# COOPERATIVE MIMO SOLUTIONS FOR HBC AND FUTURE WIRELESS APPLICATION

PhD dissertation

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# ENGLISH ABSTRACT

The Human Bond Communication (HBC) is a complete approach to describe and transmit the features of a subject in the way humans perceive it. This communication will involve all the five senses namely, optic (seeing), auditory (hearing), olfactory (smelling), gustatory (tasting) and tactile (touching) for modelling the physical subject into information domain and transmitting through communication platform. The investigation on the physical layer needs and requirements to establish the foundation of the HBC transmission has been done in this work, with regards to the proposed algorithms and measured data outputs.

Multiple-input-multiple-output (MIMO) enhanced the capacity of a radio links by using multiple transmit and receive antennas to exploit multipath propagation. Different methods and algorithms have been employed during years to increase the performance of MIMO in divers setup and scenarios. Cooperative MIMO is one of the solutions, which can be defined in different ways. Coordinated Access Point (CAP) are designed to connect access points to reach to extraordinary performance level when access points are cooperating to transmit signals.

In addition to optimizing the performance of the algorithms in MIMO and CAP architecture, the investigation on the effect of the different parameters of the real transmission environment on the proposed algorithms is a valuable achievement. The results lead to the more precise design of the network and system parameters to increase the performance of the whole system. It also shows more insights towards the application of the algorithm for the future wireless communication and its demands.

This research presented in this thesis is conducted in connection with the analysis of different cellular network system components. The analysis improves the understanding of cellular system performance. The benefit of implementing cooperative access points is determined to achieve a high data rate in the system. Weighted Minimum Mean Square (WMMSE) algorithm has been modified and extended for the CAP scenario to introduce a solution for cooperative MIMO setups in terms of maximizing the data rate. Virtual Signal-to-Interference Noise ratio (VSINR) algorithm as a solution for interference cancellation has been implemented in this research to validate the WMMSE algorithm performance.

Moreover, this thesis presents a sole data analysis of the measurement data derived from the measurement campaign, conducted in Aalborg city, in 2011. This unique analysis addressed many challenges in cellular system network. Different parameters and factors, such as correlation, Branch power Ratio(BPR), fading information, handset efficiency information and the variation in handsets, the

relative body loss effect generated by users and their handset grips were reliably and repeatedly measured during the large-scale measurement campaigns with realistic handsets. Use cases were examined, and their effect on the achieved data rate in cellular systems was determined.

Two mentioned algorithms were implemented to calculate the data rate in cellular network systems. The sensitivity of the algorithms to the aforementioned parameters and factors was evaluated as well. The influence of different frequencies on the achieved data rate based on the Long Term Evolution (LTE) standards was determined. First, the trade-offs between CAP systems and conventional communication systems were analyzed. Second, the performance levels of the two algorithms were computed given the measured data. Finally, the effect of the dissimilar variables and restrictions of the real propagation environment on the algorithms was identified.

The thesis has been wrapped up by an extensive investigation on the application of the solution proposed in this work in the future wireless communication scheme and architecture, known as Human Bond Communication.

The contributions of the thesis include a solution for data transmission for HBC application. The solution proposed a CAP algorithm for enhance data rate, which has been evaluated with simulation and measured channels. The degrading parameters of the algorithm performance have been investigated and discussed in details to the best solution for future system design.

A major outcome of this study is introducing a modified algorithm based on the WMMSE concept to work in CAP scenario for multiuser setup. The algorithm in connection with VSINR algorithms have been validated by measured data, the intensive comparison on the performance of the algorithms and reasons for selecting the best solution in different scenarios have been done in this work. An improved understanding of the influence of different elements and parameters in the overall performance of the algorithms employed in the cellular network scenario is presented in this work based on the channel propagation features in real environment measurement. Significant conclusions were also drawn for the design and measurement of mobile handsets as well as for the proposition and implementation of an appropriate algorithm; these conclusions were mainly related to BPR, correlation, and different frequencies. The application of the algorithm in the HBC concept have been discussed, and future work for adopting new models and architectures to achieve the needs of the future wireless communication are proposed at the last.

# DANSK SUMMARY


Human Bond Communication (HBC) er en komplet tilgang til at beskrive og transmittere de funktioner i en genstand via den måde, mennesker opfatter det på. Denne kommunikation vil inddrage alle de fem sanser nemlig optisk (at se), auditive (hørelse), olfaktoriske (ildelugtende/at lugte), gustatoriske (smag) og taktile (berøring) for at omforme den fysiske genstand til et domæne, hvorigennem der kan transmitteres (sendes) data gennem en kommunikationsplatform.

Til modellering af fysiske genstand i oplysninger domæne, og transmittere gennem en kommunikationsplatform.

I undersøgelse tage vi forbehold for de fysiske lag og kravene for at etablere en grundlæggende HBC transmission, vi gør dette med et fokus på de foreslåede algoritmer og opmålte data udgange.

Undersøgelsen på det fysiske lags behov og krav til at etablere grundlaget for HBC transmissionen er blevet gjort i dette arbejde, med hensyn til de foreslåede algoritmer og målte data udgange.

Multiple-input-multiple-output (MIMO) forøgede kapaciteten af radioforbindelser ved hjælp af gentagende send og modtage antenner for at forøge flervejsudbredelse. Forskellige metoder og algoritmer er blevet anvendt, i løbet af året, for at øge effektiviteten af MIMO i dykker setup og scenarier. Cooperative MIMO er en af de løsninger, som kan defineres på forskellige måder. Koordineret adgangspunkt (CAP) er designet til at forbinde adgangspunkter til at nå til ekstraordinær ydeevne, når adgangspunkterne samarbejder om at sende signaler.

Ud over at optimere ydeevnen af algoritmerne i MIMO og i CAPs arkitektur, er undersøgelsen sig selv af stor værdi, da den visereffekten af det nuværende kommunikations miljø på de foreslåede algoritmer. Resultaterne fører til en mere præcis udformning af netværket og systemparametrene, de kan øge effektiviteten i hele systemet. Det giver også en større forståelse for anvendelse af algoritmen for den fremtidige trådløse kommunikation og dens forbehold.

Forskningen i denne afhandling har inkluderet analyse af forskellige mobilnetværk systemkomponenter. Analysen forbedrer forståelsen af hvad et cellulært kan formå. Fordelen ved at have fælles adgangspunkter er, at man kan opnå en langt højere datahastighed i hele systemet. Weighted Minimum Mean Square (WMMSE (WMMSE) algoritmen er blevet tilpasset og øget således, at CAP scenariet bedre kan bruges med henblik på fælles MIMO setups til at maximere hastigheden for dataen. Virtuel Signal-interferens støj-forholdet (VSINR) algoritmen er, i denne

afhandling, blevet brugt som en løsning for interferens annullering for at validere WMMSE algoritmens ydeevne.

Denne afhandling præsenterer desuden en dataanalyse tilbage fra en optællings kampagne, foretaget i 2011 i Aalborg. Denne unikke analyse sætter fokus på mange udfordringer i mobilsystem netværket. Forskellige parametre og faktorer, såsom korrelation, Branch power Ratio (BPR), fading information, information, håndsæt effektivitet og variationer i håndsæt blev gentagne gange målt med realistiske håndsæt. Use cases blev undersøgt, og deres effekt på den opnåede datahastighed i cellulære systemer blev fastlagt.

To af de tidligere nævnte algoritmer blev examineret for at beregne datahastigheden i cellulære netværkssystemer. Følsomheden af algoritmerne i forhold til de førnævnte parametre og faktorer blev ligeledes evalueret. De forskellige frekvensers Indflydelse på den faktiske transmissionshastighed baseret på Long Term Evolution (LTE) standarder blev klarlagt. Først blev fordele og ulemeper imellem CAP systemet og almindelige kommunikationssystemerer examineret. Herefter blev ydeevnen med henblik på den opmålte data. Til sidst påvistes effekten af de uens variabler og algoritmernes begrænsninger i det virkelige miljø.

Afhandlingen opsumeres af en omfattende undersøgelse indenfor anvendelsen og implementeringen af den foreslåede løsning for fremtidens trådløs kommunikation og arkitektur, kendt som menneskelig Bond Kommunikation (HBC).

Bidragene fra afhandlingen inkludere en løsning til indberetning af data til HBC applikation. Den foreslåde løsningen er en CAP algoritme, der kan forbedre datahastigheden og som er blevet evalueret med (forskellige forsøg og frekvenser)/simulering og målte kanaler. De parametre i algoritmens ydeevne, som trækker ned er blevet undersøgt og diskuteret i detaljer for at nå frem til den bedste løsning for fremtidens system design.

Et væsentligt resultat af denne undersøgelse har været introduktionen af en bedre tilpadset algoritme, baseret på WMMSE konceptet som brugere af CAP kan bruge simultant. Algorithmen er sammen med VSINR algorithmen blevet bakket op af datamålinger og intensive (gentagde) sammenligninger af hastigheden samt for og imod vurdeinger er blevet gennemgået i detaljer. Der fremvises en øget forståelse af de forskellige parametre ydeevnes indflydelse på forskellige elementer og parametre i de samlede resultater af algoritmerne, der anvendes i det mobile netværk og disse er vel at mærke baseret på loakle hverdags målinger /baseret på kanal formering funktioner i virkelige miljø måling. Der blev også lavet væsentlige konklusioner omkring design og udformning af mobile håndsæt samt for omkring propositionerne og implementeringen af en passende algoritme; disse konklusioner er hovedsageligt relateret til BPR, korrelation, og forskellige frekvenser. Anvendelsen af algoritmen i HBC konceptet er blevet diskuteret og der afsluttes med forslagt til hvordan man bedst kan tilpasse ny modeller og arkitektur der tager hensyn til fremtidens behov for trådløs kommunikation.

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# LIST OF ACRONYMS

| Acronym | Definition / Expansion |
|---|---|
| 3D | Three Dimensional |
| 5G | Fifth Generation Mobile Communication System (IMT 2020) |
| AAU | Aalborg University |
| AP | Access Point |
| BC | Broad Cast |
| BPR | Branch Power Ratio |
| BS | Base Station |
| CAP | Coordinated Access Points |
| CoMP | Coordinated multi-point transmission/reception |
| CONASENSE | Communications, Sensing, Navigation and Services |
| CPU | Central Processing Unit |
| CSI | Channel State Information |
| CTIA | Cellular Telecommunications Industry Association |
| DMFL | Data Mode Flat on Surface |
| DML | Data Mode Landscape |
| DMLL/R | Data Mode Landscape Left / Right |
| DMP | Data Mode Portrait |
| DPC | Dirty Paper Coding |
| FIT | Feeling Identification and Transmission |
| HB | High Band |
| HBC | HBC Human Bond Communication |
| HOME | Human Bond Communications Beyond 2050 |
| ICT | Information and Communication Technologies |
| IoT | Internet of Things |
| i.i.d. | Independent and Identically Distributed |
| IMT | International Mobile Communication |
| LA | Local Average |
| LAA | license-assisted access |
| LB | Low Band |
| LBT | Listen Before Talk |
| LoS | Line of  Sight |
| Lphr | Landscape Mode Right Tilt Right Hand |
| LPR | Link Power Ratio |

| | |
|---|---|
| Lrhr | Landscape Mode Right Tilt Left Hand |
| Lrth | Landscape Mode Right Tilt Two Hands |
| LTE | Long Term Evolution |
| LTE U | Long Term Evolution Unlicensed |
| MEG | Mean Effective Gain |
| MIMO | Multiple-Input and Multiple-Output |
| MIMO BC | Multiple-Input and Multiple-Output Broad Cast |
| MISO | Multiple-Input and Single-Output |
| MISO IC | Multiple-Input and Single-Output Interference Cancellation |
| MMSE | Minimum Mean Square Error |
| Mm Waves | Millimetre Waves |
| MSE | Mean Square Error |
| MU-MIMO | Multi-user MIMO |
| OU | Optical Unit |
| PC ABS | Poly Carbonate Acrylnitrile-Butadiene-Styrene |
| PCB | Printed Circuit Board |
| Phr | Portrait Mode Right Hand |
| Pth | Portrait Mode Two Hands |
| QoS | Quality of Service |
| RF | Radio Frequency |
| RX OOU | Receiver On board Optical Unit |
| SAM | Specific Anthropomorphic Mannequin |
| SISO | Single-Input and Single-Output |
| SNR | Signal to Noise Ratio |
| TO MIMO | Transmit Optimization Multiple-Input and Multiple-Output |
| TRP | Total Radiated Power |
| TRS | Total Radiated Sensitivity |
| Tx | Transmitter |
| TxWF | Transmit Wiener Filter |
| VSINR | Virtual-signal-to-Interference and noise ratio |
| WMMSE | Weighted Sum-MMSE |
| WSR | Weighted Sum Rate |
| XPD | Cross Polar Discrimination |

# CHAPTER 1. INTRODUCTION

Fundamental concept of Human Bond Communication (HBC) has been discussed in this chapter. The proposed algorithm and solution for addressing the physical layer issues for HBC has been explained and investigated in the following subsections.

