoE region. As soon as the Macro sites fall out of the AoE region, they regain their spectrum for their regular operations.

4.3.3. SIMULATION PARAMETERS

The simulation parameters for the CRE Analysis are illustrated in the Table below.

Parameter	Value
Simulation Area	2000x2000 m^2
Propagation Environment	Urban Macro
Macro Network Topology	Hexagonal Grid
Inter-Site Distance (LTE)	500 m
Number of Macro sites	30
Number of cells/sectors per site	3
Simulation Frequency (f)	2 GHz
System Bandwidth LTE/MMWC	20/100 MHz
a/ b/ η_{LOS}/ η_{NLOS}	12.08/0.11/1.6/23
Number of Users	30 per site
User Distribution	Random and Uniform
Antenna Gain BS/HANET/UE	17/10/0 dBi
Antenna Height BS/UE	25 /1.5 m
Transmit Power Fixed BS/HANET	49/30 dBm
Average DL Spectral Efficiency (SE) BS/HANET	2.2 /3 bps/Hz/cell
UE Receiver Sensitivity	-99.79 dB
Member Altitude	108-172 m
Cell Range Extension	6 dB
Scheduler	Fair Resource Sharing
AoE region	600x600 m^2
PTC user density	50,100,200,300,400
Maximum Inter Member Distance (MMWC)	Maximum 220 m
Building Height/Width	20/20 m
η_{MM}	8 dB

Table 4.2 Simulation Parameters for the CRE Analysis [2]

4.3.4. RESULTS

In the CRE Analysis, we consider the same three Cases for comparison through the CCDF plots as described in section 4.2.4. We start with presenting the user throughputs calculated for all the cases without incorporating a CRE bias and give a comparative CCDF plots in Figures 4.15 and 4.16. We investigate Cases II and III with different PTC UE accumulation densities, namely (i) 50 UEs, (ii) 100 UEs, (iii) 200 UEs, (iv) 300 UEs and, (v) 400 UEs, in the same region of the AoE within the network area. Figure 4.15 represents the impact of the accumulations on the user throughputs for all above-mentioned user density scenarios. The plot clearly shows how the user throughputs are degraded from Case I to Case II, as we increase the number of extra users from 50 to 400 in the AoE. We can observe that the degradation in throughput values with increasing number of extra users in the AoE. The Case III corresponds to the case after the HANET deployment above the AoE. Further, an improvement in the user throughputs under all the user density scenarios is seen for Case III as illustrated in Figure 4.16. The impact of incorporating a CRE bias on the user throughputs for all the user density scenarios is shown in Figure 4.17. In the previous result (Figure 4.16), we observed that due to the dominant downlink received signal strength from the UMa sites, the UEs were not able to associate with the Members, despite having room for handling more number of users. Due to this, the UMa sites were still suffering from an overloading condition even after the deployment of the Member sites. A CRE bias of 6 dB was incorporated to make more UEs to get connected to the Members. A significant improvement in the user throughputs, notably for the cell-edge users after incorporating CRE bias were observed and are illustrated in Figure 4.17.

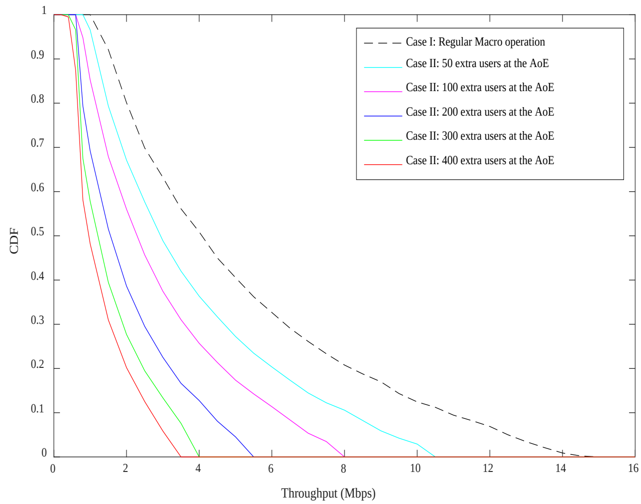

Figure 4.16 CCDF curves of UE Throughputs for Cases I and II [2]

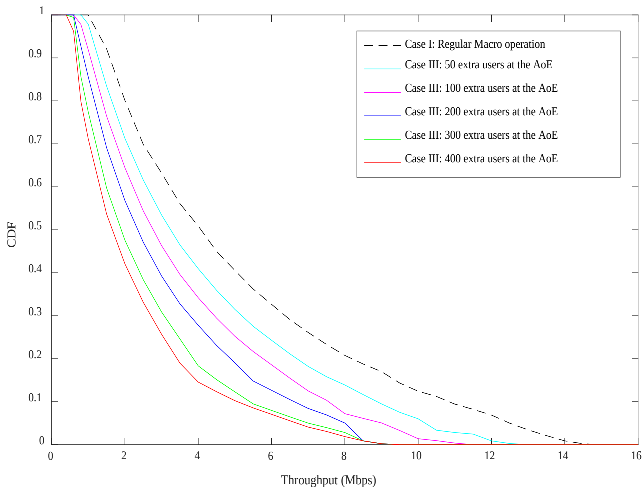

Figure 4.17 CCDF curves of UE Throughputs for Cases I and III [2]

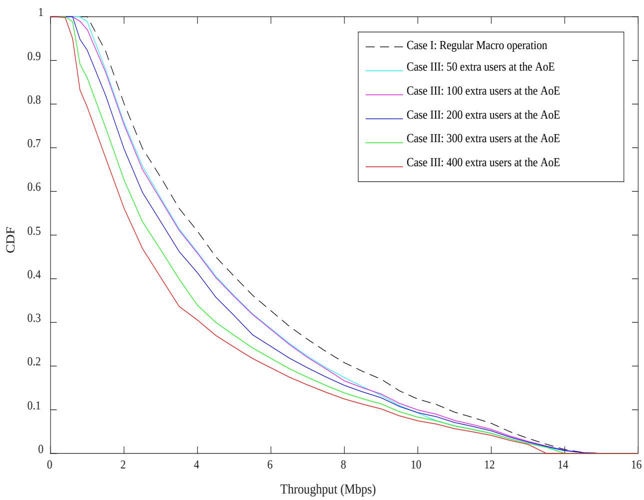

Figure 4.18 CCDF curves of UE Throughputs with CRE consideration for Cases I and III [2]

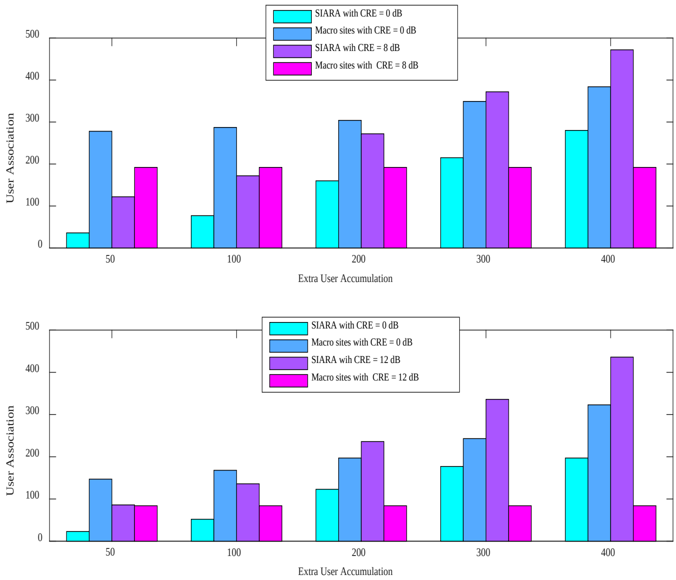

Figure 4.19 UE Association with CRE Optimization [2]

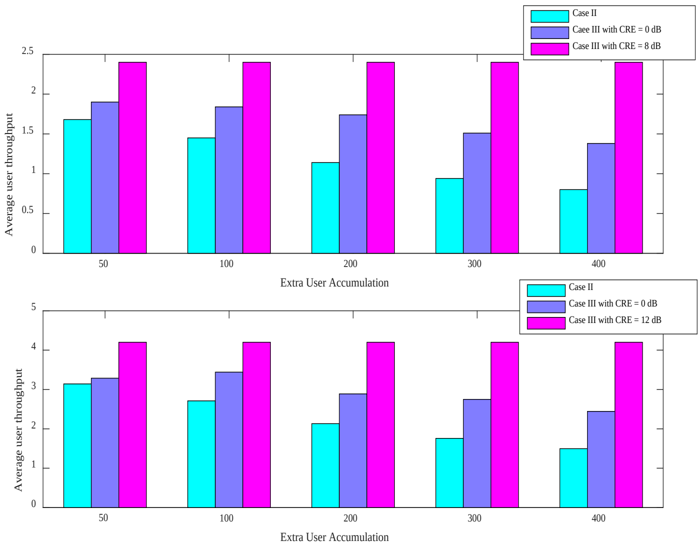

Figure 4.20 Average User Throughput Improvement for optimized CRE = 8,12 dB [2]

We now perform CRE optimization for two conditions of the user throughput thresholds of, (i) 2 Mbps and, (ii) Maximum achievable throughput of 4.4 Mbps, that can be offered by a UMa site with the given load conditions. The CRE optimization means that an optimum bias value is identified beyond which the user throughputs become unaffected. It was observed that for the first condition, the CRE optimized value obtained was 8 dB and for the second condition, the CRE optimized value obtained was 12 dB. The user association with UMa sites and Member sites for CRE = 0 dB and, optimized CRE = 8 dB, 12 dB for the above-mentioned conditions (i) and (ii) respectively are depicted in Figure 4.18. It can now be observed that more number of users have associated with the Member sites after the incorporation of optimized CRE biases. This CRE inclusion resulted in better offloading of the UMa sites.

We present our obtained for the average user throughputs achieved for Case III using the optimized CRE bias of 8 dB and 12 dB and compare them with the values obtained for Case II. Figure 4.19 presents this comparison, and we can notice a visible increase in the average throughput values for all the user density scenarios. It is clearly seen that the values are constant for the optimized CRE bias cases as beyond this value; there is no significant effect on the achievable user throughputs.

4.4. AERIAL-HETNET PERFORMANCE ANALYSIS

We have previously discussed the concept of Aerial-HetNet in Chapter 3. Here we present a performance analysis of HANET as a deployment of Aerial-HetNet and investigate different case scenarios of PTC generation.

4.4.1. SIMULATION ASSUMPTIONS

The network area considered and the other technical assumption for the Aerial-HetNet analysis is same as taken for the CRE analysis (refer section 4.3.2). Some of the other simulation assumptions are mentioned below.

1. User SINR Estimation: For the estimation of SINR, calculations are done by dividing the simulation area into small sample areas, and the SINR is estimated from each user location falling in each of the sampled area element.

2. Network SINR Estimation: We assume that when a user moves from one sector of a site to another sector of the same/different site, the SINR conditions at the leaving sector is improved and the SINR conditions at the arriving sector are deteriorated. This is experienced by all the users falling in their respective serving zones due to the migration. Migration of a single user can affect the SINR of the whole network. Hence, we present the network SINR keeping in view the points mentioned above.

3. We perform our calculations on HANET team deployment depending on the PTC generation characterized by, (i) User Accumulation Density and, (ii) AoE size. We investigate two case studies with different values of user accumulation density and size of the AoE.

4. The HANET deployment is in the formation of Aerial-HetNet, which means that the HSMs adopt variable altitudes in the space. This is determined based on the received signal levels at the various user locations. The HSMs above the weak signal areas place themselves at a lower height, and the HSMs above the strong signal areas are placed at a higher height.

5. We consider the following test case scenarios of PTC generation for our simulations and analysis:
   - Case (a): 300 UEs in 100 x 100 m^2AoE region.
   - Case (b): 800 UEs in 400 x 400 m^2AoE region.

4.4.2. SIMULATION PARAMETERS

The simulation parameters for the Aerial-HetNet Analysis are illustrated in the Table below.

Parameters	Value
Simulation Area	3000 x 3000 m^2
Channel Model	Urban Macro (UMa)
Network Layout	Hexagonal Grid
Inter-Site Distance (LTE)	500 m
BS Transmit Power	49 dBm
Carrier Frequency	2 GHz
System Bandwidth for LTE BS	20 MHz
Antenna Gain BS/UE	17/0 dBi
Antenna Height BS/UE	25 /1.5 m
BS Average DL Spectral Efficiency	2.2 bps/Hz/cell
Building Height/Width	20/20 m
Member Transmit Power	30 dBm
System Bandwidth MMWC	100 MHz
MemberAntennaGain	10 dBi
Member Average DL Spectral Efficiency	3 bps/Hz/cell
BS User/ PTC User Distribution	PPP
Air to Air Propagation Model	see equation (4.6,4.7)
Ground to Ground Propagation Model	see equation (4.9)
Number of Sectors – Member	1

Number UEs per Macro BS	30
Air to Ground Propagation Model	see equation (4.11)
a/ b/ η_{LOS}/ η_{NLOS}	12.08/0.11/1.6/23
Member Altitude (m)	variable as per the case
Cell Range Offset	7 dB

Table 4.3 Simulation Parameters for the Aerial-HetNet Analysis [3]

4.4.3. RESULTS AND DISCUSSIONS

The Urban Macro network model is shown in Figure 4.20. The scattered UEs are shown in yellow dots. Figure 4.21, illustrates the user association with respective UMa sites. The Coverage and SINR plots of UMa sites are depicted in Figures 4.22 and 4.23 respectively. The accumulation representing Case (a) and Case (b) are illustrated in Figures 4.24 and 4.33, where the accumulated UEs are shown in black dots. The accumulation occurs due to the migration of UEs from the nearby network areas. The Coverage and SINR plots after the accumulations are depicted in Figures 4.24 and 4.25 respectively for Case (a) and Figure 4.34 and 4.35 respectively for Case (b). We observe deterioration in the values of both coverage and SINR levels after the accumulation at the AoE.

The Aerial-HetNet deployment in the formation of Aerial-HetNet for both the cases is depicted in Figures 4.26 and 4.36 respectively. The pink asterisks represent the HSMs, and the blue stars represent the HRMs, forming a relay chain to a chosen HGBS (blue dot). The Coverage and SINR plots after the AH deployment are depicted in Figures 4.30 and 4.31 respectively for Case (a) and Figures 4.37 and 4.38 respectively for Case (b). We can observe improvement in both Coverage and SINR levels at the AoE in both cases after the AH deployment.

Lastly, we, explain the variations in SINR using the CCDF plots for both the cases. We consider the same test case scenarios as explained in section 4.3.4. In Case (b), 300 UEs are accumulated and distributed in the AoE region of 100 x 100 m^2. The UEs have migrated from the nearby sectors to the AoE. The green curve depicts the SINR response of the regular UMa operation. The red curve represents the network SINR response for the post-accumulation case. We observe that the network SINR have deteriorated by the PTC congestion occurred at the AoE. The blue curve represents post AH deployment case, and we observe that there is an improvement in the network SINR but not significantly. This is because quite many Members place themselves according to the requirements above the AoE and the UEs which are associated with the Member sites experience and interference from the other Member site users in the Aerial-HetNet, due to their proximity in the aerial distance. In this case, we observe a marginal improvement in the overall network SINR even after the deployment of the HANET.

In the case of Case (b), 800 UEs accumulate at the comparatively large area of 400 x 400 m^2. More users have now drifted towards the AoE, and there is a net drop in network SINR as compared to the Case (a), and the impact of the accumulation is more, in this case, resulting in heavier PTC congestion. As the user density is high at the AoE, the Member constellation is also dense. However, because the AoE region is large, the Members are placed distantly resulting in reduced intra-HANET interference. Hence, we observe a better improvement in the network SINR in this case.