## 1.1. BACKGROUND

The concept of Human Bond Communication (HBC) was proposed for the first time by [1]. Due to the concept of the HBC, five senses, namely optic, auditory, olfactory, gustatory and tactile should be transmitted via wireless communication technology. In fact, the HBC is a comprehensive approach to describe and transmit the features of a subject in the way humans perceive it. The HBC concept covers several steps from sampling the physical subject, interpreting the sample into five sense- domains, transform them into a data set, use the compatible communication medium for transmitting the information and recover the information at the receiving side. Reaching to this point is predicted by 2050 since several groups and institutes currently are working on different aspects of the concept [2].

Moreover, there are several research and works on the vision as well as the core technical enablers of the HBC paradigm. Some of the recent works were addresses in [3]. In [4], the discussion on how 3D optical vision, thermal vision, acoustic profiling, olfaction, and tactile sensing can help in remote inspection was carried on. The analytic solutions are also investigated. The authors propose a robot mounted opto-thermal and acoustic sensing system as a possible integrated system to gather such data, which can be a first step in the HBC technology development.

There are also some investigations on how the upcoming future wireless system in terms of standards and etc. should be to support the HBC architecture[5]. Dealing with security and privacy issues also were discussed in this work.

Several applications can be defined for the HBC system such as utilizing the knowledge to assist handicap people in any stage of the HBC system from sensing to transmitting data. Telemedicine applications and personal health care [6], dental and biological implant prosthesis for early warning performance [7], multi business model innovation for the future wireless technology as a platform for the HBC technology [8] and the impact of network neutrality on futuristic innovation, particularly on the HBC [9] are some of the notable applications of the HBC up to present.

This work investigates a proper method for transmitting HBC data from the subject to the receiver part. To reach this goal MIMO and cooperative base station MIMO technologies were investigated in this thesis.

Coordinated Access Points (CAP) are a new type of architecture in which Access Points (AP) are connected to one another, and their operations are coordinated. The extraordinary performance level that CAP systems can theoretically reach has been assessed in many studies based on information theory [10], [11], [12] and [13]. Gains are theoretically significant; a maximum 10 fold improvement over conventional networks was reported in [14]. Actual designs are proposed to attain the performance promised by CAP systems. Unfortunately, such designs rely on unrealistic assumptions and cannot be implemented in practical systems [15], [12], [16], [17], [18] and [19], the main issue is the prohibitively high computational complexity of the proposed methods [20]. Another problem is the excessive amount of information exchanged among APs; this process requires additional energy and processing power [21]. The challenges raised by the practical implementation of CAP systems are discussed in the present thesis to address the design problems within current systems.

Minimum Mean Square Error (MMSE) estimation plays an important role in approaching the information-theoretic limits of linear Gaussian channels [22]. The derivative of mutual information with respect to signal-to-noise ratio (SNR) is equal to half the MMSE, regardless of the input statistics, according to the recent study [23]. Moreover, the resultant interference from MMSE equalization can be considered a Gaussian distribution with zero mean given large numbers of transmission and receiver antennas [24]. Accordingly, MMSE is closely connected to other important performance measures, such as bit error rate, and capacity. MMSE transceiver optimization was studied for a single user Multiple-Input Multiple-Output (MIMO) scenario in [25] and [26]. Multiuser MIMO systems in the uplink were analyzed in [27], [28], [29] and [30], where the precoders at the mobile terminals and the MMSE receiver at the Base Station (BS) were jointly adjusted to minimize the sum- of Mean Square Errors (MSE). The present work focuses on optimizing the linear MSE of a multi-user downlink MIMO system. Given fixed receive filters, downlink MMSE strategies were independently introduced in [31] (Transmit Optimization, TO-MIMO) and in [32] (Transmit Wiener Filter, TxWF). These strategies minimize MSE modification by scaling all data streams (layers) according to a common factor. Another strategy to address the interference among users involves diagonalizing or block-diagonalizing channel as described in [33], [34] and [35]. However, this strategy requires the number of transmitting antennas to be greater than or equal to the total number of receiver antennas. Other transceiver schemes with such restrictions were proposed in[36] to maximize rates by optimizing Virtual-signal-to-Interference and noise ratio (VSINR).

The transmit beamforming design is a non-convex and non-trivial problem to maximize the Weighted Sum-Rate (WSR) subject to a transmit power constraint. A few studies have addressed the same problem and proposed an iterative algorithm based on the uplink-downlink MSE-duality [37], [38], [15], [39], [40]. In the Weighted Sum-MMSE (WMMSE) algorithm proposed in [41] a relationship was established between WSR and WMMSE in the MIMO-broadcast (MIMO-BC) in line with the results presented in [23] and [42]. The WSR problem can essentially be solved as a WMMSE-problem with optimized MSE-weights. The proposed algorithm is an iterative algorithm for WSR optimization in MIMO-BC. The algorithm iterates among the WMMSE transmit filter design, the computation of the MMSE receive filters with well-known closed-form expressions, and weighting matrix updates. Each of the three steps is performed by evaluating the closed-form expressions, and the proposed algorithm is simpler than state-of-the-art methods that require multiple-level iterations [37] and [43]. Two versions of the algorithm are presented: in the first, the weight matrix is computed based on the correspondence between WSR and WMMSE. In the second one, the weight matrix is additionally constrained to be diagonal, which optimizes WSR with de-correlated streams at each user. The details of the algorithm are provided in [41].

In the present work, the WMMSE algorithm is extended to a multi-cell system scenario with two cells; each cell has K base stations and K users. The details regarding the formulation are described in chapter 4. The simulation result of the extended algorithm is presented the result chapter.

The VSINR algorithm is an extension of the work presented in [44], which showed that all Pareto-optimal points can be achieved with a solution to the VSINR maximization problem if the weight coefficients in the VSINR expression were selected properly. In [44], however, only the necessary conditions to attain these Pareto-optimal points were provided; thus, the process of selecting parameters to guarantee the generation of desired boundary points was not completely addressed. A method of adapting weight coefficients was presented in [36] to produce a desired WSR maximizing point. Deriving the gradient expressions for the WSR and VSINR maximization problems, suggested that the weight terms for the equivalence between the two problems depend on beamforming vectors. The algorithm ran in two steps; given fixed beamformers, the weight coefficients were updated such that two problems had the same gradient expression. Then, the beamforming vectors were computed as a solution to the VSINR problem with the updated weights. Given that weight terms and beamforming vectors depend on each other, these two steps should be repeated until convergence is achieved.

In the current work, the algorithm is curtailed to work with the measurement setup. The simulation result of the shortened version of the algorithm is presented in the result chapter.

A few studies have been conducted on cellular network and CAP systems in real measured channels. In [45] the potential of BS cooperation was evaluated by measuring the information theoretic channel capacity at 5.2GHz in four overlapping urban macrocells with five users. With multi-antenna terminals, the capacity per cell can even exceed the mean capacity of the isolated cells. The cell capacity was enhanced by a factor of five in the measurement scenario as a benefit of cooperation.

Additional research was conducted as reported in [46]. The same setup was used in the measurement process, and cooperation enhanced the rank of the compound channel matrix. The spectral efficiency was five times higher under cooperation than that under a conventional frequency reuse system, in which different radio resources are assigned to adjacent cells. Measurements taken at 2.53GHz with a 20MHz bandwidth in two triple-sectored urban macro-cell deployments were investigated [47]. The results of the two multi-cell measurements characterized the interferences, delays, and fading correlations at 2.53GHz. The correlation significantly decreased with an increase in the separation of the antennas, which is important to the performance of cooperative MIMOs. Downlink cooperative MIMO systems in cellular macrocell environments were studied [48] with a coherent measurement setup. Two drive routes namely, line-of-sight and obstructed line-of-sight, were measured. Highly shadowed scenarios were also considered. Cooperation can facilitate significant capacity gains, thereby motivating the potential deployment of such distributed MIMO systems. In particular, one drive route provided more than 100% mean capacity gain at the 50% cumulative probability level. The outcomes presented in this paper notably focus on the capacity for a single user. In [49], two terminals were used in two overlapping cells and were placed in specific indoor, outdoor-to-indoor and outdoor scenarios. Intra-site and inter-site Coordinated multi-point transmission/reception (CoMP) were realized; in inter-site scenarios, the downlink CoMP over a 20MHz bandwidth was examined at 500m inter-site distance using distributed LTE system architecture. The average throughput gains by factors ranged from 4 to 22 when CoMP was used in comparison with interference-limited transmission. Three BSs were examined in [50]; each BS had a single antenna in an urban macrocell environment. The receive side consisted of two dipole and two loop antennas mounted on top of a measurement van. Fully coherent measurements of the channel running from the three base stations to a single mobile station equipped with four antennas were taken for the analysis. Gains in capacity were enabled by cooperative base stations signalling for point-to-point and multi-user communications. The analysis indicated that cooperative signalling with practical algorithms significantly increases average capacity. In [51] an investigation was conducted on the correlation of single-BS MIMO and multi-BS cooperative MIMOs based on the data measured in outdoor none-line-of-sight environments. The results clarified the spatial and the cross-polarized correlation characteristics of single-BS and multi-BS cooperative MIMOs. According to studies on the measured channels in cooperative MIMO systems, a considerable gap exists concerning combining theoretical signal processing achievements with the real measured data to determine the realistic behavior of CAP systems. Nonetheless, a few investigations measured CAP channels have reported an improvement regarding the capacity compared with non-cooperative cases. Numerous areas of research remain unexplored, such as the effect of beamforming, correlation and other parameters in the real propagation environment of CAP systems.

In addition to the physical layer solution for HBC, this work points out development of a new platform named, CONASENSE referring to COmmunications, Sensing, Navigation and Services to form the idea of HBC [52]. The concept of CONASENSE defines a platform to integrate academia, industries and researchers to build up the long-term vision for the convergence of communication in more enhanced level than today’s communication. The main goal is defining protocols, standards and business models for the future of the wireless communication beyond 2050 and beyond 5G. The main goal of proposing this solution is connecting every single person by all his/her senses (HBC) with every activity from agricultural and environmental to telehealth and remote navigation via reliable, fast and well-constructed wireless network. The demands to reach this goal are high data rates, ubiquitous connectivity and global networking. CONASENSE is the platform to address these challenges to make the dream of HBC to the reality.

## 1.2. PROBLEM DEFINITION AND CHALLENGES

The main reason of proposing HBC concept returns to the fact that current way of communication is not in the most possible complete way. It means, in the current system, the communication is limited to the audio and video transmission. But it is not enough for the growing society that we have regarding social or scientific issues. So, the first problem which has been considered is how wireless technology should evolve to achieve the goal of transmitting all senses of the human. The proposed solution was Human Bond Communication, which has been introduced to transmit all five human senses, namely optic, auditory, olfactory, gustatory and tactile via wireless communication technology.

Transmitting human bond information through a certain communication medium involves several steps, including:

- the sampling of a physical subject;
- digitization and quantization of the sample to be transmitted;
- encryption of data at an appropriate security level;
- compression of data to comply with certain fitness standards;
- transmission of data to the cloud or receiver; and
- retrieval of information at the receiving side.

Each step needs profound work as long as all steps are new to the researches. Instead of going through each of the steps, this thesis mainly focuses on the transmission of data to the cloud or receiver. Several options are also explored to ensure the transmission of the largest amount of data, the best performance and data rate, and the prevention of information loss.

The main problem, which must be addressed to achieve the HBC transmission, is selecting the best possible algorithm for data transmission. This work is divided into three parts to review the extant algorithms or methods for HBC information transmission, identify various challenges in cooperative, non-cooperative, and semi-cooperative scenarios, compare the performance of two algorithms in an actual propagation environment, and assess the effects of various parameters and scenarios on the transmission of data in cellular network systems. The performance of cellular systems is also evaluated from a novel perspective.

Despite improving the quality of communication, CAP systems are very expensive, face channel interferences, and require complex algorithm designs. These limitations must be investigated accordingly to highlight the advantages of CAP systems over non-cooperative architectures.

As one of the most important tools for achieving optimal data transmission, beamforming has a significant role in designing highly efficient data transmission algorithms. The effect of beamforming on data rate must be examined under different scenarios, including those with and without transmit beamforming.

As mentioned in the Introduction, this thesis reviews the performance of the WMMSE and VSINR algorithms based on their recorded data rates during the simulation and when using measured data. Each of the identified parameters produces a unique effect under all scenarios with measured channels. The performance of those algorithms with independent and identically distributed (i.i.d.) channels must be reviewed in consideration of their behavioral differences during the implementation of the measured channels. Any reduction in algorithm performance must be monitored using measured data to devise highly efficient algorithms for real communication purposes.

Algorithms for HBC transmission must be designed in consideration of their capacity to achieve maximum data rates. However, such capacity may be affected by the internal parameters hidden in measured channels, including fading, correlation, BPR, handsets, frequency bands, and distances from BSs, dissimilar bodies, or handset grips to block antennas. These effects of various parameters on the performance of an algorithm are thoroughly reviewed in this section, and the findings are expected to underscore the importance of certain parameters in the designing of antennas, handsets, algorithms, and communication setups.

Human bond communication (HBC), which pertains to the transmission of information through the five human senses, is examined in this thesis by focusing on broadcasting MIMO, cooperative MIMO, and low- and high-frequency bands in the Long Term Evolution (LTE) standard. The simulation results are evaluated using the measured data to identify those parameters that influence the performance of our proposed algorithm.

Moreover, this work discusses a business model for HBC concept. HBC develops rapidly at academia and research groups. But the focuses on the market development and business modeling for HBC is needed more attention and work. HBC is also known as the "Internet of beings" due to its capacity to explore in many domains and overcome the current methods of communications. It is obvious that a new business model should be defined for these huge changes, which will be expected after first implementation of the HBC in the real market. The investigation on the business opportunities of HBC development and later proposing different solutions such as persuasive business model concept and their abilities to design a comprehensive prototype for HBC technology is another problem, which has been addressed in this work [53], [54].

## 1.3. SCIENTIFIC MOTIVATION

The main motivation of this work is to address the important challenge of data transmission limitation and solution for HBC system. As it is discussed previously, the huge data in different forms should be transferred to satisfy the need of HBC system. In this work, the main assumption is that data is ready for transmitting. So which solution could be the best answer for transmitting data for HBC framework and requirements? This work tries to propose the best solution with respect of the current wireless technology limitations and abilities to achieve the enhanced data rate, which is needed for HBC transmission.

The more motivation for this work is finding the most suitable algorithm for CAP scenario, which is one of the best solutions for capacity and coverage in LTE standards. The motivation leads this research to propose an extension to the WMMSE algorithm to be applicable for CAP scenario. To evaluate the algorithm and its performance, the measured data, which is the proper system for HBC transmission, have been used to reach to the valid conclusion.

## 1.4. RESEARCH CONTRIBUTIONS

This thesis reviews the most frequently employed HBC transmission algorithms in the literature. The data were sampled and quantized for transmission, different setups and scenarios were tested to achieve maximum antenna efficiency, the best performing algorithm was evaluated using measured data, and those parameters that reduce the performance of such algorithm were identified. Our proposed solution yields the best outcome for the scenarios above.

Cellular network systems, especially their data rate, face several challenges in actual propagation environments. This thesis examines these challenges under various scenarios with measured channels, and the findings of such investigation are expected to facilitate the design of highly efficient algorithms for cellular network systems.

The performance of algorithms with i.i.d. channels and their behavior within measured channels are also examined. After comparing the cooperative scenarios with the non-cooperative ones, the performance of two algorithms are tested in the simulation and measurement scenarios. The aspects of those parameters that affect the performance of these algorithms are also investigated.

This work proposes a cellular network design that considers as many influencing parameters as possible. The importance of handsets, communication standards, antennas, communication setups, and algorithm complexity in the design of these systems is also highlighted. Each algorithm shows varying degrees of sensitivity to different parameters and scenarios, and such sensitivity must be taken into consideration when designing cellular network systems in the future. To facilitate the design, this work considers several scenarios, including the orientations and distances of handsets to and from BSs, the transmission of data with and without precoding, and MISO and MIMO cases. Data are collected from each of the aforementioned scenarios, and the effects of each parameter are discussed separately. The proposed algorithm is then applied under two frequency bands with different LTE standards, namely, 776 MHz and 2300 MHz, to test its performance.

This work offers the following major contributions:

1. The advantages and disadvantages of the cooperative broadcast MIMO over the non-cooperative one with and without precoding techniques are identified based on the measured channels. The possibility to achieve the expected data rate improvements in practice or, in real communication systems is also evaluated.

2. The WMMSE algorithm is applied under different scenarios to measure the data rate that is actually achieved by a cooperative MIMO system in real measured channels. A novel algorithm is then proposed to determine how the capacity to achieve the maximum data rate in theoretical and real scenarios may be affected by the cross-correlation among various users from one antenna at the BS and the imbalance among link powers.

3. The data rates that are achieved by both the WMMSE and VSINR algorithms are compared using simulated and measured data. A measurement campaign is also conducted to devise a novel practical algorithm. The campaign results may be used to facilitate the designing of high-performance algorithms for cellular network systems.

4. The effects of different grips on the achieved data rates and the performance of the VSNIR algorithm are examined at two frequencies. The behavior of this algorithm is then evaluated by measuring the cross-correlation among different links.

5. The performance of the best algorithm in a real propagation environment is treated as the main medium for transmitting HBC information. The data transmission requirements for HBC design are identified, and an optimal solution is eventually devised. The HBC concept is also extended to other fields by considering the anticipated demands for wireless communication.

## 1.5. THESIS OUTLINE

The thesis is divided into seven chapters. Chapter 1 provides a brief overview of MIMO, cooperative MIMO, HBC, and the proposed research problems.

Chapter 2 thoroughly discusses HBC, its architecture, and its application as a knowledge home. The frequencies, MIMO structures, and requirements for HBC data transmission are also presented. A comparison of different possible useable technologies which can be used for HBC is also given in this chapter. Further, this chapter describes the necessary bandwidth to transfer five senses and discusses the optimality of the chosen data transmission method, which connects the HBC with rest of the chapters.

Chapter 3 explains the purpose, setup, and considerations of the proposed measurement campaign. The site, handsets, users, cases, and scenarios to be investigated in this research are also introduced along with the main parameters that are considered in the measurement.

Chapter 4 presents the proposed algorithm for cooperative MIMO, the benchmark algorithm for MISO scenarios, and the performance of these algorithms in the simulation.

Chapter 5 discusses the performance and achieved data rate of the examined algorithms in a real propagation environment. These results are then used as inputs in creating various HBC transmission techniques and strategies.

Chapter 6 summarizes the application of the proposed algorithm for HBC data transmission. The data transmission performance of the WMMSE algorithm is evaluated, and the application of various LTE standards and frequencies in HBC is examined. This chapter also outlines the anticipated demands and requirements for developing a physical layer standard for HBC transmission.

Chapter 7 concludes the thesis by presenting the contributions of this research and possible directions for future work.

## 1.6. LIST OF PAPERS

**Paper 1.** M. Rahimi and Ramjee Prasad, “Performance of Human Bond Communications using Cooperative MIMO Architecture,” Special Issue on "Future Teleinfrastructure for Multisensory Devices (FIND)", Wireless Personal Communications, Vol. 95, No. 1, pp. 155-167, 2017.

**Paper 2.** M. Rahimi, “Achieved Data Rate of Cooperative MIMO in Measured Channels,” Wireless Personal Communications, Vol. 85, No. 4, pp. 1925–1943, 2015.

**Paper 3.** M. Rahim and Ehsan Foroozanfard, “On the Effect of Different Grips of Handsets on Data Rate in the Measured Channels,” International Journal of Antennas and Propagation, Vol. 1, pp. 1–8, 2015.

**Paper 4.** M. Rahimi and Ramjee Prasad, “CONASENSE as a Platform for the implementation of Human Bond Communications,” Accepted to IEEE Aerospace and Electronic Systems Magazine, Special Issue on Integrated Navigation, Sensing and Communications for Solving Problems in Society, 2017.

**Paper 5.** M. Rahimi and Ramjee Prasad, “Human Bond Communication from a Business Perspective,” submitted to International Journal of Translational Science, River Publisher, 2018.

**Paper 6.** M. Rahimi and Ramjee Prasad, “An Introduction to the Business Model for Human Bond Communications,” Accepted to Global Wireless Summit (GWS 2017), Cape Town, South Africa, October 15-18, 2017.

Different parts of the work and results, which have been mentioned in the previous chapters of this thesis, have been published in divers’ journals and conferences. Table 1-1 shows the mapping of different chapters versus publications.

*Table 1-1: Mapping of chapters versus publications*

| | Paper 1 | Paper 2 | Paper 3 | Paper 4 | Paper 5 | Paper 6 |
|---|---|---|---|---|---|---|
| **Chapter 1** | x | x | x | x | x | x |
| **Chapter 2** | | | | | | |
| **Chapter 3** | | x | | | | |
| **Chapter 4** | x | | | | | |
| **Chapter 5** | x | x | x | x | | |
| **Chapter 6** | x | | | | | |
| **Chapter 7** | | | | | x | x |

# CHAPTER 2. HUMAN BOND COMMUNICATION (HBC)

The concept of Human Bond Communication has been discussed in this chapter, the necessity of introducing the concept to the wireless communication and the requirements of implementing the idea in the real world. This chapter also points out to the solution for the physical layer of HBC implementation in epitome.

## 2.1. HBC DEFINITION

Since the beginning of time, humans have acknowledged the importance of communication in many activities, such as sharing information, influencing people, establishing a rules-based society, exercising authority, and expressing their emotions. Accordingly, many communication methods have emerged along with the evolution of man. Specifically, humans have grown from painting on caves during the Stone Age to sharing information wirelessly through text, voice, and video messaging in the modern world. The continuous developments in modern communication have also motivated scientific and technological innovations in recent years.

As one of the primary drivers of such innovations [1] and [2], HBC proposes the use of the five human senses, namely, optic, auditory, olfactory, gustatory, and tactile, as an alternative means of transmitting information wirelessly. This approach characterizes a physical subject from the human perspective by sampling and interpreting such subject through the five human senses, transforming the obtained information into a dataset, transmitting the dataset through an appropriate communication medium, and obtaining the transmitted information at the receiving side. Humans are expected to communicate via HBC around the year 2050.

Humans perceive their world through their eyes, ears, nose, tongue, and skin, with each organ serving a unique function. However, using only one sense at a time can only reveal a limited amount of information and cannot facilitate a comprehensive communication. Accordingly, humans must utilize these five organs simultaneously when discovering or acquiring information.

HBC is generally a twofold process that requires both the sender and receiver to understand and perceive a subject through their five senses. The information obtained by each “sense” is transmitted to the HBC system, which then converts these inputs into clear signals that, in turn, are sent to neuron receptors. The human brain sends neurotic pulses to comprehend the sensed information and creates a perceptual image of the sample being observed.

Wireless communication technologies are used in the HBC transmission process. As shown in Figure 2-1, an HBC system generally comprises three major components, including:

- senducers, which transduce the stimuli into electrical signals;
- a human bond sensorium, which receives and converts the signals from senducers to make them perceivable by humans; and
- a human-perceivable transporter.

*Figure 2-1: An overview on HBC architecture system*

Other extant HBC systems and structures are further described in [2], and several studies on the vision and core technical enablers of the HBC architecture have been reviewed in [3].

The roles of 3D optical vision, thermal vision, acoustic profiling, olfaction, and tactile sensing in remote inspection were investigated in [4], and the authors proposed a robot-mounted opto-thermal and acoustic sensing system to gather data for developing an HBC system.