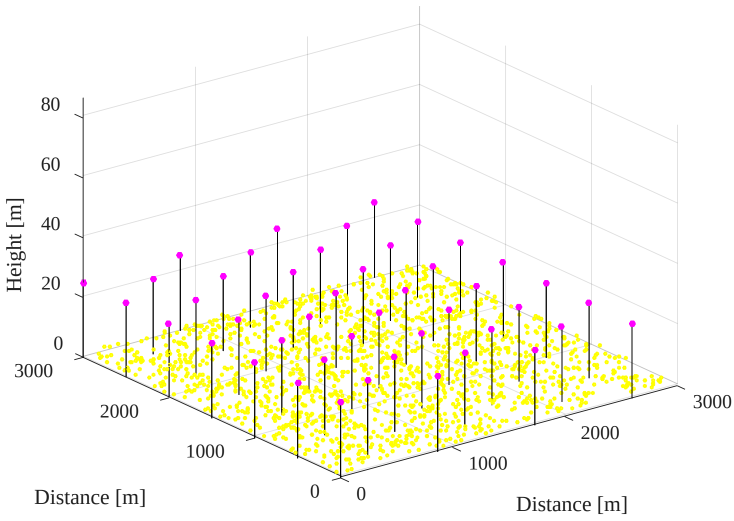

Figure 4.21 Urban Macro Network Model [3]

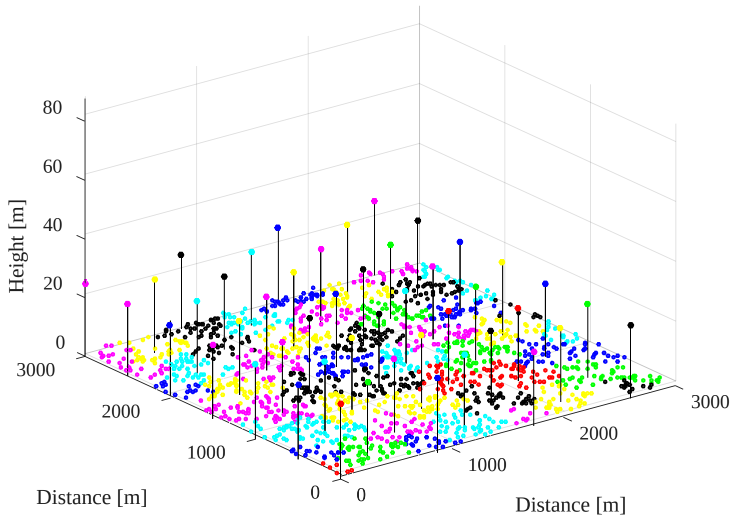

Figure 4.22 User association with respective sites [3]

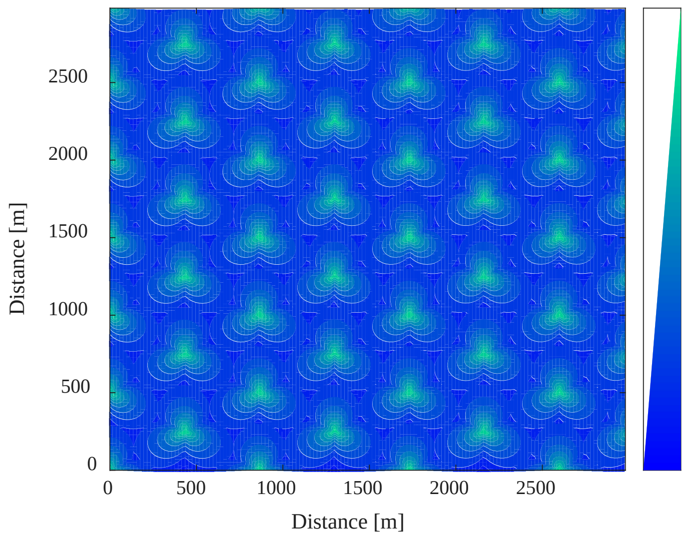

Figure 4.23 Coverage plot of UMa [3]

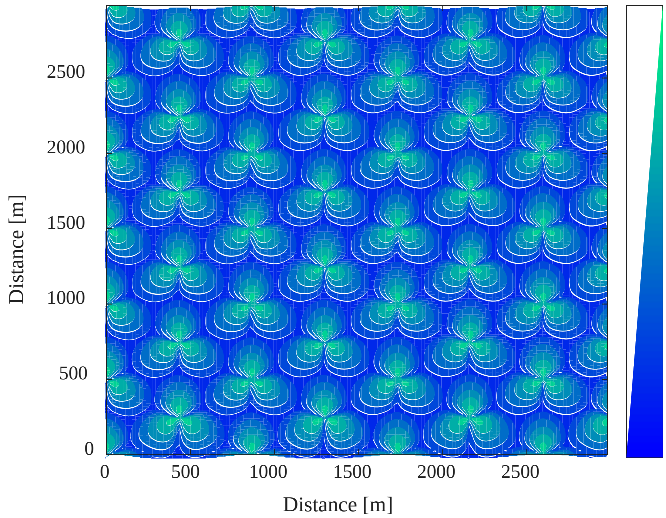

Figure 4.24 SINR Plot of UMa [3]

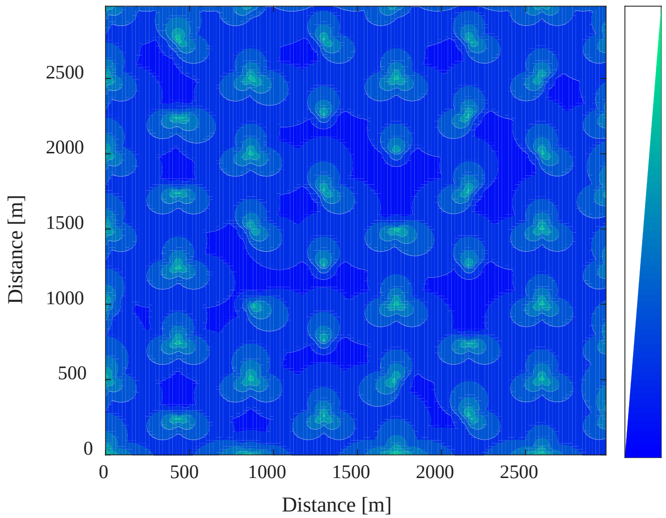

Figure 4.25 Coverage plot of UMa with scattered UEs

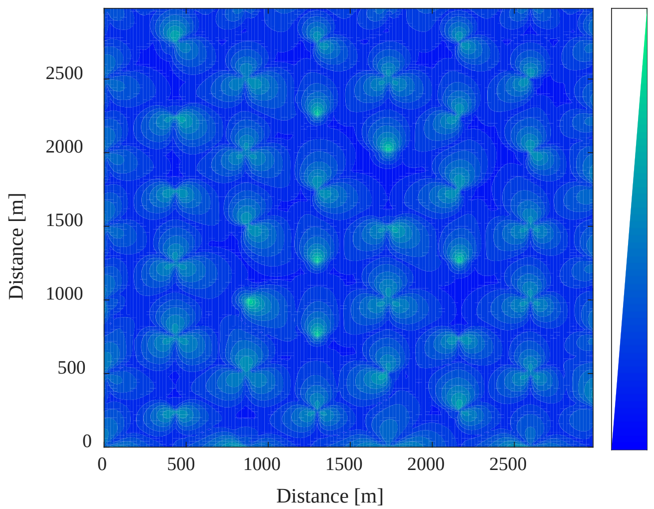

Figure 4.26 SINR plot of UMa with scattered UEs

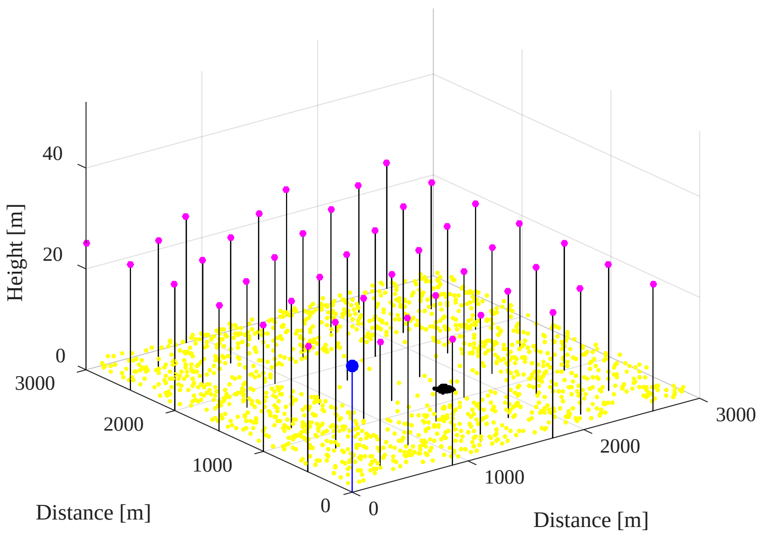

Figure 4.27 UE migration to form AoE – Case (a) [3]

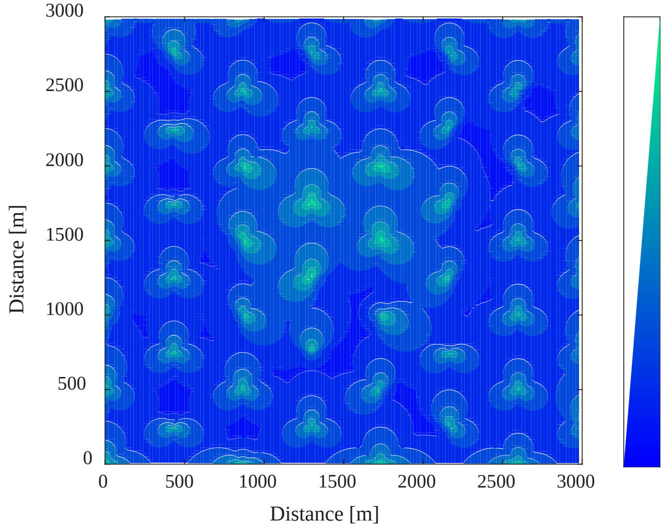

Figure 4.28 Coverage plot after accumulation

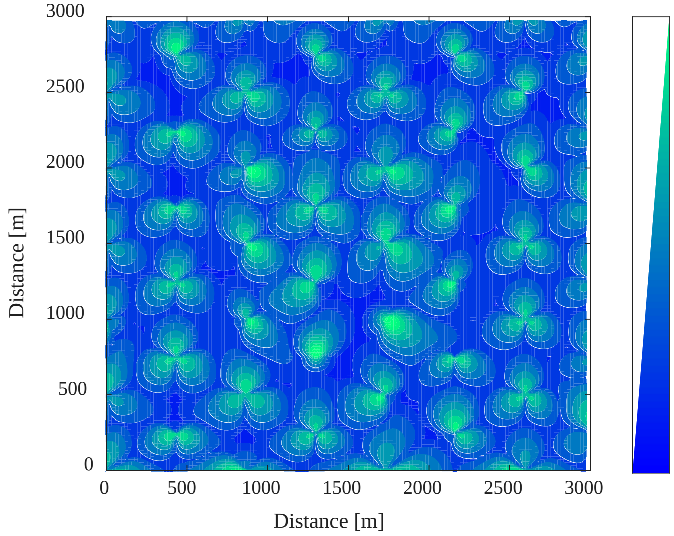

Figure 4.29 SINR plot after accumulation

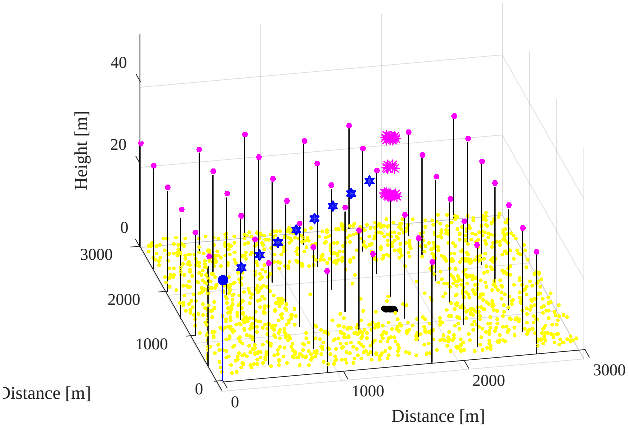

Figure 4.30 Aerial-HetNet Deployment for Case (a) [3]

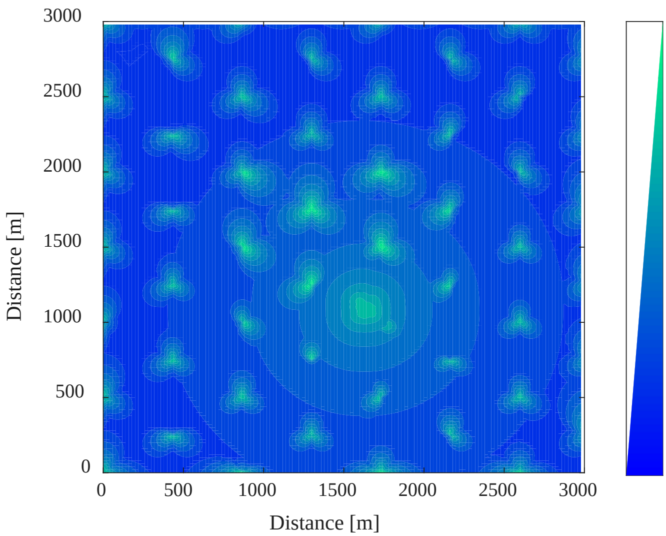

Figure 4.31 Coverage plot after Aerial-HetNet deployment

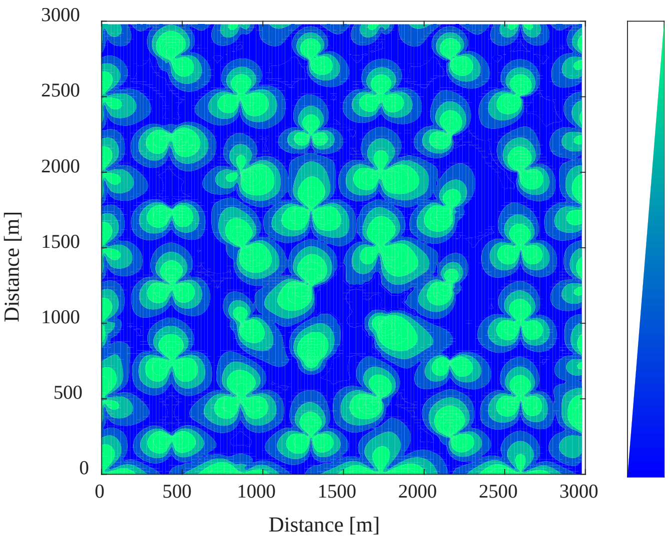

Figure 4.32 SINR plot after Aerial-HetNet deployment

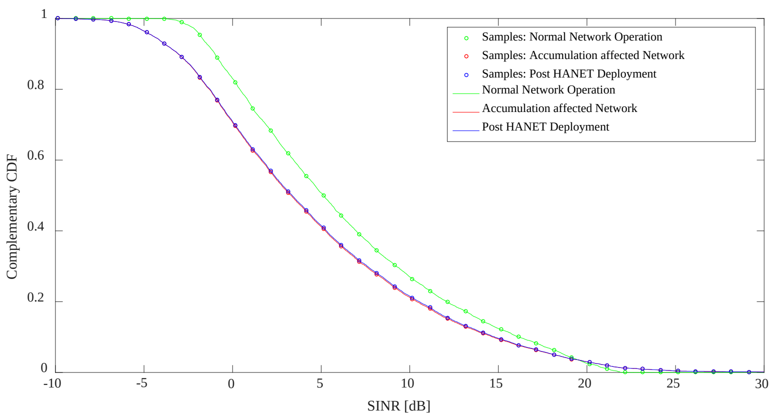

Figure 4.33 CCDF plot of SINR samples – Case (a) [3]

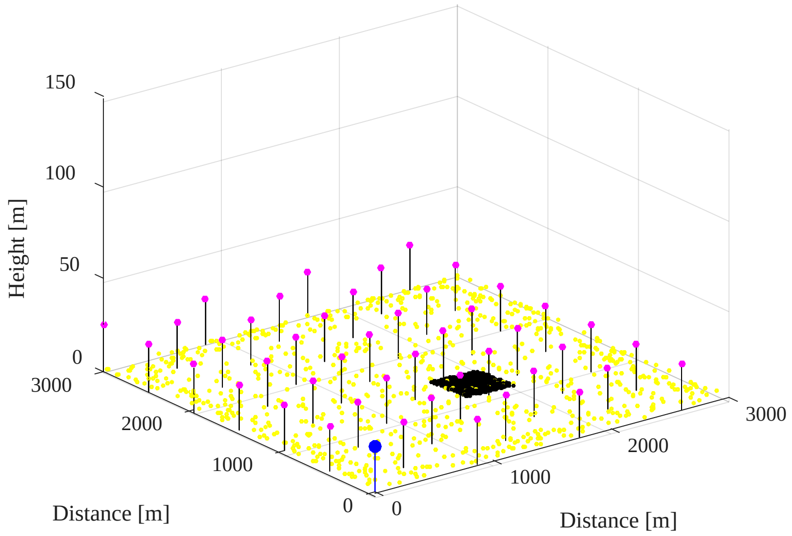

Figure 4.34 UE migration to form AoE – Case (b) [3]