Although the development direction of the HBC system is yet to be fully investigated, researchers expect that this technology will revolutionize how humans communicate with one another. Accordingly, the application of this technology on different layers of the communication network must also be examined. Given that this system greatly depends on the emotions and person-specific information of an individual, the HBC design must take reliability, security, and trust into consideration.

## 2.2. KNOWLEDGE HOME

Knowledge Home provides individuals with an area where they can convert perceptive information into an exchangeable format that they can share with others [55]. This platform, which is developed in two levels, is expected to be launched worldwide along with the HBC and Feeling Identification and Transmission (FIT) technologies around 2050. Figure 2-2 shows the Knowledge Home, where the information obtained by HBC is transformed to facilitate improvements in technology, economy, and quality of life. Knowledge Home primarily adopts the following perspectives:

- people perspective, which introduces a social platform where Information and Communication Technologies (ICT)-related materials are gathered and various types of services are offered to the members;
- academic perspective, which introduces to the ICT society the recent advancements in R&D; and
- socioeconomic perspective, which facilitates collaboration among industrialists, regulators, and venture capitalists.

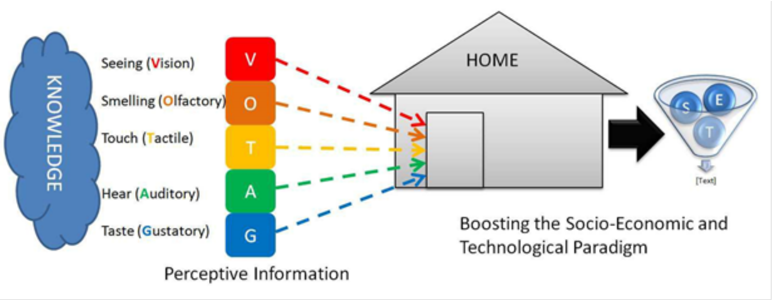



*Figure 2-2: Schematic of the Knowledge Home at first level implementing HBC technology [2]*

Knowledge Home is also expected to improve the robustness of business eco-systems by incorporating human values, such as ethnics, culture, beliefs, and art, into business models. Following the motto, “the Internet of Things (IoT) will be the Internet of beings,” Knowledge Home allows the existing technologies to develop in a human-centric manner.

Knowledge Home follows a homogeneous multi-dimensional approach to communication where the differences in language and location no longer prevent people and communities from interacting with one another.

In this case, Knowledge Home may be assumed as:

- a home in which a family lives,
- a workplace in which colleagues interact with one another; and
- a society where people communicate with one another regardless of the differences in their characteristics and backgrounds

As shown in Figure 2-2, Knowledge Home uses the information obtained by HBC as its input. This concept does not simply transmit information through the available senses but rather grants an individual the power to communicate with others by using all of his/her five senses simultaneously.

Accordingly, the term “Knowledge Home” indicates that people are living under a single roof where they use all of their five senses to impart knowledge effectively and comprehensively.

Such information can be transmitted in the following ways:

- Self-transmission, where individuals are given early warnings in the form of emotions whenever they are facing or about to face a complex situation. For instance, an individual may display aggressive or stressful behavior when attending a work meeting.
- Brain-to-brain transmission, where a person sends information directly to another person. This phenomenon is usually observed among parents communicating with their children or among specialists who communicate with the disabled.
- Device-to-device transmission, where advanced technologies, such as data centers or smartphones, receive data from sensors. This phenomenon is usually observed when the individual is attending to a healthcare situation.

The outputs of this system can be categorized as follows:

- self-awareness;
- caring for and helping others;
- controlling and guiding people who are in need; and
- guaranteeing security and public safety.

The personalization of data presents a significant issue in Knowledge Home. Each person must store personal information, such as data regarding his/her health, on a cloud server, and such data may be updated on a daily or hourly basis based on the previous behavior of this individual. These data must also be encrypted to avoid interferences or attacks.

Knowledge Home may be utilized in many situations and is particularly useful in cases where individuals attend to their health, such as when they measure their risks of suffering a fatal illness. Knowledge Home may also be used to understand children, especially at times when a parent or guardian is absent.

In sum, Knowledge Home serves many different functions aside from communication. For instance, people can improve their quality of life and social communication by showing genuine concern about the needs of others. Receiving early warning signals can also help individuals control their emotions when facing challenges or when subjected to dangerous situations, such as terrorist attacks. The potential applications of this system are expected to multiply in number in the future [56].

## 2.3. DIFFERENCE BETWEEN IOT AND HBC

A growing number of devices with embedded sensors, including computers, cars, and household appliances, connect to the Internet to form the IoT where they can obtain and share information. IoT involves many concepts, which are defined as follows:

- IoT device: A standalone device that can be tracked and/or controlled from a distance and comes equipped with Internet connectivity. Examples of IoT devices include analytics, networks, dashboards, remotes, data storage, and gateways.
- IoT ecosystem: A platform where various entities, such as corporations, governments, and consumers, connect with one another using their IoT devices.
- Physical layer: The hardware that supports an IoT device (i.e., sensors and networking gears).
- Network layer: The hardware that transmits data from the physical layer to various devices.
- Application layer: The protocols and interfaces that allow devices to communicate with one another.
- Remote: The hardware that allows various entities to control their IoT devices from a dashboard (i.e., personal computers, non-traditional remotes, and smartwatches).
- Dashboard: A program that is installed in a remote to allow users to control and obtain information about their IoT ecosystem.
- Analytics: Software that analyzes the data from IoT devices for various purposes, including predictive maintenance.
- Data storage: An IoT device where all the collected data can be stored.
- Networks: Allows entities to communicate with their devices and with one another.

In contrast to IoT, the HBC system has been defined as the “Internet of beings” where people, instead of things, are connected together. HBC collects the information being sensed by humans and then digitizes such information for transmission. Given that the human senses are not wave based, the HBC system samples the data much more exhaustively compared with IoT. However, IoT and HBC may employ similar devices or techniques to guarantee a continuous and simultaneous transmission of data.

## 2.4. HBC AND MIMO VERSUS CAP TRANSMISSION

The spectral efficiency and reliability of wireless communications are often enhanced by installing multiple antennas at BSs and mobile stations. However, the implementation of MIMO technologies demands additional MIMO concepts and technologies. Additional levels of processing must also be observed to maximize the benefits of spatial multiplexing and spatial diversity.

Spatial diversity before the 1990s was often limited to those systems that generate the optimal signal by switching between or combining two antennas. However, additional levels and degrees of processing will only limit these systems even though novel forms of beam switching have been implemented in the past.

As an improved version of MIMO technology, multi-user MIMO (MU-MIMO) allows multiple independent radio terminals to access a single system at the same time, thereby improving their communication capabilities. MU-MIMO has also been considered an extension of space division multiple access.

To achieve the maximum system capacity, MU-MIMO offers users with sufficient spatial degrees of freedom to access a single channel at the same time. Several versions of MU-MIMO are available for use by adopting various approaches.

MU-MIMO outperforms the other extant technologies in the following aspects:

- By exploiting the multiple access capacity from multi-user multiplexing schemes, MU-MIMO systems can directly achieve a gain that is proportional to the number of antennas installed at BSs.
- The propagation issues that affect single-user MIMO systems, including channel rank loss and antenna correlation, do not significantly affect MU-MIMO systems. Despite affecting the diversity per user, channel correlation does not significantly threaten multi-user diversity.
- MU-MIMO does not require the installation of multiple antennas at the UE to receive a spatial multiplexing gain at the base station. In this way, remote terminals may be created at a low cost.

Despite these advantages, MU-MIMO requires additional hardware and a large bandwidth to obtain channel state information.

A new architecture called CAP system may be implemented as soon as the requirements for MU-MIMO become available. To achieve the best system performance, each BS must obtain the channel state information. With its promising architecture, CAP achieves an outstanding communication quality, excellent quality of service, and high throughput.

The parameters mentioned above have vital roles in HBC transmission. For instance, transferring a large amount of data requires the adoption of reliable and high-performance techniques.

Despite fulfilling the requirements for HBC transmission, the CAP system is very expensive, requires a complex algorithm design, and frequently faces interference channels. Therefore, the advantages of this system over the non-cooperative architectures in measured channels warrant further investigation.

As one of the most important tools for optimal data transmission, beamforming plays a significant role in the design of highly efficient algorithms. Different scenarios, such as those with and without transmit beamforming, must be examined to understand the influence of this tool on the recorded data rate in measured channels. Previous studies have attempted to identify the most effective techniques for HBC transmission. The performance of the proposed CAP algorithm in a real propagation environment has also been validated using measurement data.

## 2.5. OTHER USABLE TECHNOLOGIES, NECESSARY BANDWIDTH AND DATA TRANSMISSION METHOD

Just now, we discussed how MIMO and CAP system could be used to implement the communication or ‘C’ part of the HBC. However, a large portion of the HBC system resides in H and B, meaning the capability to sense and recreate a subject in human perceivable way. Hence, a lot of focus also falls in the sensors and transducers category.

(a) Usable Technologies:

Digitizing sensory information is picking up pace in recent times. Among remaining three sensors that are waiting to be in the mainstream communication systems, olfactory sensing has gained a higher attention in digitization of sensory information. In [57], Hariri et al. elaborates the electrical stimulation of olfactory receptors of the nasal conchae with weak electrical pulses. This is very unique to its unlike contemporaries, in which chemical combinations are being used for the purpose. In case of HBC, electrical stimulations have priority over the material experience, as this would enable the communication systems to covert and send the digital format of the information. Besides that, the attempts are being made to use scent cartridges to replicate the smell at the distant end. One of them being ‘Vapor Communications’ [58], based in Cambridge, Massachusetts, who use a tiny cylindrical device, known as Cyrano, which has cartridges to hold scents. Cyrano can be triggered using an iPhone application, known as oNote, to release certain combination of scents, such as guava, citrus, ginger, honeysuckle, etc. to convey the information, which they call as the “scent-infused messages.” The Google Nose [59] and Smell-o-vision [60] projects are also the relevant leaps in olfactory realization., where latter is an attempt make a TV set, which releases smells along with the display.

Now, almost every modern mobile handset has touchscreen/ sensors that enables touch writing, and fingerprint sensors for fingerprint recognition to unlock the device and to do transactions on mobile banking. Nonetheless, this did not happen in blinks, and the tactile sensing is around us for a quite a long time. [61] discusses the design and implementation of tactile sensing computer, which is one of earlier stages of tactile sensing. However, this is just sensing the subject, and for HBC, we must have capability to create it. Not very accommodative, still a significant proposal is given in [62] by Hakozaki et al. to have a "tactile sensing element that communicates through two-dimensional conductive skin layers." A "Conformable and scalable tactile sensor skin for curved surfaces" [63] was proposed by Ohmura et al. where the tactile skin, having multiple module, is proposed for the creating the touch information. Very recently, Ozioko et al. proposed "SmartFingerBraille" [64], which an actuation based communication glove that can be triggered using a mobile phone to send the Braille messages to blind patients. The wearable sensors, such as "electronic skin" are now joining the mainstream applications. A very significant research is done by Puangmali et al., which is a State-of-the-art in force and tactile sensing for haptic perception [65] ( hardness and other tactile properties of a tissue) during surgery.

Just like tactile sensing, the gustatory sensing (taste) also requires the subject to be in the direct contact with the sensorium, hence requires more intensive research, like what authors of [66] discussed in their work, which is about analyzing taste sensory receptors (Mechanosensory neurons) when they are in contact with water-soluble substances. Such researches may aspire researchers to build an "Electronic Tongue," as discussed in [67], which is an analytical taste-sensing multichannel sensory system which improves the reliability over the human governed panels for qualifying taste quality of a food item.

As we can see, that unlike auditory and visual sensing, the progresses in other three sensing are fragmented. The developments in their areas are for different purposes and not on a common line. However, in HBC, we can take the advantages of these developments to build a holistic platform, which not just realize the subject, but also accommodates the specific needs, such as braille and haptic information, as mentioned before. Yet, it is not as simple to accommodate the other three sensors, as it seems. They require a completely different set of sensors and transducers to realize the information, and the form-factor varies from the case to case. In addition, their evolution requires their electronic counterparts to be in close contact, which is a very big worry, as most of us would not like a foreign object sticking to our sensorium. Further, the challenge is more on the recreation than sensing the subject, as the concept of recreation depends on the purpose of its use, as an example, the smell of a rose scent may require being much stronger than an actual rose flower.