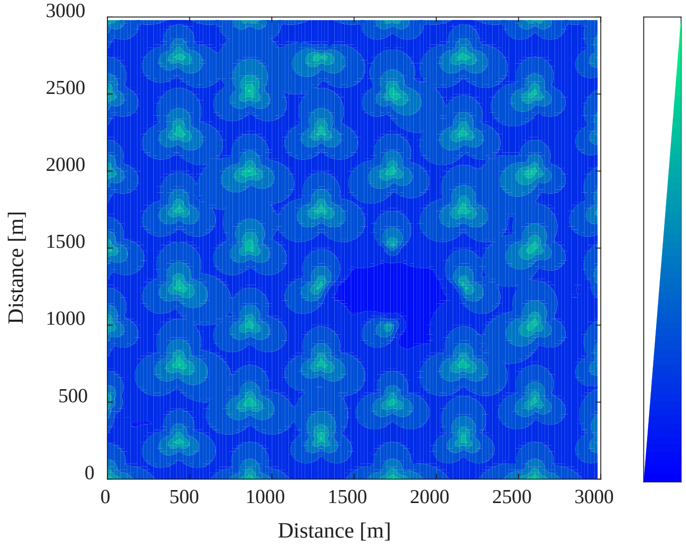

Figure 4.35 Coverage plot after accumulation

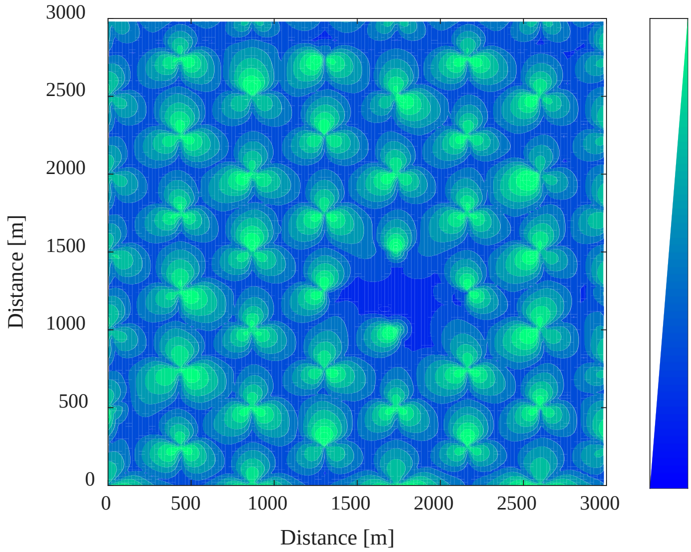

Figure 4.36 SINR plot after accumulation

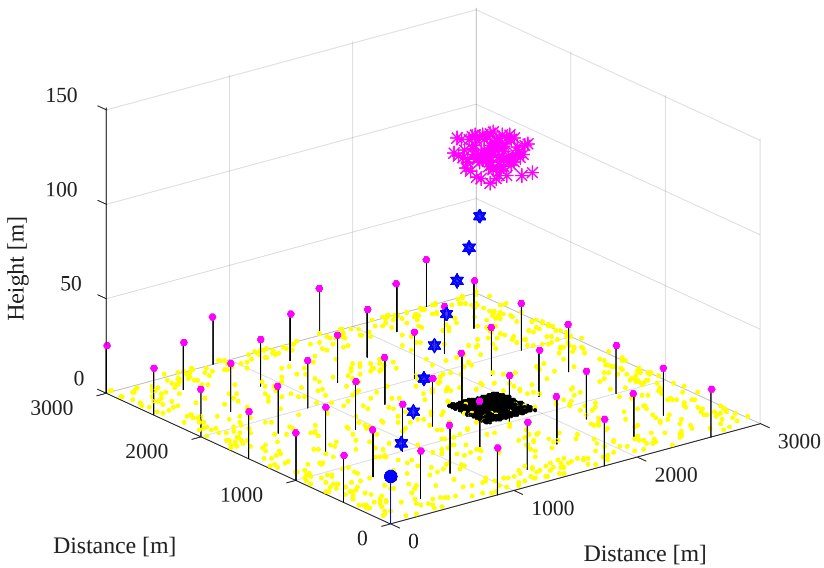

Figure 4.37 Aerial-HetNet deployment for Case (b) [3]

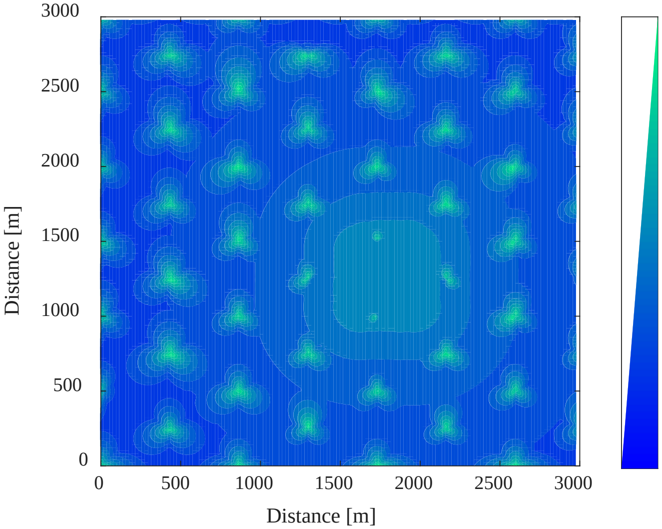

Figure 4.38 Coverage Plot after Aerial-HetNet deployment

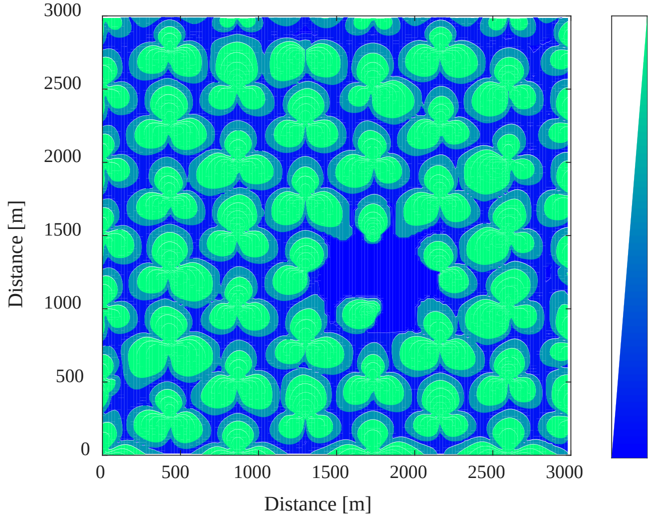

Figure 4.39 SINR Plot after Aerial-HetNet deployment

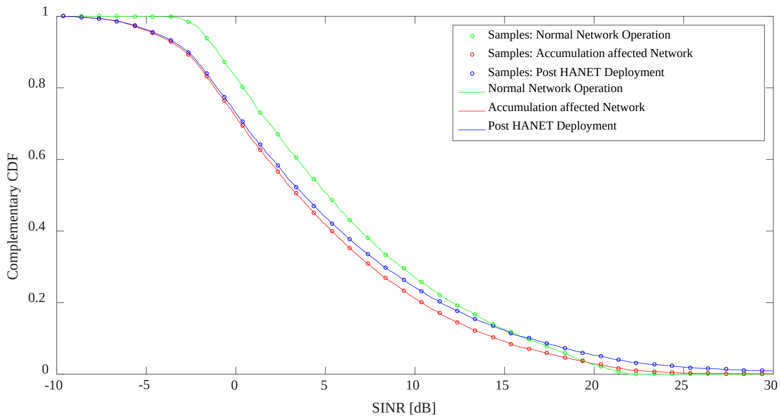

Figure 4.40 CCDF plot of SINR samples – Case (b) [3]

4.5. CONCLUSIONS

In this chapter, we have presented the Radio Analysis of our proposed aerial architecture. We have investigated three aspects of the Radio Analysis. We started with the SINR Analysis of HANET, where we see an improvement in the SINR at the user locations at the AoE after the degradation due to PTC generation. Then we gave an analysis on the User Throughputs through CRE evaluation, wherein we investigated the impact of different CRE biases on the achievable User throughputs. We observed that identifying and applying an optimized value of CRE bias yields better user throughput values. Finally, we have presented and investigated a novel dimension of Aerial-Heterogeneous Networks in this chapter. The analysis was examined through two different case studies and results obtained demonstrated a positive effect on deploying Aerial-HetNet in a PTC affected network region.

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CHAPTER 5. THE BACKHAULING NETWORK ANALYSIS OF THE AERIAL RADIO ARCHITECTURE

The previous Chapter presented the first part of the analysis of our proposed architecture i.e. the Radio Analysis. We had shown the improvement in the radio parameters that were considered, under the deployment of our proposed aerial radio architecture. In this chapter, we will elaborate the second part of the analysis which is the Backhauling Analysis, which covers and investigates our proposed concept of '*Distributed Dynamic Backhauling*' in SIIARA. We shall examine the performance of the intelligent algorithms applied to support our proposed concept of Distributed Dynamic Backhauling.

We will begin this chapter by giving a brief state of the art w.r.t. Backhauling in the aerial cellular networks. Then we will discuss our proposed concept along with our proposed Intelligent Rank Based (IRB) algorithm to execute the Distributed Dynamic Backhauling in a HetNet based Urban Macro environment. Finally, we will demonstrate the results with supporting discussion and arguments.

5.1. STATE-OF-THE-ART

Talking about the small cell deployment, the mobile operators are presently facing the challenge of backhauling the traffic from the small cell sites to the core network [1]. There can be two possible solutions for the backhauling namely, (i) *Wireline Solutions* and, (ii) *Wireless Solutions*. The Wireline Solutions prefer the copper and fiber backhauling, but the reachability to a large number of small cells with very small inter-cell distance makes it economically and practically not a good option, especially in developing countries like India [2] [3]. The alternate solution of Wireless Backhauling includes using the microwave (below6 GHz) and millimetre waves (above 6 GHz) [4] [5] i.e. Free Space Optics [6]. A much of the attention has been given in using the 60 GHz (V-band) that could be an optimal solution at the street level. Some of the benefits of 60 GHz band include (i) environment-friendly band (low power), (ii) unlicensed, (iii) high capacity and, (iv) low latency [7].

In our research work, we propose small cells in terms of small aerial cellular nodes that will operate to assist the ground network in addressing the sparse & peaky traffic arose during heavily crowded events. The backhauling of the aerial cellular networks is a less studied topic and has not been explored much in the literature. Though, of late some researches have been performed in using the aerial base stations in the cellular backhauling field. Some authors have proposed the use small

UAVs as relays to improve the reliability of wireless backhaul networks formed with high-altitude balloons launched into the stratosphere to carry wireless transceivers [8]. Their idea of using UAVs owes to the problem of the wireless links (e.g. FSO or MMW links) that can cause the link instability in the backhaul network.

The 'ABSOLUTE' project have introduced a novel cluster-head selection approach in an aerial backhauled network to cluster the wireless nodes on ground fields, through the assistance of aerial base stations [9]. They have further investigated the possibility of using a WiFi-based link between two Low Altitude Platforms (LAPs) for backhaul and, modeled the Hand Over process over the WiFi backhaul [10]. They have further suggested, Satellite and WiFi as candidate solutions for wireless backhaul in aerial networks [11] [12]. They have put across the advantages of Satellite backhauling (Ka band) with extensive coverage offering but also mention the drawback of delays due to long links. An alternate solution suggested by them is to use WiFi links, but on the other hand, this solution can lead to reduced coverage and capacity.

Recently, in [13], investigations were performed in using UAVs to transport the backhaul/fronthaul traffic between the access and core networks via point-to-point FSO links. Their investigation was done under different weather conditions and system parameters, and they observed that the proposed UAV backhaul/front haul framework offers higher data rates compared to the baseline alternatives like terrestrial FSO.

In this chapter, we will introduce our proposed framework of utilizing the HANET Members in backhauling the user traffic under severe congestion conditions.

5.2. DISTRIBUTED DYNAMIC BACKHAULING IN SIIARA- THE CONCEPT

As discussed in Chapter 3, the SIIARA works as an independent architecture, which means that it can completely deliver the services to the users as well as backhaul the data. As network architecture, the SIIARA manages and processes the SIIARA-bound users without any external assistance of the ground network. This is performed through the GAVH (described in Chapter 3), which is responsible for connecting and relaying data between any two HANET systems within the SIIARA. However, the users in the SIIARA trying to call the users associated with the ground network, or vice-versa, can only be performed if there are suitable backhaul links available between the two operating networks of SIIARA and the ground network respectively. The HANET systems must provide alternate paths to sink the user traffic back to the core network by making use of some potential ground base stations. To enable this inter-network data transfer (between aerial and ground networks), the Members are required to communicate with the ground base stations, which are the HGBSs, so that the user data is routed and sent to a backbone network for further processing.

When dealing with the moving user groups, a single backhaul link from a particular HANET system to a fixed HGBS will not suffice, as the relay link formed through the HRMs will keep on lengthening while the HANET is following the moving users. This lengthening of the relay chain will add a number of HRMs to maintain the backhaul connectivity of the HANET with the single HGBS resulting in higher cost and maintenance along with added complexity in deploying the new HRMs. To deal with this situation, we have proposed to employ multiple strategic HGBSs in our work [13]. With multiple HGBSs employed, it is important to maintain the backhaul links while the HANET is following the moving users. At every instant of travel, the backhaul links are needed to be connected and functioning so that the user data transfer remains uninterrupted throughout the travel. It is appropriate to make connections with the nearest base stations only (to function as HGBSs), for the backhauling, which means the chosen HGBSs shall always change according to the travel pattern of the moving users. Here, we propose an iterative and continuous process of releasing the old links from old HGBSs and forming new connections with the newly chosen HGBSs, and we define this process of the iterative backhauling process as the *'Distributed Dynamic Backhauling for the Aerial Architecture' (DDBAA)* [14] [15].

We give a conceptual demonstration of the DDBAA with a scenario presented in Figure 5.1 that depicts the movement of the ground users (representing a PTC problem) from the coverage area of BS1 to coverage area of BS2. The PTC congestion first occurs at the BS1 and the other sites namely, BS2 and BS3 are the underutilized and unaffected sites. These sites have the capacity to route the user data through their backhauling channels towards the backbone network (provided they have backhaul connectivity to the core network). As shown in this figure, the Members are placed right above the PTC causing users, and out of the four Members shown in the figure, three HSMs are used to service the users, and one HRM is used to relay the data to the underutilized BS2 and BS3, functioning as HGBSs. As soon as the PTC causing users reach the coverage area of BS2, it becomes overloaded and the sites BS1 and BS3 become less loaded due to the unloading of the PTC causing users. In this case, the HRM role is taken by a different Member and is now responsible for relaying the user data to BS1 and BS3 sites for backhauling. This way Members need to act as per the PTC load conditions and hence are expected to change their backhaul links and roles, and act accordingly.

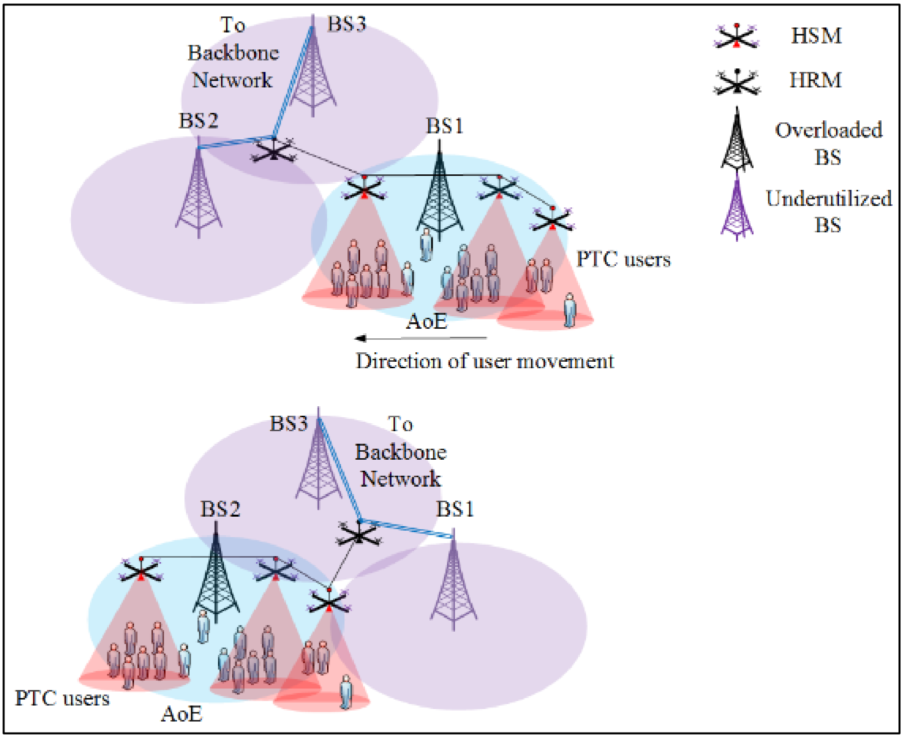

Figure 5.1 The DDBAA Concept [15]

This process of choosing more than one HGBS is the *dynamic feature* of the Member and to distribute the user data between the chosen HGBSs, depicts the *distributed feature* of the Member. This heavy user data can be backhauled through more than one HGBS, preventing the overloading of a single HGBS backhaul pipe. The number of BSs to put to function as HGBSs depends on the user data load that needs to be backhauled. Hence the count and location of the chosen HGBSs play an important role in the DDBAA process.

5.3. THE SIMULATION ANALYSIS

To perform the DDBAA procedure, it is inevitable for the Members to incorporate intelligent algorithms that will help them in control and decision-making and to adapt to the present dynamic network conditions. With the prior knowledge of the AoE like the AoE area, an estimation of the number of users present in the AoE and a rough idea of the capacity demand, major decisions can be taken by the Members in order to form an aerial LTE ad-hoc network above the AoE and serve the affected users. Some major considerations are as follows:

a. *Member Count and Roles*: Essentially how many Members are required and what roles are to be played by them (HSMs, HRMs, GAVH).
b. *Member Locations*: Suitable locations of the Members within the HANET.
c. *HGBS Selection*: The most relevant and convenient choices for the terrestrial BSs to function as HGBSs.
d. *Relay Chain formation*: After determining the chosen HGBSs, it is important to ascertain the path of the relay chain and number of HRMs needed.

The decisions mentioned above are not one-time decisions, but a continual and repetitive process owing to the different network conditions prevalent to the mobility-oriented place-time variant capacity demands of the users throughout the paths of their travel.

It is certain that the manufacturers of such Aerial Base Stations be it the NSPs or third-party operators/manufacturers will have to bear a cost to deploy and maintain every manufactured ABS. Hence, it is crucial that minimum number of Members be used at any given time and network conditions. This further calls for effective optimizations through the intelligent and adaptive algorithms.

Keeping in view the points mentioned above, we have devised an *Intelligent Rank Based (IRB)* algorithm for making HANET an autonomous decision-making system (Figure 5.2). The Members are expected to use the embedded intelligence autonomously and to act like a swarm of communicating and ad-hoc decision-making team. The IBR algorithm is divided into three parts of individual ranking procedures namely, Distance Based Ranking (DBR), Capacity Based Ranking (CBR), and Group-Based Ranking (GBR), [15], which will be explained shortly. While the Members perform the offloading, a wireless backhaul network involving the HRMs and HGBSs is required to transfer the offloaded data for backhauling. To make this happen, the foremost requirement is to identify the nearest and suitable MBSs to function as HGBSs. These ranking procedures are performed separately, and the cumulative result will help the Members to determine the best possible macro sites to exercise as HGBSs.

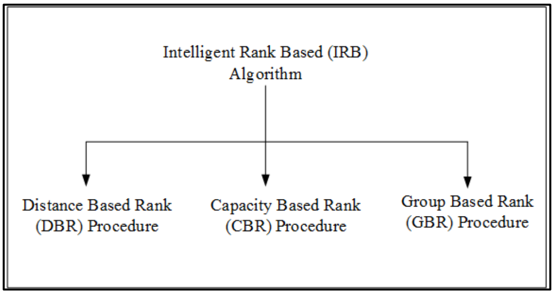

Figure 5.2 Proposed IRB Algorithm

We briefly describe the IRB procedure below. Before following the IRB algorithm (in step 2), the Members first determine the number of HSMs required (explained in step 1). The complete steps followed are elucidated below:

1. *Number of HSMs needed and their placement:*

    - *Weakest regions of the AoE*: We particularly target to provide service at events of carnivals and festivals, where the users are found to be scattered and random. Moreover, there could be a possibility of the existence of non-uniform location of the users, leaving some areas with minimal/no users that do not stand the need for service. The goal should be to determine the maximum user accumulated areas within the AoE. These regions of maximum accumulation reflect the weakest regions of poor coverage and connectivity issues that are not covered or marginally serviced by the MBSs in the vicinity. To make an effective ad-hoc team with minimum radio access nodes, we must aim to place the HSMs above such areas only. To determine these weakest regions, we attempt to identify (i) the user locations of weakest and strongest SINR reception and, (ii) the users that are well associated with the macro sites present in the AoE and are not affected. The HSMs are finally placed above the user locations receiving poor SINR and serving the users that are not connected to any of the macro sites aiding in the offloading of the macro sites. The positioning is determined by the inter-Member distance and the team formation into a hexagonal grid (same as the MBSs).

2. *The IRB Algorithm: Identification of Suitable BSs to function as HGBSs*:

    - *Distance Based Ranking (DBR)*: This is done by carrying out a ranking process based on the distance of each MBS present in the network area with each HSM in the HANET team. This distance is determined using the Euclidean distance calculation method [16]. This ranking will help in identifying the nearest macro site which is not present in the AoE but is nearest in the distance to the HANET team (specifically one of the HSMs). The top ranking indicates the closest distance of an MBS with a particular HSM. This procedure is necessary to follow because we need only those base stations which are nearest to the HANET team and have the capability to take the user load of PTC. This step must ensure in the formation of minimum relay chains and least number of HRMs needed.

- *Capacity Based Ranking (CBR)*: In this procedure, a rank based process on the utilization of the backhaul link capacity of each MBS in the network area is performed. We carry out this step to classify only those macro sites that have maximum backhaul facilities available so that the offloaded data can be sent to the core network through them for further processing. The top rank indicates the maximum individual backhaul link capacity available with a macro site. Although, the data is transferred to the macro site through MMWC channels (if selected as HGBS), the macro sites further send/receive the user data depending on the existing designed cellular backhauls connections to the core network (fiber optic/wired, etc.).

- *Aggregated Link Capacity (ALC)*: We calculate the Aggregated Link Capacity (ALC) as a precursor step to the GBR procedure. We start with grouping the macro sites by exploiting the geometry of their placement in a hexagonal grid formation. Each MBS can be grouped with the rest of the six sites following the first tier set of its neighboring macro sites forming six groups. Every group consists of three MBSs including the site in consideration (as shown in Figure 5.3 below). The ALC of any group is the summation of the backhaul link capacities of the three sites belonging to that group. There could be some macro sites which have few neighboring sites only. Such macro sites will make groups with the available macro sites around it and can also be a part of groups of some other neighboring site into consideration.

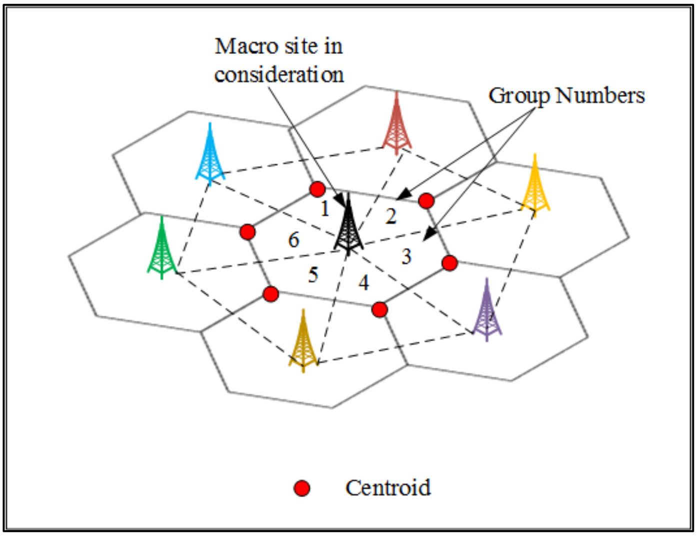

Figure 5.3 Group Formation of Macro site with its neighbors

- *Group Based Ranking (GBR)*: In this procedure, a ranking of all the groups formed are done based on their ALCs (calculated in the last step). The top rank indicates a group with the maximum ALC.

After all the above procedures are performed, the chosen HGBSs are those with maximum ALC, the minimum distance from HANET team and maximum individual backhaul link capacity (calculated for all the three sites present in the group with maximum ALC).

3. *Formation of the HRM relay chain to the final selected HGBSs*:

After identifying the groups with the order of maximum ALC, we calculate the Length of Tolerance (LoT) which is required to determine best possible group with least number of HRMsrequired to make the relay chain from the HANET to the group in consideration and is calculated as below.

- *Length of Tolerance (LoT)*: To have a strategic placement of the HRMs, we identify the centroid of the top ranked HGBSs groups based and on the GBR (as shown in Figure 5-3). The centroid of a triangle is the point of intersection of its medians (the lines joining each vertex with the midpoint of the opposite side) [17]. Then, we place an HRM at the respective centroids of the chosen groups. The placement of HRM is done at the same altitude as that of the HGBS tower height from the ground.

  Finally, we calculate a parameter called as the Length of Tolerance (LoT) as:

$$LoT = \frac{Nu_{HRM} \times (min(DBR)) \times (min(CBR))}{(ALC\ of\ the\ group)} \qquad (5.1)$$

The LoT calculation takes into consideration the product of values of top ranks of DBR and CBR in the numerator (corresponding to minimum distance and maximum capacity), and then multiplied by the number of HRMs and divides by the ALC of the group into consideration. The number of HRMs is calculated using the distance value corresponding to a particular rank and dividing it by the maximum millimetre wave link distance allowed. The number of HRMs obtained is substituted in the LoT equation to obtain the minimum value of the LoT. The aim of calculating LoT is to identify those groups that satisfy the criteria of minimum distance, maximum capacity, and least number of HRMs needed that can collectively process the most amount of user data. The LoT calculation will be performed until we achieve a certain number of groups that are collectively able to transfer the entire offloaded user data. The groups that contain a macro site already present in a selected group is not taken for further calculations. The final selected groups are ones that include the selected HGBSs.

5.3.1. THE SYSTEM MODEL

The DDBAA concept of a single HANET system was investigated on heterogeneous Urban Macro (UMa), hexagonal cellular network model for evaluating IMT-A, based on the simulation assumptions in ITU-R M.2135-1 report. We assess and present the analysis for two different PTC situations in the network area. In the simulations, we investigate our proposed algorithm in three different network scenarios (A, B, and C), affected by the PTC user accumulation. Scenario A represents the case when AoE region is created at the bottom left of the network region. Scenario B accounts for the case when the AoE region is created at top right in the network region owing to the movement of the same PTC users. Scenario C demonstrates scenario B, affected with a building obstruction in the AoE vicinity. The ground users and the PTC users are randomly placed using Poisson's Point Process (PPP). The AoE region spans an area of 500x500 m^2 and comprises of 196 PTC users.

The simulation assumptions are further summarized in Table 5.1.

Parameter	Value
Simulation Area	3000x3000 m^2
Propagation Environment	Urban Macro
Transmit Power Macro/HANET	49/30 dBm
Simulation Frequency (f)	2 GHz
System Bandwidth LTE/MMWC	20/100 MHz
Number of Macro sites	38
Number of users per site	30
Average DL Spectral Efficiency (SE) BS/HANET	2.2 /3bps/Hz/cell
Number of Sectors in Macro/HANET	3
Member Altitude	90 m
AoE Region	500x500 m^2
PTC user distribution at AoE region	PPP (λ= 267 per km^2)
Air to Ground Propagation Model	Dense Urban Environment

Macro to User Propagation Model	ITU-R Path Loss Model
Member to MemberPropagation Model	Free Space
Maximum Inter Member Distance (MMWC)	283 m
MMWC Backhaul link capacity	220 Mbps

Table 5.1 Simulation Parameters for the Backhaul Analysis [13]

5.3.2. RESULTS

The UMa network scenario with randomly placed UEs are shown in blue and the PTC causing UEs are shown in orange red in Figures 5.5, 5.6, 5.8 and 5.10. The legends with their description are illustrated in Figure 5.4. Figure 5.5 represents the 3D view of Scenario A. The figure illustrates the AoE (with PTC congestion) in the network area, UMa sites, HSMs, HRMs, HGBSs, etc. On executing the IRB procedure for all the scenarios considered, we achieve the graphs of DBRs as shown in Figures 5.7, 5.8 and 5.9 respectively. Although the ranking was performed for every HSM, we present the example perspective from results of four HSMs only. The seventeen circled UMa sites represent the HGBSs selected, and the pink dots represent the HRMs. These HRMs are strategically placed at the centroid of the selected HGBSs groups, with altitude same as the macro site (as explained in section 5.3). The yellow dots also represent the HRMs that placed themselves to form relay chains between the pink strategic HRMs and the corner HSMs.

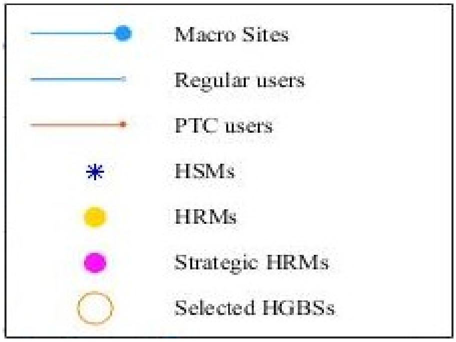

Figure 5.4 Legends description [13]

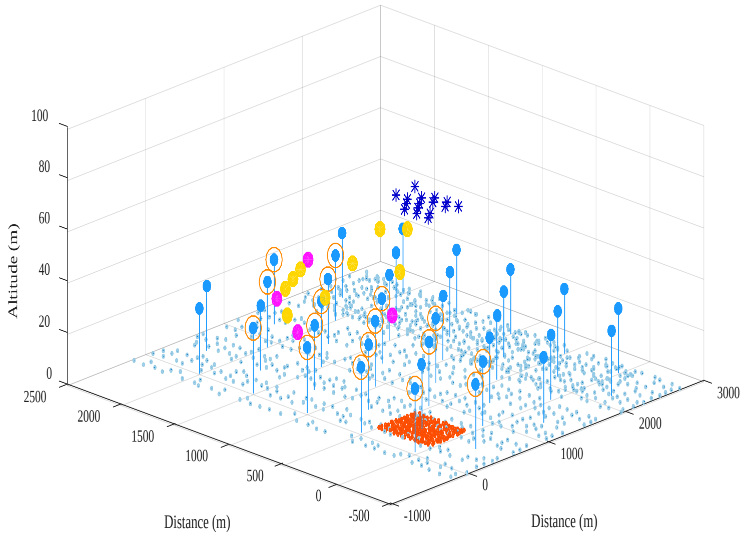

Figure 5.5 DDBAA- Scenario A in 3D [13]

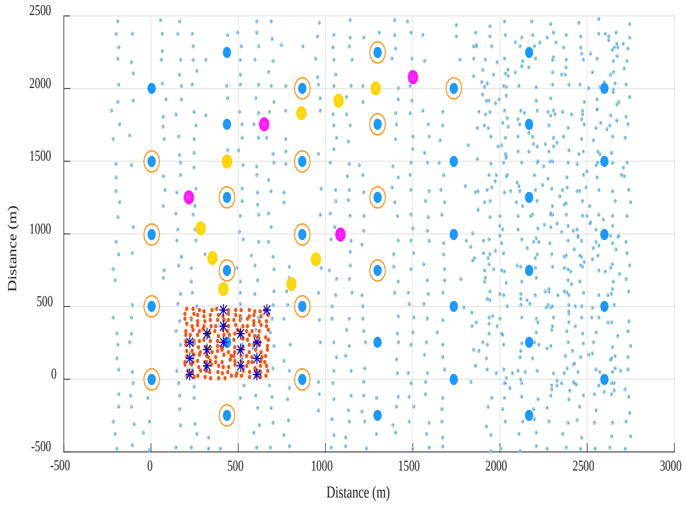

Figure 5.6 DDBAA- Scenario A in 2D [13]

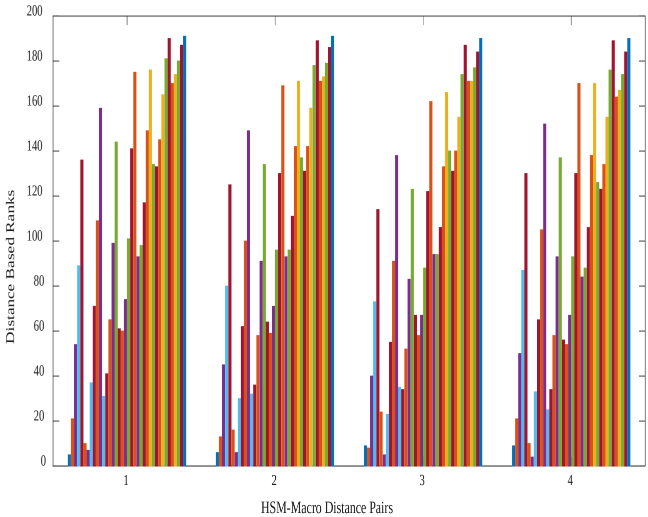

Figure 5.7 Distance Based Ranking- Scenario A [13]

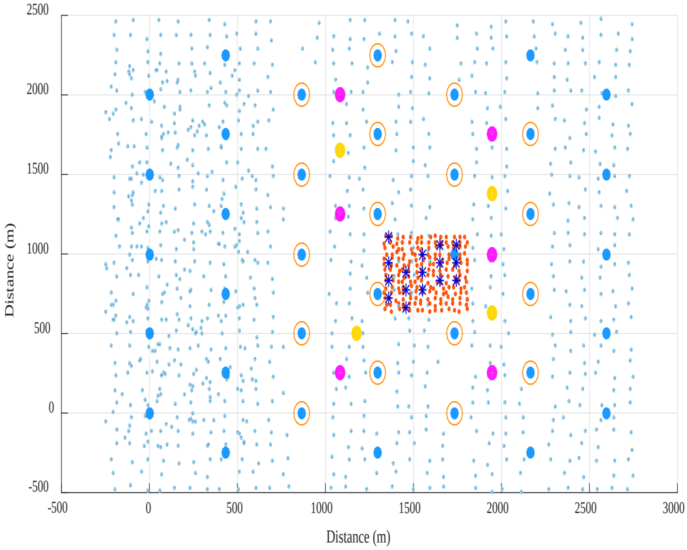

Figure 5.8 DDBAA- Scenario B [13]

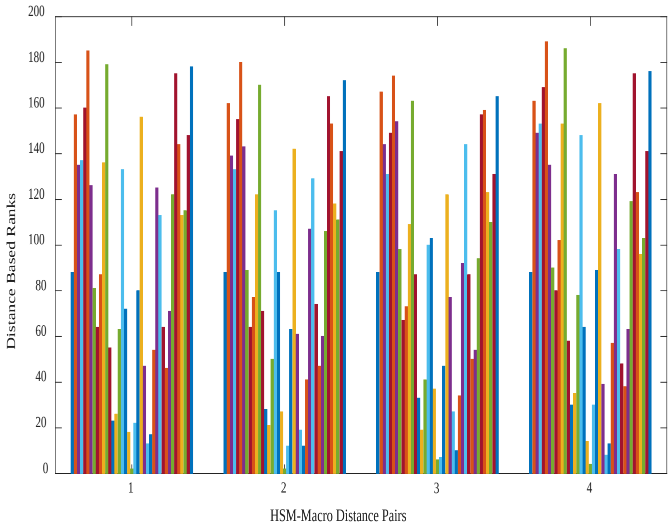

Figure 5.9 Distance Based Ranking- Scenario B [13]