(b) Bandwidth necessity for an HBC scenario:

The choice of bandwidth is very tricky for HBC and requires many trade-off in the selection. Already, visual information is eating up most of the bandwidth in wireless communications and adding on other sensor information might lead up to manifolds of spectrum requirements. Also, the bandwidth of the sensory information also depends on the human capabilities. As an example, we humans can comfortably realize a video file if the set of images change at least with a rate of 24 images (frames) per second. Below 16 frames per second, our retina can no longer have a smooth transition, and we see flickering videos. However, no other sensory information is so rigorous and dynamic as compared to visual and auditory information, and at the same time can be even more rigorous than the two, visual and audio, information.

In case of olfactory sensing, if we choose to recreate the information with the cartridge based technology, then, the bandwidth requirement will be fairly low, as compared to the electronic-based implementation. This because a few binary codes can trigger the specific combination of cartridges to create the olfactory effect. This information can be very well accommodate along with the present LTE-A (4G) data rates and, this also holds true for tactile and gustatory based sensing. What we mean here is that with cartridge systems, we have a platform with a very low level of resolution, and user may or may not get the replica of the subject. This may not give a very clear realization of the subject, but at least the information is conveyed. In such cases, the bandwidth requirement to add other sensory information is very low and can well accommodate in the present data rates for the few bytes of additional information exchanged.

However, if we want to increase the fineness in the realization, we need to opt for the electrical transducers that create electrical pulses to stimulate the human sensorium. Let us say that if, a user wants to feel a silk embroidery cloth with the dimensions of $2048 \times 1024$ millimeters with the resolution of $1\times1$ millimeters, and depth of embroidery has 64 variations, then, the information has $2048\times1024\times 64$ data points, each data point having location and depth of the pixel, which is a 16 MB of information. If, at the senducer (senses based transducers) end, user swipes fingers lengthwise such that each time he swipes 16mm wide, and he takes 10 seconds to swipe from one end to another, then, he would take 640 seconds to realize whole piece of cloth. In such case, the required bandwidth to transmit the information will be approximately 400 Kbps. The requirement severely changes with the depth and resolution.

A similar approach may be applied for other senses. Higher the information depth (steps) and intensity (resolution), larger is the bandwidth requirement. However, for the best case, if all the pixel that a visual sensor detects, must have a taste, touch, and smell, with 16 bit per pixel depth, then, to transmit 1900× 1200 size information with 120 frames per second of refresh rate, a HBC system must have the bandwidth requirement of at least 28 GBPS per channel

(c) optimality of the chosen data transmission method:

The next chapters of this thesis discuss and endorse the cooperative MIMO as the optimal data transmission method. We believe that to encompass such a heavy user demand, the system must be realized in the Beyond 5G environment when the data rates per user are expected to be in the GBPS range. However, the basic ingredient to boost up this requirement shall be the cooperative massive MIMO, which we shall see in the upcoming chapters, where we elaborate the discussion to align them with the HBC requirements.

## 2.6. SUMMARY

This chapter defines and presents the motivations for developing HBC, which will allow humans to communicate using all of their five senses. Sensory communication is currently limited to sight and hearing, and HBC allows for the sampling, quantization, encryption, and wireless transmission of the three other senses (i.e., smell, taste, and touch).

HBC may also be used to establish a Knowledge Home where people can improve their quality of life by communicating with one another using their five senses.

Given its many network layers, IoT offers the base requirements for the implementation of Knowledge Home and HBC transmission. As previously mentioned, IoT is an entirely different concept from HBC.

This thesis examines the application of three techniques, namely, MIMO, MU-MIMO, and CAP, in finding the best solution for HBC transmission at the physical layer. An appropriate algorithm for CAP systems is also devised to facilitate the transmission of data required for HBC. Different parameters and measured data are used to evaluate the performance of this algorithm, and the results may be used as reference to identify the ideal architecture for HBC transmission as well as those parameters that influence the algorithm performance.

# CHAPTER 3. MEASUREMENT SETUPS AND SCENARIOS

The details of the measurement campaign, setups, scenarios, and facilities have been discussed in this chapter.

## 3.1. INTRODUCTION

This work investigates MIMO and cooperative MIMO scenarios using different handsets, users, and two sets of measured data. These sets have similar BS configurations and employ different handset designs, measurement scenarios, indoor environments, and number of handsets.

A measurement campaign is also performed with an aim to identify those real-world parameters that influence the capacity of MIMO and cooperative MIMO with varying LTE standards under different scenarios. However, certain assumptions and simplifications are inevitable in this campaign. To simulate real-world situations as closely as possible, the performance of handset antennas are evaluated in consideration of 3D patterns, near-field user interactions, and propagation environments. The book mentioned in [68] was a great help in this measurement campaign.

The measurement setup employed in this work shows many similarities with those described in [69] and [70]. The measurement data are used to generate the preliminary conclusions.

## 3.2. MEASUREMENT CAMPAIGN SETUP

Various forms of handsets with antennas that cover one or both bands are used in the measurement campaign. As shown in Figure 3-1, these handsets have thin, flexible optical fibers and built-in optical units. A plastic case made of Poly Carbonate Acrylnitrile-Butadiene-Styrene (PC-ABS) was manufactured using a rapid prototype printer to encase the Printed Circuit Board (PCB). Along with the absence of thick and heavy coaxial cables and large RF chokes, the familiar feel provided by this plastic case helped the users operate the handsets without encountering any mechanical problems.

All measurements in the campaign are described in [71]. An urban macrocellular environment at the core of Aalborg, Denmark was used as the site for the measurement campaign. The cooperation between two BSs was taken into consideration during the campaign by installing two BSs at two separate locations.

On the one hand, BS1 was located 13 m above and 150 m away from the measurement site to provide high capacity channels and reach a compromise between high capacity and coverage. On the other hand, BS2 was located 60 m above and 500 m away from the measurement site to extend the coverage of the cellular system. Both BS1 and BS2 were equipped with two transmit antennas in the low band (LB) and high band (HB) frequencies. Selected in accordance to LTE standards, these frequency bands were measured simultaneously and centered at 776 MHz and 2300 MHz, respectively. This work specifically focuses on the HB frequency. To simulate real-world transmissions as closely as possible, the transmissions from both BS1 and BS2 to four users were measured simultaneously. The reliability of the adopted measurement methods was assessed through repetition and analysis.

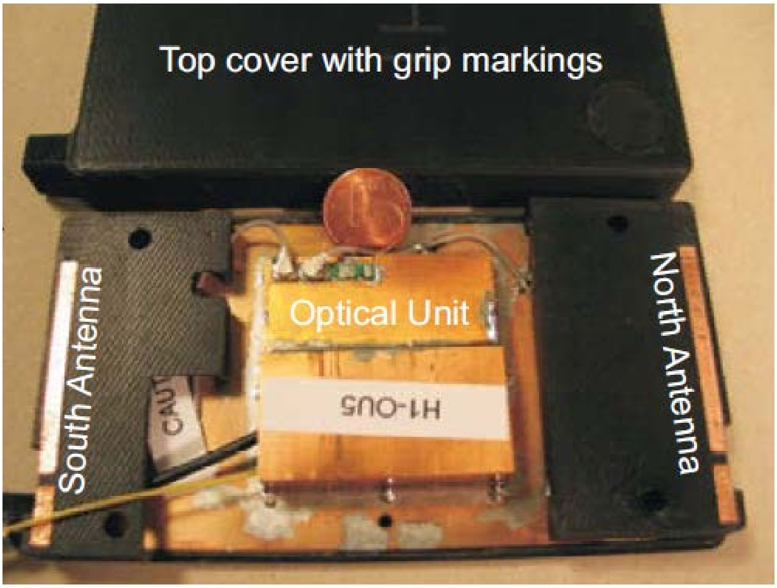



*Figure 3-1: Dual antenna handset with optical unit and plastic covers [69]*

The third floor of the Aalborg University (AAU) building at the Aalborg city center was selected as the location of the measurement room. This room was deliberately constructed without any windows to block the line of sight toward any of the BSs. To measure the local average (LA), the users were asked to move in and out of four 1×1 m squares drawn on the measurement room floor. Different handsets and users were involved in the measurements. Apart from the channel sounder of the AAU, the measurements also utilized four handsets to sound both LB and HB simultaneously. Each spatial position generated around 2000 impulse response samples, including Transmitter (Tx) antennas, propagation channels, and handset antennas with or without user influence (depending on their use case), as outputs at a

400 MHz sampling frequency and 60 Hz spatial sampling rate because of low speed. A total of 1200 spatial samples were eventually generated in each measurement within 16 m and 20 seconds. Tx separation was achieved using code division multiple access. All other components, including the amplifiers, filters, and optical units, were discarded as samples.

## 3.3. MEASUREMENT SITE

Figure 3-2 presents the street map of the AAU building as well as the locations of the measurement routes and BSs. The structures in the measurement site had the same height, materials, and architecture of buildings in European cities. Two BSs, namely, an umbrella cell (BS2) and a gap filler (BS1), were considered in the network architecture. BS2 had a high altitude and, similar to a broadcasting scenario, could only operate at the LB frequency. To accommodate the local high capacity requirements, B1 was equipped with many antennas and was operated at both the HB and LB frequencies. The measurement site was approximately 50 m long as shown in Figure 3-3. The building roof has large glass openings, and the measurement room was hidden 30 m deep into the building. The farthest BS had a direct Line of Sight (LoS) to the roof.


*Figure 3-2: Measurement site with view of the two BSs [72]*

During the measurement, four squares were drawn inside a large square on the measurement room floor as shown in Figure 3-4. The users (represented by the androids) moved back and forth in certain directions (represented by arrows) to measure the LA for four orientations. The measurement time was split into four equal sections, and the users moved from one corner to another and around the entire square. The sounder was installed 5 m away from the measurement site. To prevent the optical fibers from bending and twisting, they were distributed to the handsets from a unified station.


*Figure 3-3: Measurement site and base station distance*

*Figure 3-4: Measurement site [73]*

## 3.4. HANDSETS AND ANTENNA FEATURES

Several handsets with integrated optical units and dual antennas were specifically designed for the measurement campaign. To encase these devices and guarantee their robust design, a plastic casing made of PC-ABS was manufactured using a rapid prototyping printer. This material had $\varepsilon_r = 3$ to ensure that the handsets used in the simulation would reflect their real-life counterparts as closely as possible. Covering the handset in such material may also help the users familiarize themselves with the device and prevent them from touching the PCB and from disturbing the currents and fields. Three handsets with electrical dimensions of 100×40×10, 200×40×10, and 110×60×10 mm were designed for the most common forms of factors bars, clamshells, and smartphones, respectively. The plastic cases extended the length of these by 1.5 mm in all directions. The Optical Unit (OU) was fed by the antennas through thin RF cables, and the feeding process was terminated using the micro-coaxial connectors that were installed at different locations. Ten handsets were used in the experiments. All handsets were equipped with a second-generation Receiver On board Optical Unit (RX OOU). To confirm the absence of any damage, efficiency measurements were conducted both before and after the campaign. The differences in the efficiency of the handsets before and after the campaign were as low as 0.2 dB. However, handset H12 showed around 1 dB of difference.

Total radiated power (TRP) and total radiated sensitivity (TRS) were recently introduced as metrics for comparing the performance and antenna designs of the handsets [74]. Several examples are presented herein to examine the metrics of single antennas and to enhance the extant MIMO systems. This work does not target a specific system and instead examines the antenna metrics described in [75] to generate generalizable conclusions. However, in this way, this work limits its scope to the narrowband case. Similar to [75], this work examines all radiation patterns and power distribution models as well as uses the standard spherical coordinate system where the feeding point is positioned at the coordinate system origin, and the analytical dipole of a wire with infinite thickness and finite length is positioned at the Z axis. The radiation patterns examined in the measurements were taken from the center of the PCB (corresponding to a phone screen) and showed some similarities with the patterns generated by phone antennas. The X, Y, and Z axes represent the thickness, width, and length of the phone, respectively. The radiation patterns of the antennas were rotated in spherical coordinates to imitate the orientations in a real environment. However, regardless of its 3D orientation, the electric field and gain components of a phone were defined and recalculated in the original coordinate system using a rotation matrix. The radiation pattern and power distribution in real environments may greatly affect the parameters of antennas. The power distribution is often assumed to be isotropic, but many propagation measurements have since refuted such assumption by showing that a direct, or, clustered distribution of power in many directions. Several measurements were performed in [76] to compare the recently proposed and most popular channel models. Given the greater necessity of using a power distribution model than a full-scale channel model in the measurements, simplified models, such as the Gaussian model, have been proposed in the literature [77] and [78]. Accordingly, this work proposes the AAU model to preserve the angle of arrival, overall channel directivity, angular spread, and Cross Polar Discrimination (XPD). As expected in an isotropic environment, the dipoles reached the theoretical efficiency limit of Mean Effective Gain (MEG) = −3dB regardless of the handset orientation. Handset H4 was also able to reach such limit but suffered from efficiency losses. Instead of roll variation, only yaw and pitch were observed in the measurements, which could be attributed to the azimuth uniformity of the Gaussian model. The standard deviations, three percentiles, and means of the statistical samples were compared in the other evaluations.