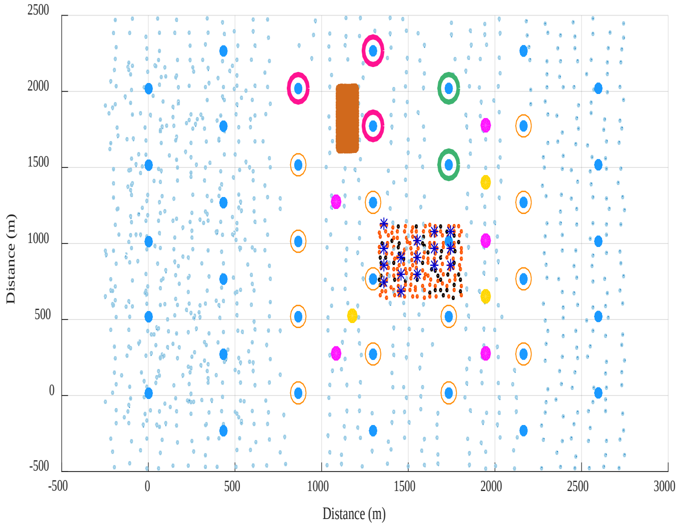

Figure 5.10 DDBAA- Scenario C [13]

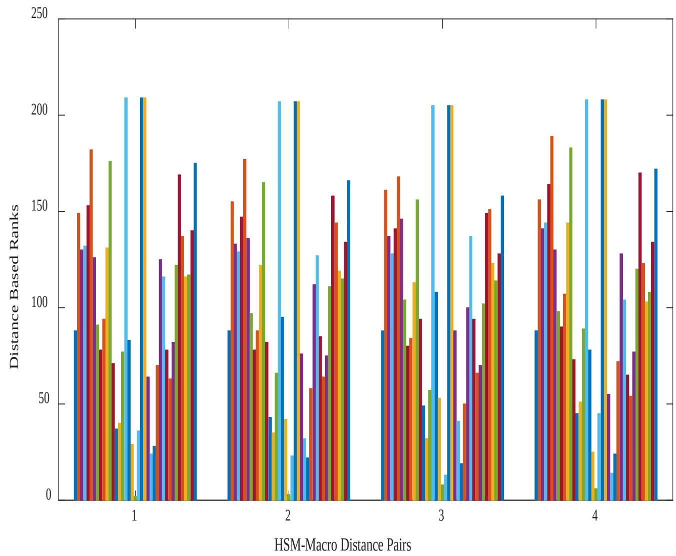

Figure 5.11 Distance Based Ranking- Scenario C [13]

In scenario C, which is the case with a building obstruction at a random location in the network area, the HBGSs close to the obstruction (circled in pink) are avoided, and their load is distributed to the neighboring HGBSs (closer to AoE and are circled in green). The GBR for all the three scenarios is demonstrated in Figure 5.12.

In this analysis, we compare the DDBAA process with the Static Backhauling (SBH) case for the user movement iterations. In SBH, we assume only one HGBS was chosen to backhaul the entire user data. As the PTC causing UEs move from one place to another, the number of HRMs are required to maintain the relay chain with that single selected HGBS. However, with DDBAA process, the number of HRMs required increases to a certain count limit. This is due to the fact that the link with previous HGBSs is not broken, and as soon as the new links with the nearby HGBSs are formed, the number of HRMs required reduces. In the case of DDBAA, the number of HRMs required staying within a certain count only. This is demonstrated in Figure 5.13.

We further compare the static BH and DDBAA through a cost of deployment in terms of the ratio of HSMs per user (which is expected to be minimum). In this comparison (see Figure 5.14), we check the ratio of HSMs/UE for two different HGBSs chosen, and we observe that the ratio of HSMs/UE goes to infinity in the case of SBH. This is because a single HGBS can transmit/receive user data upto certain limit only, so, even if HSMs increase indefinitely, the services are not delivered to the extra users. However, in case of DDBAA, the HSMs/UE ratio becomes almost constant as for an effective service delivery, multiple backhauling links to multiple HGBS groups and optimizations, tend to limit the number of HSMs at the AoE for any given user distribution and hence the ratio of HSMs/user stays constant on adding extra users (Figure 5.15).

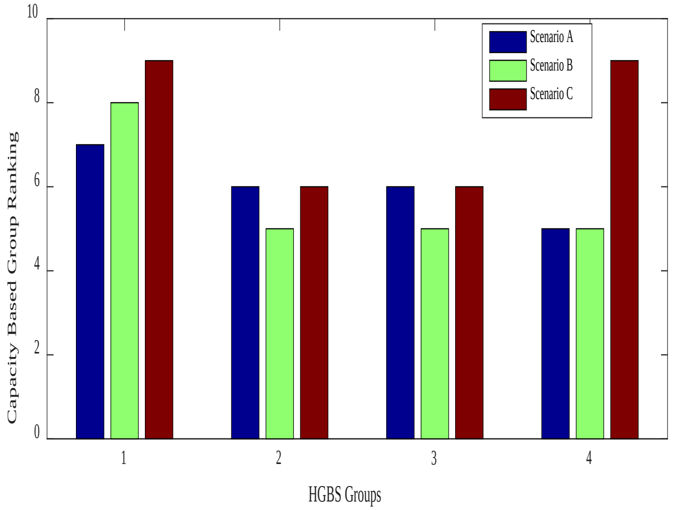

Figure 5.12 ALC ranking of HBGS Groups-Scenarios A, B, and C [13]

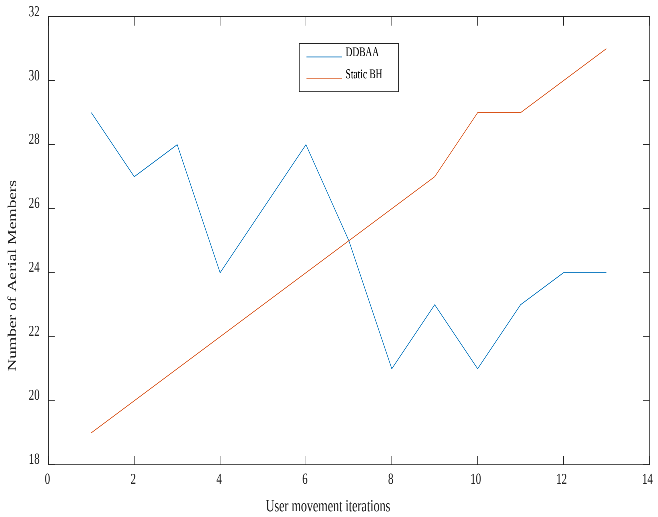

Figure 5.13 Comparison of Static BH and DDBAA [13]

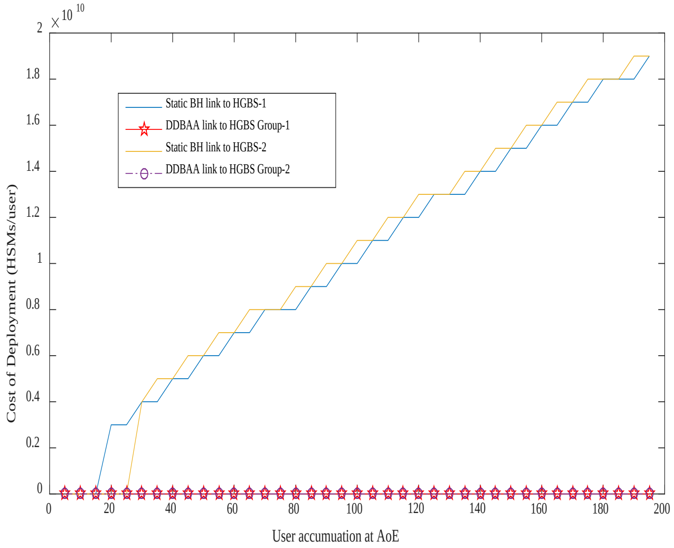

Figure 5.14 Comparison: Cost of Deployment [13]

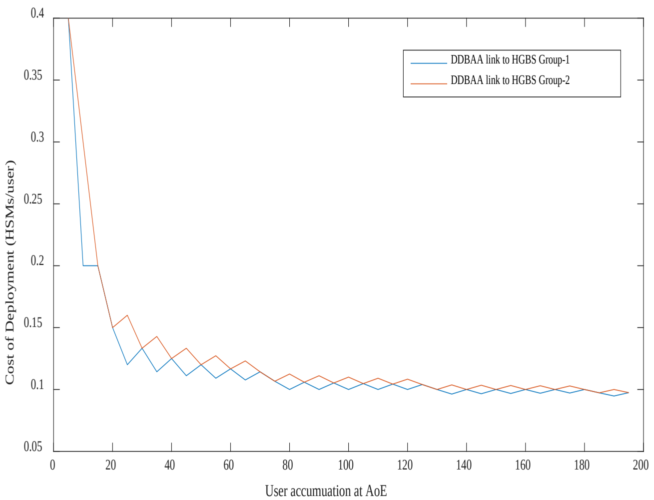

Figure 5.15 Comparison: Cost of Deployment [13]

Furthermore, the Distributed Dynamic Backhauling procedure has been implemented with Aerial Heterogeneous Networks in [19]. The procedure followed is an advanced implementation of what has been discussed above.

5.4. CONCLUSIONS

This chapter focused on the backhauling analysis of our proposed aerial architecture discussed in Chapter 3. We introduce and describe the concept of *Distributed Dynamic Backhauling of the Aerial Architecture (DDBAA)* and describe the system model that we have considered for the simulation and investigation of our proposed concept in an Urban Macro environment. To be able to process the DDBAA, the Members are required to be assimilated with intelligent algorithms to make a decision that is dynamic and adaptive in nature. As the PTC problem is mobility-oriented, the solution of the problem in context to the backhauling needs to be adaptive and flexible in operation. Hence, we propose an *Intelligent Rank Based (IRB)* procedure, as an approach to executing the DDBAA in a PTC disturbed network environment. Lastly, we present our analysis of the obtained simulation results and discuss the investigations performed.

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CHAPTER 6. THE BUSINESS MODEL PERSPECTIVE TO THE AERIAL RADIO ARCHITECTURE

This chapter focuses upon the business aspect of our proposed aerial radio architecture, endowing an added dimension to our research work. We start by discussing the need and objective of comprehending a business perspective to our proposed concept, followed by a brief state-of-the-art. Then, we discuss some relevant business scenarios of our proposed concept of AH/SIIARA. At the end of this chapter, we give some conclusions.

6.1. INTRODUCTION

In the previous chapters of this thesis, we have introduced and defined a novel radio architecture that strives for the airborne deployment strategy to contend the network jitters and congestions. We have particularly targeted the network problems caused due to arbitrary user accumulations at random locations within the service area of a Wireless Communication Network (WCN), defined as Place Time Capacity (PTC) [1] [2]. Previous chapters of this thesis have analyzed the radio, backhauling and intelligence aspects of our proposed architecture of SIIARA. However, in the light of my ambition and to carry on with this research in the near future, it is imperative to think about the suitability of this research work in the real world. Certainly, as a researcher, it is my inevitability to give a pragmatic meaning to my investigations. Through this chapter, I have raised the need for an investigation of my novel concept in a more tangible way and have attempted to dig deeper and look beyond the usual research roadmap. This chapter discusses our research work that is presented in our paper in [18].

6.1.1. THE OBJECTIVE OF INTRODUCING A BUSINESS MODEL FOR THIS RESEARCH WORK

Ever since I started contemplating to research into Aerial Radio Architectures, what started boggling me were the questions that how and where my research investigations shall fit? Having the opportunity to work with some radio researchers during my investigations, I came across several business models, both in Business to Business (B2B) and Business to Customer (B2C) domains. Being a new area, the business aspects of this research is very limited. The kindergarten analogy, where a newly admitted child finds a way to make friends and starts learning a social skill, gleamed me to investigate the suitable business models for SIIARA. As discussed earlier in the previous chapters of this thesis, the SIIARA architecture is largely generic and complex in nature. Meaning that, although our investigations are for Long Term Evolution (LTE) technology, UAVs that are used to function as the Base Stations (BSs) in the air, are technologically independent. We can say that the SIIARA architecture can work on the radio of any technology that is mounted on the SIIARA UAVs (also termed as Members), giving a unique Business Model (BM) for each technology, it operates upon. In addition to that, the SIIARA architecture is the integration of several Aerial HetNets (AHs), working in coordination, and each AH can be visualized as a separate BM.

Therefore, it is evident that several BM dimensions can bloom up with AH/SIIARA stepping into the reality. The objective of this chapter discusses our work presented in [18], which focusses on the deeper investigation on the suitability of the AH/SIIARA concepts in the business domain.

6.1.2. HOW IS BUSINESS MODEL APPROACH JUSTIFIED IN THE PRESENT RESEARCH?

The paper [18] deeply investigates the BM for the deployment of AH as a complementary solution to the existing Terrestrial Mobile Communication Networks (TMCNs). For assuring the progress of the present research, the prototyping of the architecture is essential. We expect the prototyping of the basic architecture to be very much NSP-oriented and should serve a certain business objective. In this chapter, we shall show what is the kaleidoscopic business applications of the aerial radio architecture that is discussed so far in this thesis document, based on which the next level of research that shall be performed. Another justification of this research work is to involve multi-disciplinary areas in the research work. We have already covered the aspects of radio and backhaul with intelligence for our proposed AH and SIIARA architectures. The business understanding to this research work shall pave a new dimension to our research work.

6.2. LITERATURE SURVEY

By a simple definition, a business model is a way in which a company generates revenue and makes a profit from company operations [3]. According to Magretta [4], the business model tells a logical story explaining who your customers are, what they value, and how you will make money in providing them with that value. Some of the core objectives to achieve and maintain a business are profitability, productivity, customer service, growth, etc. [5].

It is vital to know why we need business models. A business kick starts with an innovative and an exemplary idea. As discussed in [6], a business model helps us as an entrepreneur, to put make a realistic evaluation of the potential success of our business idea. Before the actual execution and implementation of the proposed idea, it is essential to turn the idea into a business concept through business modeling and planning. The success not only lies with the idea but continues with a good and effective business model until it is exercised in the actual market.

It is important to overcome the challenges of the traditional models and hence a need for business model innovation. There is always a scope of improvement, enhancement, and advancement of the currently used models. Figure 6.1 represents the key considerations for business model innovation and suggests that novel approaches to enrich the existing sources of competitive advantage and to build a new value proposition arenecessary to the innovations in the business [7].

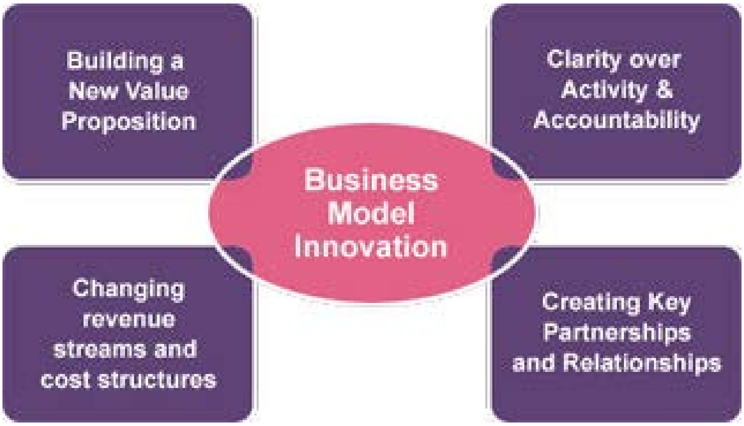

Figure 6.1 Business Model Innovation [7]

As defined in [8], 'The business model innovation is the multi-stage process whereby organizations transform ideas into new/improved products, service or processes, in order to advance, compete and differentiate themselves successfully in theirmarketplace'. It requires building and accommodating new capabilities and offerings that are competent enough to sustain in the market, reap financial benefits and satisfy the customer needs.

Talking specifically about the future communication technologies aka 5G heterogeneous communications, changes in the existing technologies and service offerings must consider the business model innovation to accommodate and satisfy a variety of high-speed services to the expected large subscriber base. A leading global telecommunications equipment supplier Ericsson has identified the need for new and innovative business for the 5G technologies [9]. According to their report, the stakeholders in the wireless industry must provide creative business models to utilize the emerging 5G technologies effectively. The telecom market today is prone to rapid changes in the technologies, user needs, policies, and regulations. A core asset to the network operators has been in providing the required network infrastructure that plays a fundamental role in providing subscriber relationships and profitable business in terms of revenues. With 5G emerging as the next generation communications, the aim to deliver high data-rate, low latency, and highly reliable network services to the continuously growing wireless subscribers must accommodate a distinct and novel business models. Presently this is a much-needed task to be considered by the network operators. Moreover, the massive growth scaling of the subscribers is not proportionating to the growth rate of the revenues fetch by the wireless service providers. This need for business model innovation will make the market investors, telecom giants and the equipment manufacturers question their profit making in the mobile and communication service deliverables.

Dwelling on to the requirements of the new business perspectives, models that are time, place and people independent should be a crucial consideration to the future market to the mobile operators [10]. To achieve this, one of the key consideration should be on the infrastructure that needs to be deployed and operated [2]. The traditional mobile network infrastructure is not designed for flexible spectrum usage, or to carry mission critical, massive machine type of traffic [11]. The next generation of ubiquitous ultra-broadband network infrastructure implementation will require a rethinking, restructuring and redesigning of approaches to mobile network construction and expansion [12]. The objective of radio access network infrastructure implementation for the future mobile communications must serve to accommodate four crucial factors namely, (i) Massive Capacity, (ii) Massive Coverage/Connectivity, (iii) Quality of Services, anytime anywhere and, (iii) User Mobility.

In [13], the authors have discussed a business model in context to mobile communication sector. They have presented a generic business model framework which is purely value-based, called as the *’V^4 model’*, for the mobile network operators that is formed of four dimensions, namely Value Proposition, Value Network, Value Architecture, and Value Finance. They put forward a strong need by the network operators to enhance their ability in determining what constitutes the most viable business model, essential to meet their strategic objectives in the rapidly changing communication scenarios.

The future communication networks will create an ecosystem for both technical and business innovation with most of the network services relying on software [14] that require the infrastructure to be flexible and responsive. 5G will further bring new industrial stakeholders (e.g. vertical industries, novel forms of service providers or infrastructure owners and vendors) [14] to build the top network architectures and infrastructures. Hence, the new business models must support the 5G infrastructure in a way to reinforce flexibility and programmability (advanced software embedded with Artificial Intelligence), apart from supporting a variety of services everywhere and user mobility conditions.

Another much-needed requirement is to optimize the network resources on time to time basis. For this, the infrastructure should be sensitive enough to be informed of the changing network conditions in view of varying user demands w.r.t. their locations and the ability of the network to match to the requirements in providing the quality services.

The 5G business models study is still into inception. We shall discuss upon some of the models proposed in the literature. A few business model examples were given in [15], discussing three main business models based on the roles played by a Service Provider, namely, as an Asset Provider (AP), Connectivity Provider (CP) and Partner Service Provider (PSP). The first business model mentions asset as different parts of a network infrastructure that are operated for or on behalf of third parties resulting in a service proposition. This model presents an 'Anything as a Service (XaaS)', where *X* represents Infrastructure, Network, or Platform. Another dimension is the ability to share the network infrastructure between two or more service operators based on static/dynamic policies (e.g. congestion/excess capacity policies). The second business model describes the service operator to provide the best effort IP connectivity for retail and wholesale customers. A feature like a self-configuration option for the customer or the third party is proposed to enrich this business proposition. In their last model, two variants are proposed for the PSP role, one where the operator directly addresses the end customers and provides integrated service offerings based on operator capabilities. The second variant empowers partners (third parties, etc.) to directly make offers to the end customers enriched by the operator network.

In [16], authors have suggested a new business model based on HetNet infrastructure sharing for maximizing users' data rate and creating more revenue to the operators. As per their suggestion, the owners of infrastructure and the operators are different. This can be done through passive sharing, where the passive elements of the network like physical space, rooftops, towers, masts, etc. and backhaul connections can be shared by sharing the sites in a larger geographical area, and on the other hand choose for active sharing where the active infrastructure involving antennas, BSs, radio access networks and even core networks can be shared.

Authors in [17], discuss few revenue-sharing contracts, where they present that sharing increases the investment from the wireless service providers involved. According to their study, for the capacity sharing between the SPs, the incentive is greater if the owner of the infrastructure gets the larger fraction of the revenue carrying the overflow traffic.

Herein, we conclude that the new business models must be adopted to obtain cost benefits to the operators, service providers, investors, equipment manufacturers, etc. and all the other parties involved with the aim of serving the mass users in the small-cell environments of future communication networks.

6.3. BUSINESS MODEL SCENARIOS FOR AERIAL RADIO ARCHITECTURE

In Chapter 2, we have discussed the limitations of the ground infrastructure in handling and managing PTC-like network conditions. We have proposed a need for augmentation and enhancement of the terrestrial ground infrastructure through our proposed solutions of SIIARA. In this sub-section, we will discuss different business model scenarios of deploying an aerial network with the terrestrial ground network.

1) *Core Network Extension*: As described in our proposition, the Aerial-HetNet (AH) connects to the core network and rest of the terrestrial ground network through the HABSs. Through this connectivity, the AHs attempt to extend the core network of the terrestrial ground network. The aerial infrastructure of the AH can be reused multiple times at multiple places. As shown in Figure 6.2, the AH cloud follows the PTC moving through a difficult terrain, at different times and positions ((t1, p1), (t2, p2), (t3, p3), (t4, p4)). We can observe that the footprint of the ground network increases without any additional cost. Even from the user point of view, the connection footprint is enhancing, with services being available to them anytime and anywhere. This, in turn, increases the Average Revenue Per User (ARPU) and accentuates the network health and revenue.

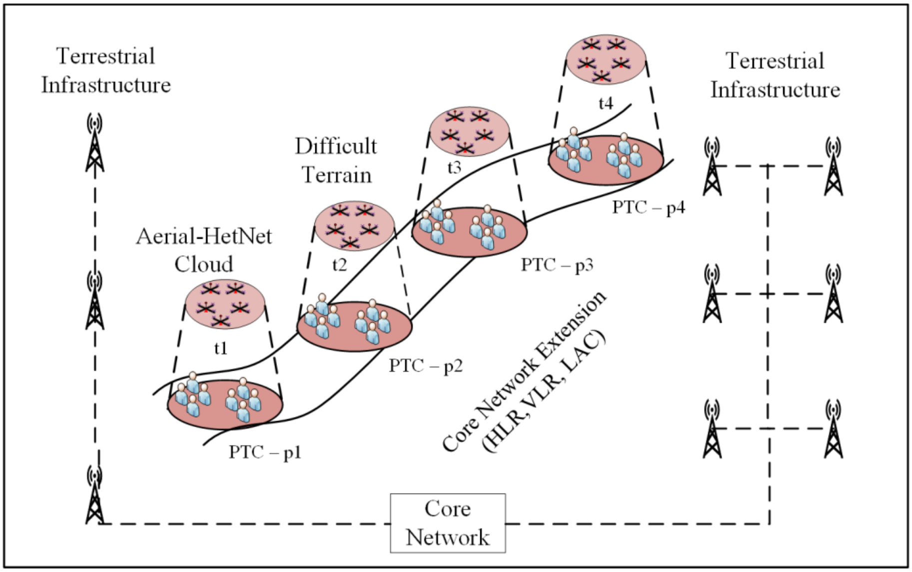

Figure 6.2 Core Network Extension

2) *Radio Access Network (RAN) Sharing*: With the deployment of AH to serve a PTC-driven network condition, there can be users from different service

operators that are required to be served by the AH above. Moreover, the ground base stations in and around the AoE, which are to function as HGBSs during PTC conditions can be operated by multiple networks. This gives AH a leverage to provide services to users from multiple operators and its backhauling to be connected to different HGBSs from multiple operators. This means that the same aerial infrastructure of AH is giving services to various networks operator present in the terrestrial ground network system. As depicted in Figure 6.3, the AH is providing services to the PTC causing users belonging to different service operators and enforcing backhauling with HGBSs belonging to multiple service operators. This implements a RAN sharing by augmenting the footprints of multiple network operators by the deployment of a single AH system.

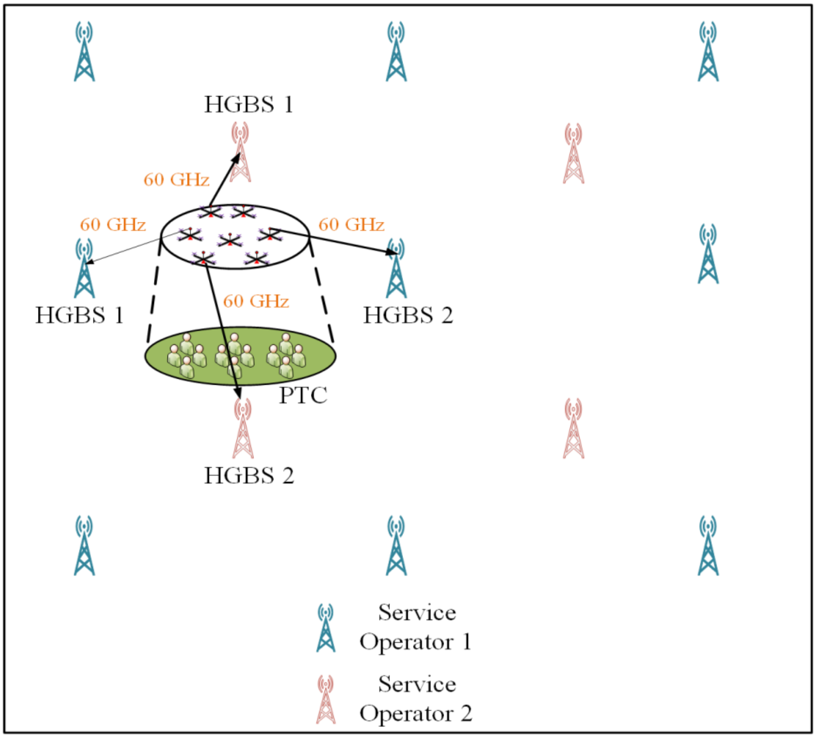

Figure 6.3 RAN Sharing

3) *Spectrum Sharing*: The spectrum sharing can be implemented in three ways;

- Space Limitation – In PTC situations where there is a single operator network present, the AH deployment serving the users of that service provider only. The same AH can provide service to new users belonging to some other service operator whose coverage is not reachable at the AoE. This prevents a need for an additional deployment of AH as a single existing AH carries the capability of providing services to users of multiple operators at the same time. This can be performed by reducing a certain percentage of throughputs delivered to the existing users and give some channels to accommodate the new users. Through this, the cost of adding another AH can be saved, revenue of the service operator present in the AoE is increased, and a need for spectrum planning is detoured for the service operator whose network coverage is not available at the AoE. Figure 6.4 presents a PTC situation where the AoE is created having services available only from Service Operator 1. However, the new users coming from a Service Operator 2 can also be served by the same AH cloud.

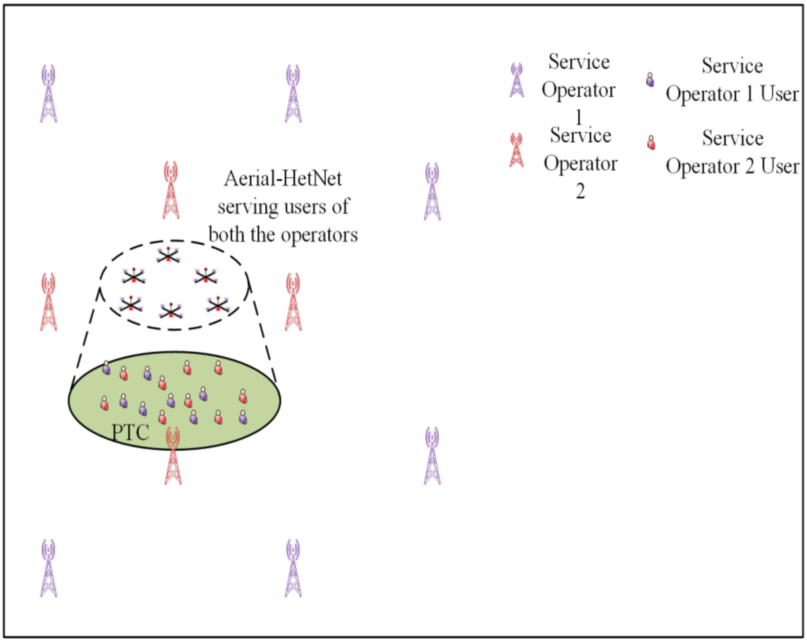

Figure 6.4 Spectrum Sharing example

- Spectrum Limitation – There could be conditions of PTC generations, where a particular service operator has consumed its spectrum entirely, and no channels are further available to accommodate additional users. Neither the service operator has the capability to deploy an AH at the AoE. The possible resolution to the service operator could be to hire an AH available with some other service operator and to overcome the limitations of the former service operator. This makes the service provisioning of the first service operator intact and gain of revenue to the second service operator through hiring.

- SINR limitation: As we have concluded from Chapter 4, under the investigation of SINR at situations where both terrestrial and aerial network operates together. We proposed the need for having a spectrum partitioning between the two networks to minimize the co-channel interference. We suggested that about 25 % of the available spectrum to be reserved for the AH system and remaining with the ground base stations in the AoE. This improvised the SINR conditions at the user locations belonging to either of the networks. Considering a scenario where the Service Operator 1 is likely to deploy AH to serve a PTC condition, Service Operator 2 can request the first operator to share the spectrum and serve its users. This saves operator 2 to deploy a separate AH system with its own spectrum. Because of this, a poor SINR condition shall deteriorate further reducing the throughput service.

4) Mobile Virtual Network Operator (MVNO): A third party, as a startup company can manufacture AHs and provide them on lease to the service operators. Their task includes porting and locate the AH Members close to target areas where they can be rapidly deployed when needed. They can be ported and placed in trucks or specific strategic locations (just like fire stations, etc.), or can be chosen to build storage houses to house the aerial Members. This third-party manufacturer is named here as a 'Wireless Itinerant Aerial Infrastructure Provider (WIAIP).' In needs, a service provider can follow an ad-hoc service payment scheme through hiring the AH Members and pay the WIAIP for the duration of AH deployment. With this, the service provider saves manufacturing cost of making and deploying AH Members.

   In Figure 6.5 below, we show a business model scenario with WIAIP that deals with the NSPs for different situations. The NSPs can hire AH systems from the WIAIP for PTC-generation network situations like Ganesh Visarjan, etc. The WIAIP fetches revenue from the NSPs for the duration of their needs for AH systems, and NSPs gains revenue for serving mass user demands. This helps in maintaining the customer trust and retentivity which are other important business criteria for the NSPs other than the revenue. On the other hand, during catastrophe events, a quick network can be provided at the impacted areas by the NSPs by hiring AHs from WIAIP. Further, AHs can be employed by the defense for operations at warzones, etc.

   With WIAIP, not every NSP is required to manufacture its own AH systems but hire from WIAIP for their temporary requirements. This saves a cost of manufacturing the AH systems by the NSPs.

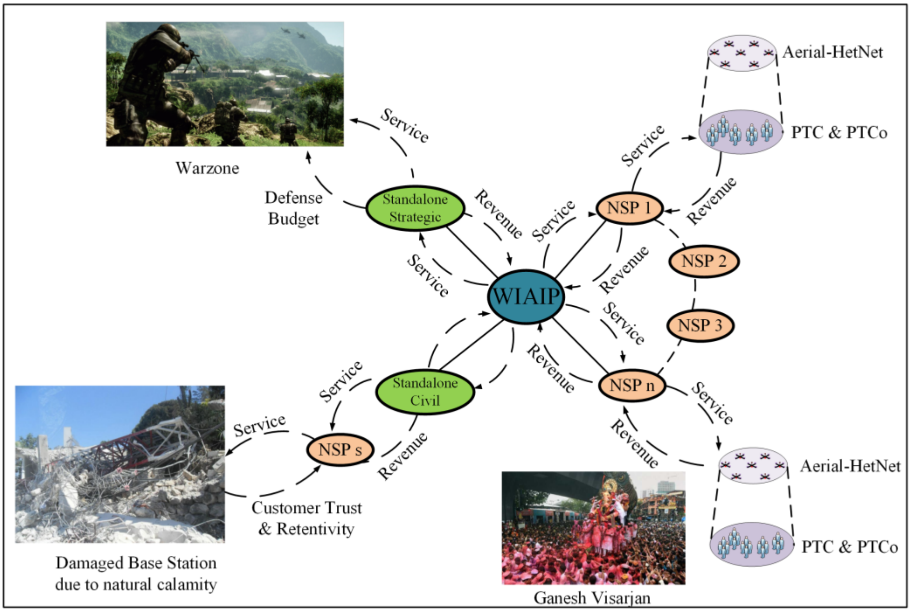

Figure 6.5 Wireless Itinerant Aerial Infrastructure Provider (WIAIP)

5) *TV White Space* – A different approach to utilizing spectrum by the AH Members in case of emergencies or spectrum scarcity scenario, the AH can use the TV white space or white space spectrum to provide the coverage to the PTC causing users. Figure 6.6 depicts a scenario where multiple AHs are serving multiple PTC generation scenarios within the coverage of TV tower transceiver. This approach will ensure a minimum interference to the adjacent TV receivers present in the nearby households (as seen in Figure 6.6). This is because our solution is airborne and isolationin terms of radio propagation can be achieved. The cost in adding new spectrum to the AH Members can also be avoided, and an additional boost to the spectrum sharing of TV white space can be achieved.