A comparison of the full 3D case and the isotropic value reveals that the mean MEG in the Gaussian and AAU models may vary within a few tens of DB and up to 1 dB, respectively, which may further increase up to 2.5 dB and 6 dB. Despite having the same level of efficiency, the 90th percentile of the λ dipole is 2 dB larger than that of 6λ. In a similar vein, the H4-LB makes up for its poor efficiency by being equal to the 2λ dipole. Such compensation shows how the directive channel power may influence the perceived performance of an antenna. By aligning the null dipole radiation pattern with the peak power of the model, the Data Mode Portrait (DMP) and Data Mode Landscape (DML) extremes are captured by the AAU model. The LB of the realistic mock-up (H4) also shows this phenomenon. Therefore, in contrast to the isotropic estimates, the 6λ dipole shows the best percentile balance between DMP and DML. Given that analysis efficiency offsets the variations in the incoming and radiation powers, the efficiency in isotropic conditions cannot fully describe the performance of an antenna in directive environments. Moreover, channel power directivity has a negative effect on a highly directive antenna. The variances in the DMP and DML of the antennas of H4 range between 35% and 38% in the HB, but may reach up to 89% in the LB. Doubling the directivity of the dipoles produces a similar effect, which can be attributed to the fact that unlike the directive HB antenna, the origins of the extremes (i.e., the low and high gain regions of LB and HB antennas) reduce the number of permissible orientations and the probability of hitting these regions on a 1/2λ dipole. However, this finding is only applicable for specific cuts. Moreover, the influence of the user increases such variances by approximately 0.5 dB and shifts the mean estimate away from the isotropic value by up to 3 dB. The introduced losses then decrease the overall efficiency by approximately 3 dB. The measurements in [72] show that such influence may produce a similar reduction in MEG. Although approximately 1.3 dB and 2.5 dB variances were observed in the free space and the space with users, respectively, no isotropic reference case was measured. The measured data in all cases were only comparable to the DMP case, which was utilized as the measurement setup in either the free space or the space with users. The pre-antenna statistics for both bands of the multiple antenna case H1 were nearly the same as those for H4 and were offset by low efficiency. However, how such statistics can be converted into MIMO parameters, including Brand Power Ratio (BPR) and correlation, remains unknown. Given the equal efficiency of both antennas, the BPR may be equivalent to 0. Despite having more or less the same rotational statistics, both antennas are not symmetrical, that is, the bottom antenna is placed at an unfavorable position when the top antenna is placed at a favorable one, and vice versa. The variances in the BPR increase by approximately 0.5 dB after the addition of phantom hands. By contrast, the mean DMP/DML estimate in the AAU model shifts away from the isotropic value and the extremes by approximately 1.5 dB and 3 dB, respectively. The above cases demonstrate a simple roll sweep. Given the similar probability of each roll angle, the BPR of a handset in an unfavorable orientation may differ from the isotropic estimate by up to 4 dB, and such variance may significantly decrease and increase the correlation for LB and HB to approximately 0.4 and 0.15, respectively. Nevertheless, the rotational changes around these new averages are very similar. Consistent with the AAU model, the BPR measured in [72] shows a 1 dB variance, while the mean correlation in the free space is 0.78 and 0.12 for LB and HB, respectively, with corresponding variances of 0.07 and 0.08. The influence of the users shifts the mean values of such correlation to 0.36 and 0.15 for LB and HB, respectively, with corresponding variances of 0.15 and 0.11. The power models successfully predicted such phenomenon using the measured data, which were similar to the simulated data in the AAU model.

## 3.5. DIFFERENT USE CASES

Several use cases at walking speed were considered in this work, the set of measurements was performed with 12 users in a room without direct LoS to any of the BSs. A 4×4 m square was drawn on the measurement room floor, and a handset was placed at each side of the square to cover approximately 40 wavelengths in the free space and the space with users under low frequency. BS1 had a direct LoS to two sides of the square, whereas the other sides had no direct LoS to any of the BSs. The usability of the prototypes was taken in consideration during the development of an optical unit. The users were able to operate the handsets without any problems because these devices used a soft and flexible optical fiber instead of coaxial cables.

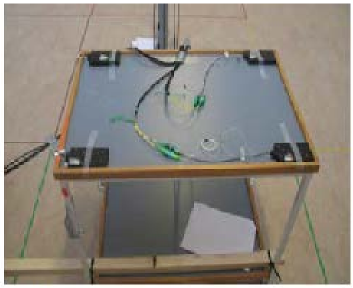
Table 3-1shows gives an overview of the antenna types and locations in different handsets. The Specific Anthropomorphic Mannequin (SAM) head and torso presented in [79] were used as the phantom, and a pre-compliant Cellular Telecommunications Industry Association (CTIA) bar phone was used as the hand at each measurement. It is worth noting that the hand used is not specified for the larger form factor phones. However, these devices are still usable from a practical perspective. Although the results can reflect user sufficiency, they cannot be compared with the chamber measurements taken using the CTIA-approved data mode hand phantom.

*Table 3-1: Handset overview*

| Handset | El. Size [mm] | Ant. No. | Ant. Type | Antenna Location | Low Band | High Band |
|---|---|---|---|---|---|---|
| H1 PDA | 59*111 | 1 | mono | Top-Center | ✓ | ✓ |
| | | 2 | mono | Bottom -Center | ✓ | ✓ |
| H2 PDA | 59*111 | 1 | mono | Top-Right | ✓ | ✓ |
| | | 2 | mono | Bottom -Right | ✓ | ✓ |
| H3 PDA | 59*111 | 1 | mono | Top-Right | ✓ | ✓ |
| | | 2 | mono | Bottom -Right | X | ✓ |
| H4 PDA | 59*111 | 1 | mono | Top-Right | X | ✓ |
| | | 2 | mono | Top-Centr | ✓ | ✓ |
| H5 PDA | 59*111 | 1 | mono | Top-Right | ✓ | ✓ |
| | | 2 | mono | Top-Left | ✓ | ✓ |
| H6 PDA | 59*111 | 1 | mono | Top-Right | ✓ | ✓ |
| | | 2 | mono | Top-Center | ✓ | ✓ |
| H11 PDA | 59*111 | 1 | PIFA | Top | ✓ | ✓ |
| | | 2 | PIFA | Bottom | ✓ | ✓ |
| H12 bar | 40*100 | 1 | PIFA | Top | ✓ | ✓ |
| | | 2 | PIFA | Bottom | ✓ | ✓ |
| H13 PDA | 59*111 | 1 | helix | Top-Left | ✓ | X |
| | | 2 | helix | Bottom-Left | ✓ | X |
| H14 bar | 40*100 | 1 | mono | Top-Left | ✓ | ✓ |
| | | 2 | mono | Top-Right | ✓ | ✓ |

The free space measurements in the Data Mode Landscape Left (DMLL) tilt, Data Mode Landscape Right (DMLR) tilt, and DMP cases were performed by placing the handsets on styrofoam holders mounted on a styrofoam block that was, in turn, moved along the measurement tracks in a trolley. To simulate tethering on an office table, the handsets in the Data Mode Flat on Surface (DMFL) case were directly placed on a trolley. Some free space and phantom measurements are presented in Figure 3-5, and the measurements with users are presented in Figure 3-6, which are Five different grips of handsets are considered: portrait mode right hand only (phr); portrait mode two hands (pth); landscape mode, right tilt, right hand only (lphr); landscape mode, right tilt, left hand only (lrhl); landscape mode, right tilt, two hands (lrth).

a) FS Data Mode Portrait case



b) FS Data Mode FLat on surface case

c) SAM and CTIA hand phantoms measurement set-up

*Figure 3-5: Free Space measurement cases and SAM phantom set-up*


*Figure 3-6: Different grips of handsets*

## 3.6. CONSIDERED PARAMETERS FOR THE INVESTIGATION

Figure 3-7 shows the two BSs that are equipped with one or two antennas as well as the handset that is equipped with one antenna. The channel matrix can be reduced from a scenario into a MISO case. The capacity of the BSs in the cooperative and non-cooperative cases is also measured.

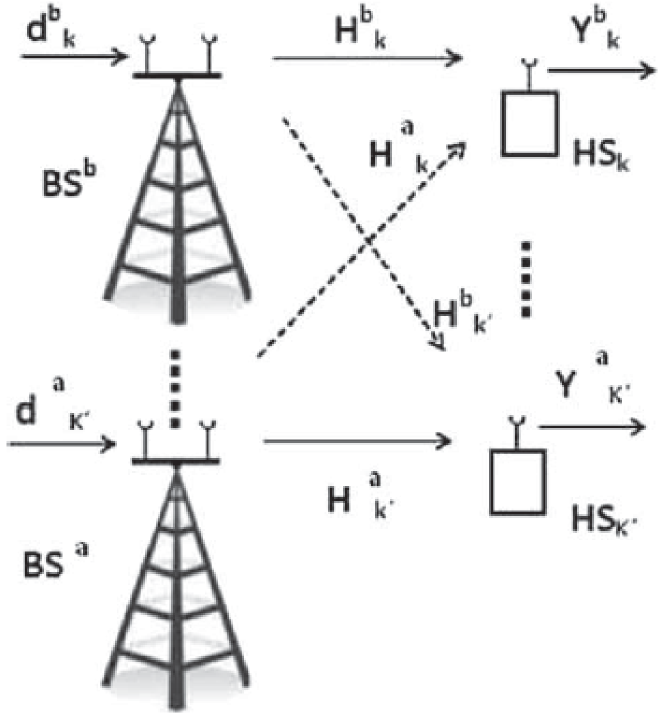



*Figure 3-7: MIMO/ MISO scenario [73]*

The system design includes two users, with each user having one antenna. One BS may serve these two users simultaneously to enhance its capacity. Future studies may consider highly complex scenarios, such as when different BSs are assigned to various users. Part of this work investigates the influence of MMSE beamforming on the capacity of the MIMO system in full and semi cooperation scenarios. The behavior in each of these scenarios is also compared. An extended algorithm is applied to a cooperative multicell MIMO system in a real propagation environment in order to take into account the influence of several parameters that are present in such environment, including correlation, branch power ratio, fading, distances, and handsets. We compare the performance of the algorithm using ideal and measured channels. Correlated channels or imbalanced links may be manually generated and applied in the algorithm. However, unlike measured ones, these manually generated data lack certain parameters, including the antenna-blocking effects of different handset grips. The experimental data may be used to examine whether and to what extent these parameters affect algorithm performance. The outcomes of this work are expected to improve the extant systems or algorithms. In this case, the objectives of this work are threefold:

1. To extend the applicability of an algorithm to a cooperative BS scenario. We use ideal and measured channels to evaluate the extended algorithm and to assess the performance of the WMMSE algorithm in a real propagation environment. The measured channels in such environment are very similar and may be either correlated or uncorrelated to ideal channels depending on the Rayleigh distributions. The theoretical and practical applications of these systems are also reviewed.

2. To determine the effects of the separation distance between handsets by comparing those data obtained from closer handsets (near case) with those obtained from further handsets (far case). These comparisons may also reveal the presence of correlations in the near case.

3. To introduce a power imbalance between channels in the near and far scenarios as well as to examine whether such imbalance affects the data collection and/or transmission rate.

## 3.7. SUMMARY

This chapter summarizes the background work for the two measurement campaigns. As its major contribution, this chapter outlines the principles and describes the implementation of the measurement systems. The handsets were operated, the cable effect was removed, and the state-of-the-art rapid prototyping system was used for case manufacturing in the measurement setup to simulate real conditions.