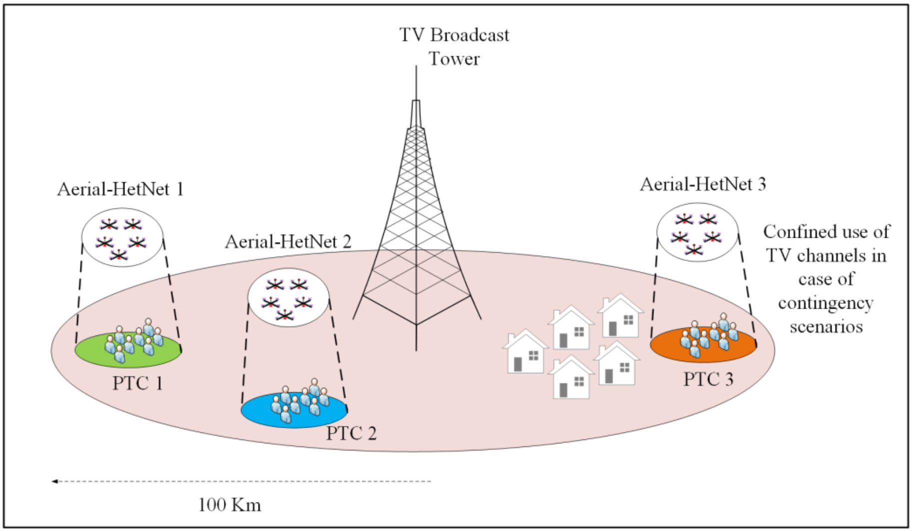

Figure 6.6 TV white space usage

6) *Standalone Services*:

- Catastrophe conditions – During conditions of network failure due to natural calamities (floods, earthquakes,etc.), the AH can provide services to the affected users, trying to communicate locally. Figure 6.7 below depicts such a situation, where ground base stations are damaged, and some people are stranded attempting to make emergency calls for rescue operation or to know the wellbeing of their closed ones in the affected area. A rapid deployment of AH can serve such users and communicate through satellites.

- Strategic conditions – Under defense and military applications, service, survey, and monitoring operations can be carried out by the AHs, where the terrestrial network is absent (due to tough terrains, un-reachability of the coverage, etc.). Figure 6.8 shows such a scenario, where some users, unserved and unreachable can be managed by AH Members forming a long relay chain and make their connectivity possible with the nearest HGBS. Alternate routes (backup routes) can also be deployed in challenging conditions (weather, terrain, etc.).

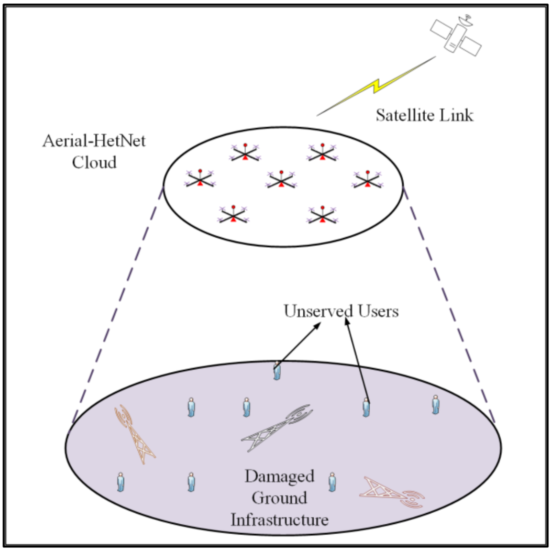

Figure 6.7 Catastrophe conditions

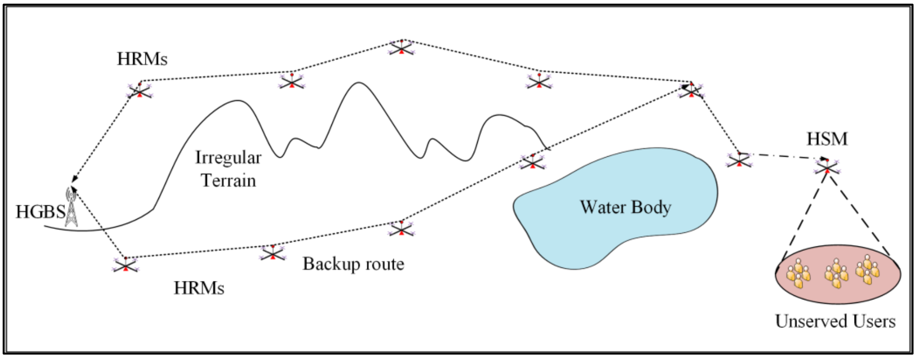

Figure 6.8 Strategic conditions

6.4. CONCLUSIONS

This chapter basically presented a business aspect to our proposed solution of aerial architecture. We have presented different applications, each worthy of converting into a business model. Every technical idea converted to an appropriate business model gives a market edge in the business field. A basic requirement in the telecom sector is in provisioning the required services to its customers and make revenues from them. This relationship of NSP and customer is critical to maintain in the competitive market. With changing technologies, service types and demands, etc. a need for business model innovation arises, and one of the crucial factors is to re-consider the network infrastructure through which the NSPs reach to the user end.

We have presented a state-of-the-art in this regard and further emphasized the need for enhance and new network infrastructures. With our concept of aerial architecture, we have presented multiple business model scenarios that can contribute to increased revenues and customer satisfaction. We put forward our idea of Aerial HetNet systems that can be deployed under various scenarios discussed in this chapter. We observed that this concept of aerial network architecture could support NSPs in building both Business to Business (B2B) as well as Business to Customer (B2C) relations.

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CHAPTER 7. CONCLUSIONS AND FUTURE RESEARCH PARADIGMS

This chapter is the closing chapter of this thesis work. First, we will draw conclusions and summarize our thesis work in this chapter. Lastly, we will discuss some future research scopes related our proposed aerial radio architecture in detail.

7.1. CONCLUSIONS

This thesis has targeted to present a suitable solution to the problem of Place Time Capacity (PTC). The PTC problem is network congestion issue that we feel is necessary to combat owing to extremely high-data-rate service offerings to massive subscribers, as promised in the future wireless communications. The PTC problem is a mobility-oriented network problem under which the existing network infrastructure flounders to perform. We define PTC as a congestion crunch caused due to movement of a vast number of users traveling from one place to another in the network area, demanding for high-speed services at every instant of their motion activity. Such problems are easily seen at events of mass people like carnivals, festivals, etc., and we refer to the affected region as the Area of Event (AoE), that needs an added network servicing during PTC congestions.

In this thesis, we present a disparate way of exploiting small Unmanned Aerial Vehicles (UAVs) in dealing with the network areas suffering from the PTC problem. The small UAVs are low-power and low-altitude airborne devices that can follow the PTC causing user groups and are easy to locate above the places of demand. This thesis work has proposed the use of such small UAVs into a cloud of the ad-hoc network, to collaborate and manage the PTC conditions in the network collectively. We have presented our research work as an evolution of our proposed architecture. We started with the formation of a Hovering Ad-Hoc Network (HANET) which corresponds to a team of self-itinerant and intelligent aerial radios equipped with base station facilities, deployed with the aim of servicing the ground users affected by the PTC congestion and offload the affected Macro Base Stations. We investigated the deployment of HANET in an Urban Macro environment and analyzed the SINR performance of the network pre-and post-deployment of the HANET. It was observed that SINR conditions at affected user location were improved with the HANET deployment.

Then, we have illustrated a novel and distinct way of formation of HANET systems into Aerial Heterogeneous Networks (Aerial-HetNets), to adaptively and flexibly target only the core network areas under PTC aberrations. Aerial-HetNets correspond to the formation of HANET Members into different altitudes such that footprints of various cell sizes are created on the ground, with a similar analogy to ground HetNets. We have investigated and analyzed the SINR and Coverage at the afflicted user locations and the overall network SINR under the deployment of Aerial-HetNets. The size of the affected PTC region i.e. the AoE and the density of users within the AoE play a major role in determining the SINR performance of the entire network.

As a final proposition, we construe a holistic and a complete architectural view of the aerial networks as ‘Self-Itinerant Intelligent Radio Architecture (SIIARA).’ The SIIARA corresponds to an additional architecture of cellular network provisioning that works in coordination with the ground cellular network. The SIIARA incorporates all the functionalities and capabilities of a terrestrial ground infrastructure, but with multiple HANETs in operation. The most distinguishing feature of SIIARA is the ‘Distributed Dynamic Backhauling of the Aerial Architecture (DDBAA)’ that facilitates intelligent algorithm based dynamic backhauling capabilities of the multiple HANET systems within the SIIARA under the mobility-driven dynamic PTC conditions. We have performed some analysis and examined the DDBAA process in a network environment and highlighted the intelligence if this architecture for performing the backhauling operations.

Lastly, we gave a Business perspective to our proposed aerial architecture and described the network scenarios that can consummate to the profit making of the Network Service Providers (NSPs) along with satisfying user Quality of Service (QoS) criteria.

To conclude, this thesis has contributed in presenting, analyzing and discussing the aerial solutions as an additional network layer in dealing with network problems like PTC along with the terrestrial infrastructure. This field of research is still into an amateur phase, and not all the dimensions and aspects have been considered. However, as a future research work, we intend to add complexity in terms of intelligence and aim to build a prototype of an aerial vehicle suitable for applications into the cellular networks.

7.2. PROPOSED FUTURE SCOPES FOR AN AERIAL NETWORK

In this section, we will discuss two future scopes of our proposed aerial architecture. The first one will describe our vision of how an aerial vehicle for our application should look like and what are the necessary features and parts are required for its making. The second scope will discuss the complementary architecture of ’Heterodox Network’ which is an amalgamation of SCIDAS and HANET to deal with PTC-driven conditions.

7.2.1. STRUCTURE OF AN AERIAL VEHICLE: ESSENTIALS OF A UAV

The popularity of commercial drone development has increased in recent years to be exploited for civilian applications.

The essentials of making a UAV include [1] [2]:

1) A Multi-Rotor Frame: This is an important part of the UAV as it needs to be light and stable to perform the required tasks in the target areas. There can be different UAV platform configurations like tricopter (three motors), quadcopters (four motors), hexacopters (six motors), etc.
2) Flight Controller: This is the brain of any machine i.e. the microcontroller, with the programmed instructions for the decision and control of the flight.
3) Motors & Propellers: To make a UAV fly, motors and propellers have an impact on the flight endurance and payload carrying capability.
4) Speed Controllers: To control the speed of each motor.
5) Cameras: To able to see while flying will be valuable information to the UAV.
6) Sensors: Accelerometer, Gyroscope, GPS sensor, Distance sensors, etc. are some important sensors required for the UAV to obtain basic information during the flight.
7) Battery: To provide power to the UAV platform. The battery has a direct relation with the chosen motors.

7.2.1.1 The QuadcopterStructure

The choice of a drone for PTC-driven situations requires a robust, reliable, and compact physical structure that can work as an aerial base station, with the purpose of functioning as a full-fledged base station and delivering the assured QOS services to a real-time moving hotspot event. In [3], we have proposed a thought-driven physical structure design for acting as an aerial base station.

The added requirements for deploying the UAV for our purpose are:

1) Quadcopter Frame: The quadcopter is the most stable form of a multi-copter [4].
2) Transceiver Unit: To operate as an aerial base station and to be able to deliver the cellular services to the ground users.
3) Antennas: Different types and configuration of antennas to allow transmit and receive the signals in the cellular range.
4) Solar-powered battery: For better flight time duration, an alternate source of energy can be beneficial.

As depicted in the Figure 7.1, we have proposed a Quadcopter based HANET vehicle design consisting of four brushless rotors with propellers wide in diameter for better stability and low power consumption [3]. The weight of the device should be sufficient to carry communication equipment and sensors for its operation during PTC situation and still bear high-level endurance.

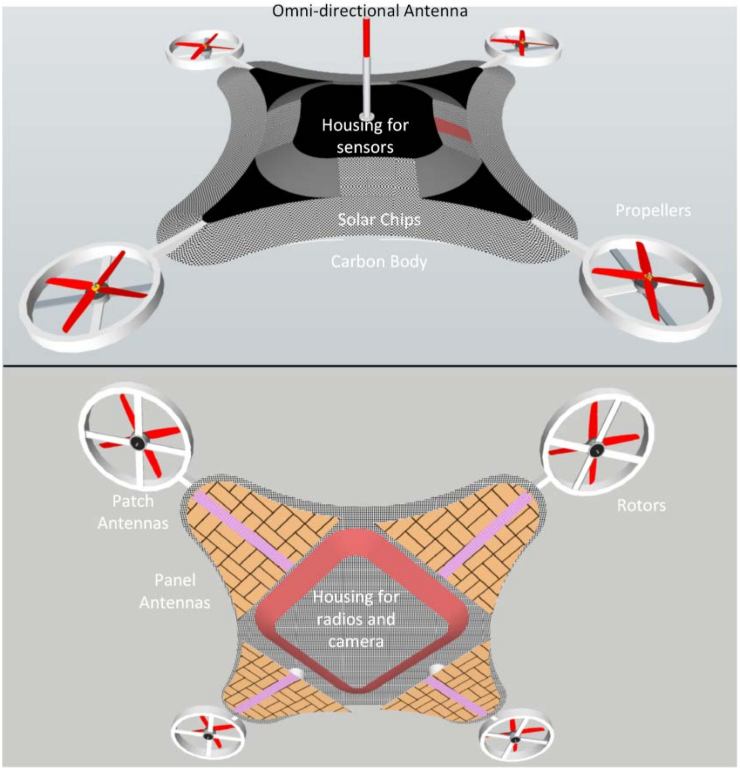

Figure 7.1 Proposed physical structure of the HANET Member [3]

There are broadly four units of the HANET-quadcopter vehicle:

A. ***The Radio Unit***: This unit is the main unit for the UAV to operate as an aerial base station. It will act as eNodeB in the 3D space to establish wireless communication with the ground users. The communication antennas will be incorporated in this unit. We employ both the directional antennas and omnidirectional antennas for our purpose (as discussed in Section 3.2.2.4). The lower part of the chassis consists of a carbon fibre panel that will contain two types of antenna's metallic wafers to provide coverage underneath the hovering altitude. The first antenna type is the *panel antenna* for IMT devices and the second type of antenna will be *patch antenna* for MMWC devices. The wings of the quadcopter will affix four such assemblages of panel and patch antennas to cater four sectors with four distinct carriers to serve different clusters of subscribers. The IMT radio will be connected to the port of panel antennas, and similarly, millimetre wave radio will be connected to the port of patch antennas on each of the quadcopter wings. The carriers of the HANET Member can be distributed among its four sectors thus improvising frequency re-uses at the local level. The coverage area to be served by each of the panel antennas can be steered according to the user pattern behavior. The top surface of the frame will mount the omnidirectional MMWC antenna for the Member to Member/HGBS communication.

B. ***The Inertial Measurement Unit (IMU)***: The lower part of HANET device structure will also encapsulate the Inertial Measurement Unit (IMU) consisting of necessary sensors (as mentioned in section 7.2.1) along with the GPS sensors and cameras.

C. ***The Control and Maneuvering Unit (CMU)***: The members have a Control and Manoeuvring Unit (CMU) that is connected to the rotors and propellers for adjustment of angular velocity to perform operations like turn, hold, hover, etc. The IMU will be composed of sensors to measure the physical parameters like direction, speed, and coordinates of the HANET device structure. The CPU of the member will account for all the information from radios and IMU to instruct CMU to move the mechanical parts of the device and to control further the physical parameters of the radios.

The block diagram shown below in Figure 7.2, illustrates the working of the UAV BS. The CPU collects its inputs from IMU unit and Radio Unit, and with programmed algorithms processes the input data and takes decisions and control of the aerial device. The decisions on the control instruct the aerial device to orient itself accordingly like turn, hold and hover.

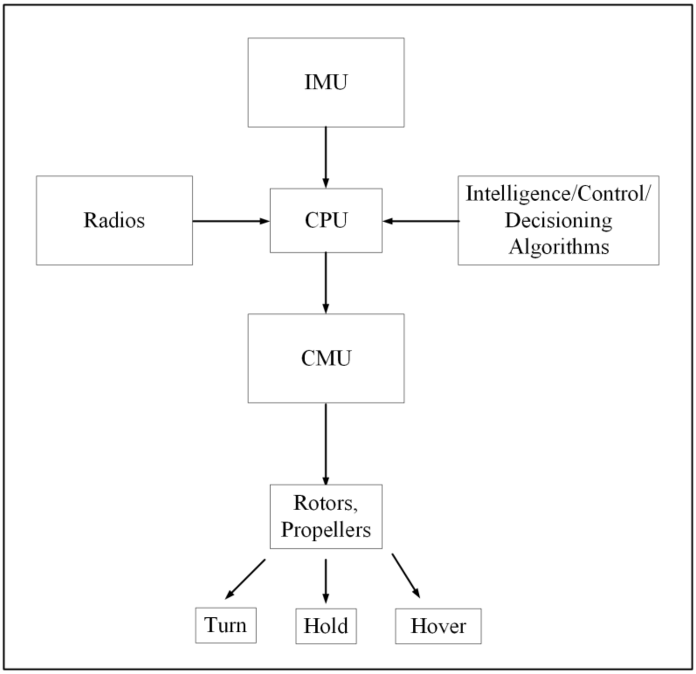

Figure 7.2 Block Diagram of the UAV functioning

7.2.2. HETERODOX NETWORK – AN ALTERNATE SOLUTION TO SOLVE THE PTC PROBLEM

Towards the end of the thesis work, we will now describe a complementary and alternate solution to resolve the PTC^2 problem. This solution is a cascaded network of SCIDAS and HANET and has been named as '*Heterodox Networks(HN)*' [5].The individual architectures of SCIDAS and HANET have been proposed to operate as standalone solutions to solve the PTC problem, however, cascading both the architecture would provide a wholesome approach and provide an added edge, considering all the aspects of a network provisioning system including the PTC^2 challenge.