# CHAPTER 4. COOPERATIVE MIMO ALGORITHMS

In this chapter, the solution for HBC transmission is proposed and discussed in details. The solution involves the extension of the cooperative MIMO algorithm for multi-user scenario. Moreover, the VSINR algorithm has been discussed in this chapter for MISO cases for related use cases.

## 4.1. INTRODUCTION

Cooperative BSs have crucial roles in increasing the data rate at the side of the receiver [80] [81]. Using CAP systems to prevent interferences and maximize data rates requires the use of a simple, high-performance algorithm in the measured channels. However, the data rate may be reduced by some unwanted parameters, and such challenge may be addressed by performing an accurate channel propagation analysis.

This chapter examines the challenges in cooperative, non-cooperative, and semi-cooperative scenarios as well as compares the performance of the proposed algorithm with another well-known algorithm in a real propagation environment. Three issues are addressed in three different parts of this chapter to establish a novel method for improving the performance of cellular systems.

## 4.2. MIMO VERSUS COOPERATIVE MIMO

Despite their promising architecture and great potential to enhance the quality of communication, CAP systems are very expensive, require a complex algorithm design, and often encounter channel interference. Therefore, these systems must be investigated further to determine their advantages over non-cooperative architectures in measured channels.

To control inter-cell interference, a new cellular architecture with coordinated cells has been proposed in [82]. Such coordination focuses on downlink transmission where backhaul links connect the cooperating BSs to a Central Processing Unit (CPU). Apart from collecting information from multiple cells, the CPU coordinates the distribution of resources within the architecture to centralize the operations of multiple cells. Accordingly, recent studies have attempted to improve the performance of coordinated multi-cell systems [83], [84], and [85] .

As one of the major tools for achieving optimal data transmission, beamforming plays a significant role in the design of highly efficient algorithms. Different scenarios, such as those with and without transmit beamforming, have been analyzed to understand the influence of this tool on the data rate in the measured channels and on the capacity of the entire system.

MISO or MIMO broadcast channels (BC) are used to model the transmission of cooperative BSs, and dirty paper coding (DPC) has been applied to identify the capacity region of these channels. Linear beamforming has recently attracted research attention in response to the complexity and difficulty of applying DPC in a real system. On the one hand, zero-forcing beamforming is a known precoder that multiplies the transmitted signal using a precoder matrix and then cancels all detected inter-cell interferences. On the other hand, MMSE beamforming is an optimal precoder for cases where more receive antennas than transmit antennas are being used. When the transmitter is limited by a transmit power constraint, the MMSE principle can be applied during the precoding to achieve an optimal balance between the signal pre-equalization and the noise level after receive processing [85].

## 4.3. PROPOSED WMMSE ALGORITHM FOR THE CAP SCENARIO

This work applies the WMMSE approach to create transmit filters with simple designs. In the traditional WMMSE approach, a polynomial equation is solved to calculate the Lagrange multiplier that corresponds to the transmit power for each BS [85]. By avoiding any complexity, the proposed WMMSE approach produces low-complexity transmit filters and solves the polynomial equation easily.

Following [86], a scalar was introduced as an additional degree of freedom for the point-to-point MIMO channel to scale the transmit power constraint and the received signal.

Such design of transmit filters produces closed-form expressions of Lagrange multipliers. Given that the proposed method was based on a modified WMMSE cost function, this method is considered suboptimal. Nevertheless, no performance losses were observed in the simulations when compared with those in [85].

Following [41] and [87], the WMMSE optimization becomes equivalent to the weighted sum-rate (WSR) optimization by adjusting the mean squared error (MSE) weights.

A cooperative BS MIMO was used as the architecture for HBC transmission to achieve an excellent performance. The transducer and receiver were equipped with more than one antenna, and each terminal was equipped with more than one transducer to transmit the sampled data to the cloud or receivers.

As discussed in [88], HBC transmission uses the WMMSE algorithm for MIMO broadcast to achieve an excellent performance. This algorithm was extended to the CAP scenario as follows.

A system with k BSs and k users containing two cells is considered in this work. Figure 3-7 presents the setup of this multi-cell system, in which each BS can only serve one user, and the same formula may be applied to numerous cells. The BSs and receivers are equipped with a M transmitted antenna, and N received antennas, respectively. The wireless channels between BS k and user k in cells b and a are represented by the channel matrices $\mathrm{H}_{\mathrm{k}}^{\mathrm{b}} \in \mathbb{C}^{[\mathrm{N}\times\mathrm{M}]}$ and $\mathrm{H}_{\mathrm{k}}^{\mathrm{a}} \in \mathbb{C}^{[\mathrm{N}\times\mathrm{M}]}$, respectively. Cell b transmits a signal that is computed as $\mathrm{X}^{\mathrm{b}} = \sum_{\mathrm{k}=1}^{\mathrm{K}} \mathrm{B}_{\mathrm{k}}^{\mathrm{b}}\mathrm{d}_{\mathrm{k}}^{\mathrm{b}} = \mathrm{B}^{\mathrm{b}}\mathrm{d}^{\mathrm{b}}$, where the precoder matrix for each BS and the pre-coder of cell b are represented by $\mathrm{B}_{\mathrm{k}}^{\mathrm{b}} \in \mathbb{C}^{[\mathrm{N}\times\mathrm{M}]}$ and $\mathrm{B}^{\mathrm{b}} = \left[\mathrm{B}_{\mathrm{k}}^{\mathrm{b}}, \dots, \mathrm{B}_{\mathrm{K}}^{\mathrm{b}}\right] \in \mathbb{C}^{[\mathrm{M}\times\mathrm{KN}]}$, respectively.

Each transmitter and receiver is equipped with N data streams, where $\mathrm{N} \leq \mathrm{M}$. The complex vector of data streams is represented by $\mathrm{d}_{\mathrm{k}}^{\mathrm{b}} \in \mathbb{C}^{[\mathrm{N}\times 1]}$, the data for all users in cell b are represented by $\mathrm{d}^{\mathrm{b}} = \left[\mathrm{d}_{\mathrm{k}}^{\mathrm{bT}}, \dots, \mathrm{d}_{\mathrm{K}}^{\mathrm{b}}\mathrm{T}\right] \in \mathbb{C}^{[\mathrm{KN}\times 1]}$, and the transposition of vector d is represented by $\mathrm{d}^{\mathrm{T}}$. $\mathrm{B}_{\mathrm{k}}^{\mathrm{a}}$ and $\mathrm{d}_{\mathrm{k}}^{\mathrm{a}}$ apply the same definitions for cell a. In cell b, user k receives a signal that is computed as follows:

$$Y_k^b = \boldsymbol{H}_k^b \boldsymbol{B}_k^b d_k^b + \boldsymbol{H}_k^b \sum_{i=1, i\neq k}^{K} \boldsymbol{B}_i^b d_i^b + \boldsymbol{H}_k^a \sum_{k=1}^{K} \boldsymbol{B}_k^a d_k^a + n_k^b, \qquad \text{4- 1}$$

where the white Gaussian noise vector is represented by $\mathrm{n}_{\mathrm{k}}^{\mathrm{b}} \in \mathbb{C}^{[\mathrm{N}\times 1]}$ with a covariance of $\mathrm{R}_{\mathrm{nknk}} = \mathbb{E}\left[\mathrm{n}_{\mathrm{k}}\mathrm{n}_{\mathrm{k}}^{\mathrm{H}}\right] = \mathrm{I}_{\mathrm{N}}$, the conjugate transposition of $\mathrm{n}_{\mathrm{k}}$ is represented by $\mathrm{n}_{\mathrm{k}}^{\mathrm{H}}$, and the expected value of $\left[\mathrm{n}_{\mathrm{k}}\mathrm{n}_{\mathrm{k}}^{\mathrm{H}}\right]$ is represented by $\mathbb{E}\left[\mathrm{n}_{\mathrm{k}}\mathrm{n}_{\mathrm{k}}^{\mathrm{H}}\right]$. The first three terms in the above equation denote the desired signal of the user, the undesired signal that user k transmits from a BS within cell b, and the inter-cell interference where a neighboring cell receives an undesired signal to user k. This work assumes that constant channel matrices are available for each block. Both the transmitter and receiver know the channel state information, and the assumption $\mathbb{E}\left[\mathrm{d}_{\mathrm{k}}\mathrm{d}_{\mathrm{k}}^{\mathrm{H}}\right] = \mathrm{I}_{\mathrm{N}}$ holds for the entire system. The following power constraint is observed by the transmit vectors:

$$\mathbb{E}[X^{bH} X^b] = \sum_{k=1}^{K} Tr\left(\boldsymbol{B}_k^b \boldsymbol{B}_k^{bH}\right) \leq E_{tx}^b \qquad \text{4- 2}$$

where the transmission power of each BS in cell b is represented by $\mathrm{E}_{\mathrm{tx}}^{\mathrm{b}}$, while the trace of the matrix is represented by $\mathrm{Tr}\left(\mathrm{B}_{\mathrm{k}}^{\mathrm{b}}\mathrm{B}_{\mathrm{k}}^{\mathrm{bH}}\right)$.

The simulation employs the WMMSE algorithm and considers several scenarios.

The WMMSE algorithm follows the MMSE criterion and computes for the transmit filter $\mathrm{B}^{\mathrm{b}}$, which will be used to relate the WSR with the weighted MMSE in the MIMO broadcast channel and to increase the data rates that can be achieved by all users in cell b [41]. The application of this algorithm has been extended to the MIMO interference channel in [88]. This work modifies the WMMSE algorithm for the multi-cell cooperative MIMO scenario to expand the findings of the two above mentioned studies.

The data rate that can be achieved by user k in cell b can be computed as follows [41] :

$$R_k^b = log\,det\left(\boldsymbol{I}_k + \boldsymbol{B}_k^{bH}\boldsymbol{H}_k^{bH}\boldsymbol{R}_{v_k v_k}^{-1}\boldsymbol{H}_k^b\boldsymbol{B}_k^b\right) \quad 4\text{- }3$$

where the noise and interference covariance matrix at user k is computed as follows:

$$\boldsymbol{R}_{v_k v_k} = \boldsymbol{I}_k + \sum_{i=1,i\neq k}^{K}\boldsymbol{H}_k^b\boldsymbol{B}_i^b\boldsymbol{B}_i^{bH} + \boldsymbol{H}_k^a\boldsymbol{B}_k^a\boldsymbol{B}_k^{aH}\boldsymbol{H}_k^{aH} \quad 4\text{- }4$$

This thesis extends the proposed interference matrix in [41] by adding the last term in Eq. (4). The other equations also include this same term to avoid inter-cell interference.