In the dissertation work of [6], the author has proposed, defined, and discussed an innovative architecture, termed as the 'Self Configurable Intelligent Distributed Antenna System (SCIDAS),' which, as per our best knowledge, is the proximate solution to serve the PTC^2 challenge. Figure 7.3 shows a deployed scenario of the SCIDAS network in a target area. As we can see in the figure, the working of the SCIDAS architecture is based on the traditional Distributed Antenna System (DAS) to disseminate services across the network. Moreover, the 'Intelligent Sub-architecture', defined as ISa in [6], uses the same DAS platform, used for catering network services to perform the intelligent functions. The ISa is the additional novel element introduced in the proposed architecture and is controlled by the Network Intelligence Unit (NIU) that resides within the Base Station Hub (BSH).

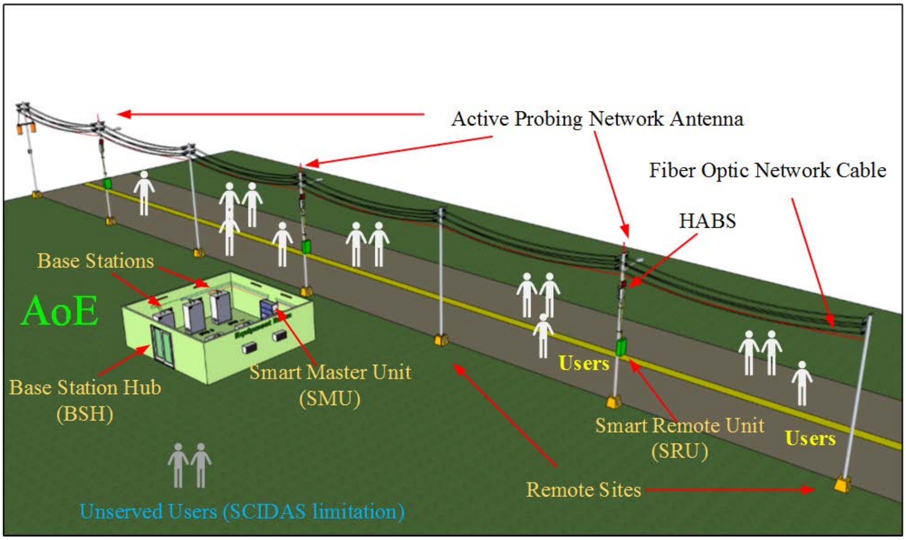

Figure 7.3 A deployment scenario of SCIDAS Architecture

Figure 7.3 depicts the elements (equipment) common to both intelligent and service layers, namely, Smart Master Unit (SMU), Smart Remote Unit (SRU), service antennas, and the Fiber Optic Network (FoN). The SMU takes the input at the BSH and distributes the information through FoN, which is eventually, received and decoded at remote sites by the SRUs. To distribute services in the network, the Base Stations (BSs) are placed at BSH and are connected to SMU that converts the RF signals into the optical signals to be distributed via FoN. All the remote ends receive the same information via FoN by their respective SRUs, which demodulate the optical signals back to RF. Hence, each remote site radiates the same RF signals across the network area. This is the behavior of normal DAS operation, where the services are evenly smeared in the Personal Area Network (PAN). However, in SCIDAS, the ISa plays an important role to alter the behavior of the normal DAS operation to an intelligent, responsive system. The NIU, which is the brain of ISa, uses the same DAS network to propagate packets of instructions to be sent to all SRUs. Each of these SRU then extracts the information relevant to them and rejects the rest. In this way, each SRU receives the instructions that are especially dedicated to them, separately and iteratively. Each remote SRUs, then configure the respective remote sites according to the instructions they receive. The configurations can be, choosing which carrier to be allowed to be converted to RF, what will the orientation and heights of the respective antenna, for how long any carrier group should be radiated in those particular remote sites, etc. The instructions related to orientation and height of the antenna, which is decoded by the SRU, is obeyed by another novel architecture mentioned in [6], defined as a Maneuverable and Controllable Platform (MCP) that resides at each remote site for the mounting of the respective antenna. There is another sub-architectural layer of ISa, defined as Active Probing Network (APN), which is the sensory architecture of SCIDAS. The APN architecture can be either deployed as a separate independent system or by defining SRU and the connected antenna to act in coordination to sense the surrounding environments. For both options, NIU uses the APN to send the low and high amplitude signal burst, in the vacant band, from each of the SCIDAS antennas, to illuminate the target surrounding. These signal bursts can thus, be sensed by other SCIDAS antenna, which is operating in coordination with the transmitting antenna, to understand the present surrounding situations. Depending upon the signal strength at each receiving antenna, the values of PTC^2 can be found. Performing the whole process sequentially and iteratively, defined as the Amoebic Place Time Response (APT), the PTC^2 can be evaluated, and the locus of the dynamic groups can be traced. The NIU can, therefore, instruct involved SRUs to act promptly, individually, and iteratively to cater the moving problem, thereby mitigating the PTC^2 effect.

The discussion made so far shows the architectural superiority of SCIDAS, for its dexterity in handling the PTC^2 challenges. We can expect that an area, which is deployed by SCIDAS, will be much less prone to PTC^2 wobbling, than those that are deprived of such intelligent systems. However, what about those situations where SCIDAS fails to serve? As discussed earlier, SCIDAS deployment uses mounts, poles, and may be towers for placing SRUs, antenna, and MCPs, which again puts a challenge for the innovative architecture. The challenge is that the services of the SCIDAS are limited to the areas where its infrastructure exists, and therefore cannot be expected to serve indefinitely. Also, due to horizontal propagation, there is a limitation of carrier reuse, and therefore, the number of sites per unit area is limited, preventing the SINR deterioration. Moreover, as the total BSs govern the total SCIDAS network capacity at the BSH, the prompt increment in the network capacity is not possible, and therefore cannot serve PTC^2 beyond a certain limit.

Looking at the limitations mentioned above of the SCIDAS concept, we thought of improvising its applicability by combating its limitation by amalgamating the architectures SCIDAS with the HANET/ Aerial-HetNet (AH). The new architecture evolved thus, is defined and termed in our previous work [5] as the '*Heterodox Network (HN)*'. In HN, the SCIDAS operates under normal conditions. However, under the ofPTC^2 where an itinerant user group is crossing the network boundary, land morphology becomes complicated, and the usual SCIDAS may struggle to perform at its best. Under such scenarios, the add-on architecture of AH over SCIDAS (to form HN) can be used. In such cases, the AH will be the aerial sub-architecture, ASa, of the new HN architecture will work in control of NIU to have a unique network with seamless and ubiquitous PTC^2 catering ability. Figure 7.4 illustrates the HN architecture and illustrates the blending of the two distinctively functional intelligent architecture that have come together for a more comprehensive approach in catering of the everlasting challenge of PTC^2.

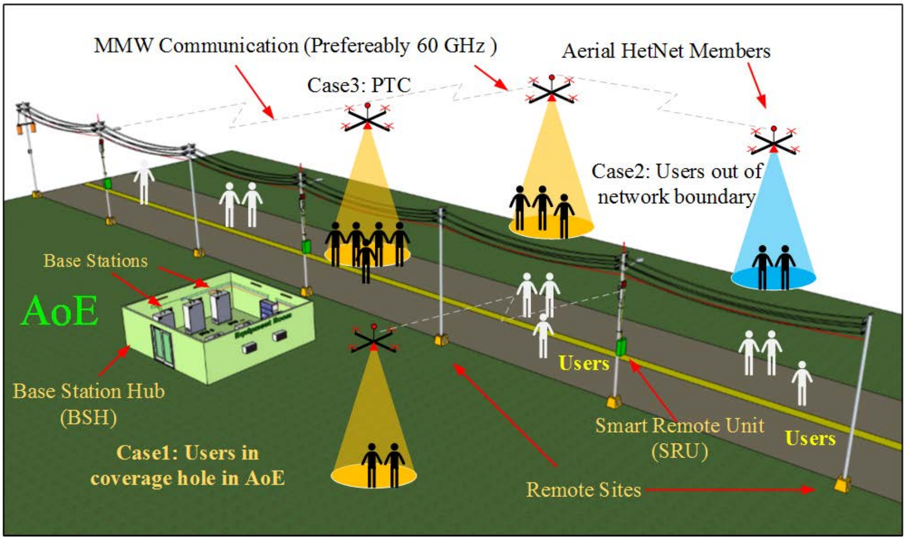

Figure 7.4 Amalgamation of SCIDAS and Aerial-HetNet forming the Heterodox Network

The situation can be very promising for future networks. The SCIDAS portion of HN network can be deployed as the umbrella coverage in the PAN area. The SCIDAS architecture shall perform its operations of sensing the PTC^2 wobbles and catering them. In the case when SCIDAS reaches its limits, as mentioned earlier in this section, the AH can be invoked to serve the purpose. Such coordinated approach allows foreseeing a new business model where the network architecture and network service providers can be two different entities. For its ubiquity and seamlessness, multiple NSPs shall be interested in sharing the same infrastructure, and therefore, we can anticipate not only RAN sharing, but the whole architecture sharing for the future NSPs.

The prompt AH will save a lot of CapEx on the incessant demands of network extensions that are placed to cater to the trespassing users. The AH can complement SCIDAS to cater users, to a significant space, that is out of reach for the SCIDAS network area, ensuring the users' satisfaction and trust to be intact. The infrastructure-less architecture of the AH can also be very useful for the situation when the primary SCIDAS network is damaged or sabotaged, as shown in the Figure 7.5, where it (AH) can take over as a primary network to serve the targeted locations (catastrophe events), thereby saving lives.

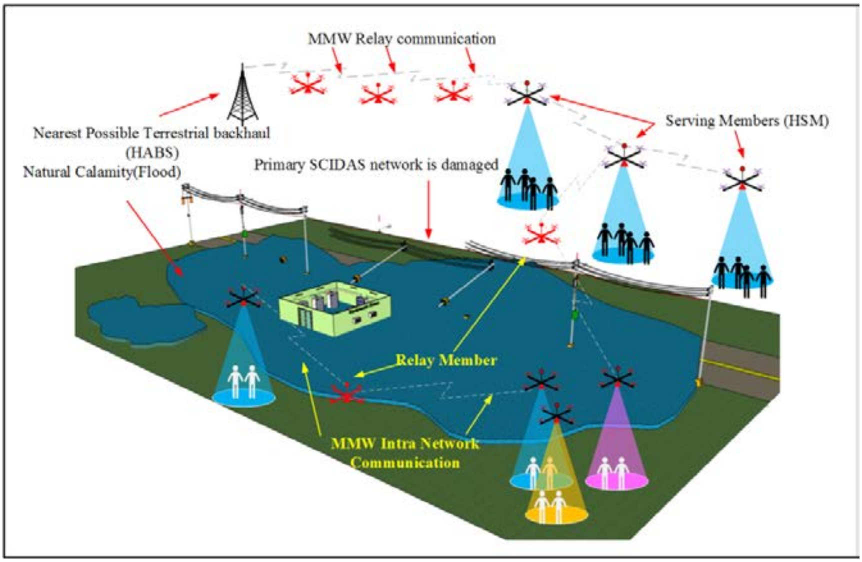

Figure 7.5 Advantage of having Aerial-HetNet in coordination with the Terrestrial Architecture

The HN shall also promote the inter-disciplinary research, one being the terrestrial (SCIDAS) and another, the aerial (AH) sub-architectures. The amalgamation of the two distinct approaches to solving the common problem isdefinitely a challenging and enchanting proposition for the future works.

7.2.3. DISTRIBUTED DYNAMIC BACKHAULING IN AERIAL HETEROGENEOUS NETWORKS

In this research work, a part of the study focusses in proposing and evaluating an intelligent Rank Based Algorithm (RBA) that executes the Distributed Dynamic Backhauling procedure in the Aerial Radio Architecture [7]. The procedure was evaluated in the network scenario where the HANET Members are placed at a same altitude. The radio analysis with a different configuration of using the HANET Members at variable and adaptive altitudes was also introduced and evaluated in [8] as Aerial Heterogeneous Networks (Aerial-HetNets). The next part of this research study will examine the Distributed Dynamic Backhauling concept in the Aerial-HetNets. However, the RBA proposed in [7] might suffer from computational and time complexity due to the following factors:

1. Variable Heights of the Members leading to formation of variable cell sizes on the ground.
2. Individual team status of HANETs.
3. Changing physical morphologies.

4. Connectivity between multiple HANET teams.
5. Dynamics owing to user group movements.
6. Individual and Group capacity demands.
7. Availability of sufficient backhaul link capacities with the ground base stations

The parameters mentioned above are subject to changes with place-time variant user groups. Hence, improvisations in terms of intelligence and adaptability is required in the RBA to accommodate these parameters in real time. We attempt to extend the RBA for Aerial-HetNets in our paper titles **‘Distributed Dynamic Backhauling in Aerial Heterogeneous Networks’** which is under preparation and one of the future research scopes of this PhD study.

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[8] P. L. Mehta and R. Prasad, “Aerial-Heterogeneous Network: A Case Study Analysis on the Network Performance Under Heavy User Accumulations,” Wirel. Pers. Commun., pp. 1–20, May 2017.

CO-AUTHOR STATEMENTS

Co-author statements for the below mentioned scientific contributions are attached in the following pages.

Serial #	Contribution Details	Page
A	**Conference Publications**	
A.1	Kumar, A.; Mehta, P.L.; Prasad, R., "**Place Time Capacity- A novel concept for defining challenges in 5G networks and beyond in India**," Global Conference on Wireless Computing and Networking (GCWCN), 2014, IEEE Global Conference, vol., no., pp.278,282, 22-24 Dec. 2014.	153
A.2	P. L. Mehta, T. B. Sorensen, and R. Prasad, "**HANET: Millimetre wave based intelligent radio architecture for serving place time capacity issue**," Wireless VITAE, 2015 Global Wireless Summit, Dec. 2015.	154
A.3	P. L. Mehta, T. B. Sorensen, and R. Prasad, "**A Self-Itinerant Aerial Radio Architecture for Serving Place Time Variant User Accumulations**," Wireless World Research Forum (WWRF), Oct 2016.	155
A.4	P. L. Mehta, T. B. Sorensen, and R. Prasad, "**SINR based capacity performance analysis of hovering Ad-Hoc network**," in 2016 19th International Symposium on Wireless Personal Multimedia Communications (WPMC), 2016, pp. 147–152.	156
A.5	P. L. Mehta, T. B. Sorensen, and R. Prasad, "**Distributed Dynamic Backhauling in Self-Itinerant Intelligent Aerial Radio Architecture**," Global Wireless Summit, Nov. 2016.	157

B	Journal Publications	Page
B.1	P. L. Mehta and R. Prasad, "**Aerial-Heterogeneous Network: A Case Study Analysis on the Network Performance Under Heavy User Accumulations**," Wirel. Pers. Commun., pp. 1–20, May 2017.	158
B.2	P. L. Mehta, Ambuj Kumar and R. Prasad, "**A Pragmatic Business Approach to a Novel Aerial Radio Architecture**," Journal of Multi Business Model Innovation and Technology, River Publishers (Submitted).	159
B.3	P. L. Mehta and R. Prasad, "**Distributed Dynamic Backhauling in Aerial Heterogeneous Networks**," Wireless Personal Communications (Submitted).	160
C	**Book Chapter**	
C.1	Purnima Lala Mehta, Ambuj Kumar, "**Heterodox Networks: An innovative and alternate approach to future wireless communications**," Book chapter in Role of ICT for Multi-Disciplinary Applications in 2030. River Publishers, 2016.	161

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Declaration of co-authorship*

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Title:	Place Time Capacity- A novel concept for defining challenges in SG networks and beyond in India
Authors:	Ambuj Kumar, Purnima Lala Mehta, Ramjee Prasad

The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference: Global Conference on Wireless Computing and Networking (GCWCN), 2014, IEEE Global Conference, vol., no., pp.278,282, 22-24 Dec. 2014.

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- 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	C
4. Interpretation of the results	C
5. Writing of the first draft of the manuscript	D
6. Finalization of the manuscript and submission	C

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The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference:

If accepted or submitted, state journal: Wireless VITAE, 2015 Global Wireless Summit, Dec. 2015

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The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference: Wireless World Research Forum (WWRF), Oct 2016.

If accepted or submitted, state journal:

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

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The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference: 19th International Symposium on Wireless Personal Multimedia Communications (WPMC), 2016, pp. 147–152.

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Authors:	Purnima Lala Mehta, Troels Bundgaard Sorensen, Ramjee Prasad

The article/manuscript is: Published ☒ Accepted ☐ Submitted ☐ In preparation ☐

If published, state full reference:

If accepted or submitted, state journal: Global Wireless Summit, Nov. 2016.

Has the article/manuscript previously been used in other PhD or doctoral dissertations?

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If published, state full reference: Wireless. Personal Communication, pp. 1–20, May 2017.

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If published, state full reference:

If accepted or submitted, state journal: Journal of Multi Business Model Innovation and Technology, River Publishers

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Authors:	Purnima Lala Mehta, Ramjee Prasad

The article/manuscript is: Published ☐ Accepted ☒ Submitted ☐ In preparation ☐

If published, state full reference:

If accepted or submitted, state journal: Wireless. Personal Communication, an international journal of Springer-Nature.

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If published, state full reference: Book chapter in Role of ICT for Multi-Disciplinary Applications in 2030. River Publishers, 2016.

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