Following [88], the filter $A_k^{b,MSE}$ received by the MMSE at user k can be computed as follows:

$$\boldsymbol{A}_k^{b,MSE} = \boldsymbol{B}_k^{bH}\boldsymbol{H}_k^{bH}\left(\boldsymbol{H}_k^b\boldsymbol{B}_k^b\boldsymbol{B}_k^{bH}\boldsymbol{H}_k^{bH} + \boldsymbol{R}_{v_k v_k}\right)^{-1} \quad 4\text{- }5$$

Afterward, the corresponding MMSE matrix can be computed as follows [41]:

$$\boldsymbol{E}_k^b = \left(\boldsymbol{I}_k + \boldsymbol{B}_k^{bH}\boldsymbol{H}_k^{bH}\boldsymbol{R}_{v_k v_k}^{-1}\boldsymbol{H}_k^b\boldsymbol{B}_k^b\right)^{-1} \quad 4\text{- }6$$

A cost function is defined as follows to maximize the WSR problem:

$$\arg \min_{\mathbf{B}_1^1,\ldots,\mathbf{B}_k^C} \sum_{k=1}^{K}\left(u_{R_k^b}\mathbf{R}_k^b + u_{R_k^a}\mathbf{R}_k^a\right)$$

$$s.t.\ \sum_{k=1}^{K} Tr\left(\boldsymbol{B}_k^b\boldsymbol{B}_k^{bH}\right) = E_{tx}^b \forall b \quad 4\text{- }7$$

Expressed using Lagrange's formula, Eq. (4-7) includes the new term $R_k^a$ and is derived with respect to $B_k^{b*}$ and $B_k^{a*}$, where $B_k^{a*}$ represents the conjugate of $B_k^a$. This equation is then compared with the following derivation of the WMMSE problem:

$$\arg \min_{\mathbf{B}_1^1,\ldots,\mathbf{B}_k^C} \sum_{k=1}^{K}\mathrm{Tr}\left(\mathbf{W}_k^b\mathbf{E}_k^b + \mathbf{W}_k^a\mathbf{E}_k^a\right)$$

$$s.t.\ \sum_{k=1}^{K} Tr\left(\boldsymbol{B}_k^b\boldsymbol{B}_k^{bH}\right) = E_{tx}^b \forall b \quad 4\text{- }8$$

where the weight matrices for user k in cells b and a are represented by $W_k^b \in \mathbb{C}^{[N\times N]}$ and $W_k^a$, respectively. The MSE weights are then adjusted as follows after comparing the gradients:

$$\boldsymbol{W}_k^b = u_k^b \boldsymbol{E}_k^{b-1} \; and \qquad 4\text{- }9$$

$$\boldsymbol{E}_k^b = (\boldsymbol{H}^{bH}\boldsymbol{A}^{bH}\boldsymbol{W}^b\boldsymbol{A}^b\boldsymbol{H}^b + \boldsymbol{H}^{aH}\boldsymbol{A}^{aH}\boldsymbol{W}^a\boldsymbol{A}^a\boldsymbol{H}^b + \lambda^b\boldsymbol{I})^{-1}\boldsymbol{H}^{bH}\boldsymbol{A}^{bH}\boldsymbol{W}^b \qquad 4\text{- }10$$

where those matrices that comprise diagonal blocks equivalent to the weight matrix are represented by $\mathrm{W}^{\mathrm{b}} = \mathrm{diag}\{\mathrm{W}_1^{\mathrm{b}}, \dots, \mathrm{W}_{\mathrm{K}}^{\mathrm{b}}\}$ and $\mathrm{A}^{\mathrm{b}} = \mathrm{diag}\{\mathrm{A}_1^{\mathrm{b}}, \dots, \mathrm{A}_{\mathrm{K}}^{\mathrm{b}}\}$. Those filters that correspond to each user are sent to these diagonal blocks. In $\mathrm{H}^{\mathrm{b}} = [\mathrm{H}_1^{\mathrm{bT}}, \dots, \mathrm{H}_{\mathrm{K}}^{\mathrm{bT}}]^{\mathrm{T}}$, several channel links are used to connect each BS to all the available users in a single cell. The Lagrangian multiplier is calculated using the method applied in [89]. The parenthesized term in Eq. (4-10) is added to avoid inter-cell interference.

Following [14], the MSE weights and beam formers are optimized until they converge to a fixed point.

The initial value for $\mathrm{B}_{\mathrm{k}}^{\mathrm{b}}$ is assumed during the application of the WMMSE algorithm. This assumed value is also applied in Eqs. (4-5) and (4-9) to compute for the received filter and weight matrix $\mathrm{W}_{\mathrm{k}}^{\mathrm{b}}$, respectively. Eq. (4-10) then computes for $\mathrm{A}_{\mathrm{k}}^{\mathrm{b}}$ and $\mathrm{W}_{\mathrm{k}}^{\mathrm{b}}$ to update $\mathrm{B}^{\mathrm{b}}$. These steps are repeated until the parameters above converge to the local minimum of the main problem.

## 4.4. VIRTUAL SIGNAL-TO-INTERFERENCE ALGORITHM SIMULATION

The visual signal-to-interference plus noise ratio (VSINR) algorithm was introduced in [36] to reach the desired WSR maximizing point for huge transmissions in the HBC transmission structure.

The beamforming design in this algorithm is for Multiple Input and Single Output Interference Cancellation (MISO IC). According to [44], all Pareto-optimal points may be reached by selecting the appropriate weight coefficients in the VSINR algorithm, which differs from the actual signal interference of a single beamforming vector. However, this study only outlined the conditions required for achieving such Pareto-optimal points and did not select those required parameters for reaching the desired boundary points.

Accordingly, this work attempts to reach the desired WSR maximizing point by using the weight coefficients. The gradient expressions for both the WSR and VSINR maximization problems reveal that beamforming vectors can influence the weight terms for the equivalence between such problems. To address this challenge, this work proposes a two-step algorithm. First, the weight coefficients for the fixed beam formers are updated to make these problems have the same gradient expression. Second, the beamforming vectors are computed using the updated weights to solve the VSINR problem. Given the strong dependence between weight terms and beamforming vectors, the steps above are repeated until convergence was reached. This work also proposes a decentralized scheme based on the local channel state information (CSI).

The numerical results of the proposed algorithm show that the WSR performance of the proposed VSINR-based schemes is nearly optimal, while the decentralized scheme has a significantly lower CSI exchange overhead compared with the centralized method.

As shown in Figure 3-7, each transmitter i in the K-user MISO IC supports receiver i (i=1,…, K) through transmit beamforming. Following the recommendations in [90], this work assumes that M≥K. In this case, the signal received at k can be expressed as follows:

$$y_k = \boldsymbol{h}_{k,k}^H \boldsymbol{v}_k \boldsymbol{s}_k + \sum_{j \neq k} \boldsymbol{h}_{k,j}^H \boldsymbol{v}_j \boldsymbol{s}_j + n_k \qquad 4\text{-}\ 11$$

where the channel vector from transmitter j to receiver k is represented by $\mathbf{h}_{k,j}^H \in \mathbb{C}^M$, the additive white Gaussian noise at receiver k is represented by $n_k \sim \mathcal{CN}(0, N_0)$, the data symbol for receiver k is denoted by $s_k \sim \mathcal{CN}(0, N_0)$, and the beamforming vector at transmitter k is denoted by $\mathbf{v}_k$. To satisfy the per-transmitter power constraint, the beam former $\mathbf{v}_k$ is subjected to $\|\mathbf{v}_k\|^2 \leq 1$. User k refers to a pair of transmitter $k$ and receiver $k$.

Under the SUD assumption, the individual rate of user $k$ can be expressed as $R_k(\{\mathbf{v}_l\}) = \log\left(1 + \mathrm{SINR}_k(\{\mathbf{v}_l\})\right)$, where the individual SINR or $\mathrm{SINR}_k(\{\mathbf{v}_l\})$ is computed as follows:

$$SINR_k(\{\boldsymbol{v}_l\}) = \frac{\left|\boldsymbol{h}_{k,k}^H \boldsymbol{v}_k\right|^2}{N_0 + \sum_{j \neq k} \left|\boldsymbol{h}_{k,k}^H \boldsymbol{v}_k\right|^2} \qquad 4\text{-}\ 12$$

This work aims to determine those beamforming vectors that maximize WSR. These vectors are computed as $R_\Sigma\ (\{\mathbf{v}_l\}) = \sum_{k=1}^{K} \omega_k R_k(\{\mathbf{v}_l\})$, where the weight term $\omega_k$ is determined according to the required quality of service. The research problem can then be mathematically expressed as follows:

$$\max_{\boldsymbol{v}_{1,\dots,}\boldsymbol{v}_k} R_\Sigma\ (\{\boldsymbol{v}_l\}) \ s.t.\ \|\boldsymbol{v}_i\|^2 \leq 1\ \forall i \qquad 4\text{-}\ 13$$

After selecting the appropriate weight coefficients $\alpha_{j,k}$ $(j \neq k)$, this work adopts the following VSINR maximizing beam formers to achieve all Pareto optimal points:

$$\boldsymbol{v}_k = \underset{\|\boldsymbol{v}_i\|^2 = 1}{\arg\max}\ VSINR_k = \frac{\left(N_0 \boldsymbol{I} + \sum_{j \neq k} \alpha_{j,k} \boldsymbol{h}_{j,k} \boldsymbol{h}_{k,k}^H\right)^{-1} \boldsymbol{h}_{k,k}}{\left\|\left(N_0 \boldsymbol{I} + \sum_{j \neq k} \alpha_{j,k} \boldsymbol{h}_{j,k} \boldsymbol{h}_{k,k}^H\right)^{-1} \boldsymbol{h}_{k,k}\right\|} \qquad 4\text{-}\ 14$$

Following the manipulations presented in [91], the gradient expressions for the two aforementioned problems can be expressed as follows:

$$\nabla_{\mathbf{v}_k}\left[R_{\Sigma}\left(\{\mathbf{v}_l\}\right)\right] = \frac{2\omega_k}{I_l+D_l}\mathbf{h}_{l,l}\mathbf{h}_{l,l}^{H}\mathbf{v}_l - 2\sum_{k\neq l}\frac{\omega_k D_k}{I_k(I_k+D_k)}\mathbf{h}_{k,l}\mathbf{h}_{k,l}^{H}\mathbf{v}_l \text{ AND}$$

$$\nabla_{\boldsymbol{v}_k}[log(VSINR_l)] = \frac{2}{D_l}\boldsymbol{h}_{l,l}\boldsymbol{h}_{l,l}^{H}\boldsymbol{v}_l - 2\sum_{k\neq l}\frac{\alpha_{k,l}}{N_0+\sum_{j\neq l}\alpha_{j,l}\left|\boldsymbol{h}_{j,l}^{H}\boldsymbol{v}_l\right|^2}\boldsymbol{h}_{k,l}\boldsymbol{h}_{k,l}^{H}\boldsymbol{v}_l \quad 4\text{- }15$$

where the interference-plus-noise and desired signal power at receiver k are computed as follows:

$$I_k = N_0 + \sum_{j\neq k}\left|\mathbf{h}_{k,j}^{H}\mathbf{v}_j\right|^2 \text{ and}$$

$$D_k = \left|\boldsymbol{h}_{k,k}^{H}\boldsymbol{v}_k\right|^2 \text{, respectively} \quad 4\text{- }16$$

Afterward, $A_l$ and $\overline{\propto}_l$ can be defined as follows:

$$A_l = \frac{\omega_k D_l}{I_l+D_l}\, diag\left(\left\{\frac{I_k(I_k+D_k)}{\omega_k D_k}, k\neq l\right\}\right) - 1_{K-1}\left[\left|\boldsymbol{h}_{1,l}^{H}\boldsymbol{v}_l\right|^2 \ldots \left|\boldsymbol{h}_{l-1,l}^{H}\boldsymbol{v}_l\right|^2\left|\boldsymbol{h}_{l+1,l}^{H}\boldsymbol{v}_l\right|^2 \ldots \left|\boldsymbol{h}_{K,l}^{H}\boldsymbol{v}_l\right|^2\right]$$

$$4\text{- }17$$

$$\overline{\propto}_l = \left[\propto_{1,l} \ldots \propto_{l-1,l}\propto_{l+1,l} \ldots \propto_{K,l}\right]^T \quad 4\text{- }18$$

The proposed VSINR-based approach is then summarized as follows:

———————————————————————————-

1. Initialize vl for l = 1, · · · ,K.

2. Compute Dl, Il, Al for l = 1, · · ·, K.

3. Update the weight coefficients using ¯αl ← N0A−1 l 1K−1

for l = 1, · · · ,K.

4. Compute the beamforming vectors vl maximizing VSINR

according to (2) for l = 1, · · ·, K.

5. Repeat step 2 until convergence.

## 4.5. SUMMARY

The different components of a cellular network system are analyzed in this chapter to explore further the performance of this system. The effects of cooperative BSs and of certain techniques, such as MMSE beamforming, on increasing the data rate in the system are also reviewed. The application of the WMMSE algorithm is extended, and the potential of the VSINR algorithm in solving MISO scenarios is discussed. A new HBC transmission method at the physical layer is also proposed.

# CHAPTER 5. RESULTS, EXPERIMENTS, AND SIMULATIONS

The results including different graphs of the work has been presented in this chapter. Results are mainly divided to two main categories, namely, simulation results by using the ideal channels in MATLAB programming and, measured results, which have been achieved by implementing the real measured channels and have been analyzed with MATLAB programming to investigate different parameters and their effect on the performance of the algorithms to reach the best solution for transmission data for HBC purpose.

## 5.1. INTRODUCTION

This thesis is conceptualized to analyze the various components in a cellular network system for HBC transmission. The results from this study are expected to enhance the understanding of the performance of cellular systems.

High data rate is attained by exploring the advantages of applying cooperative BSs. The influence of several methods, such as MMSE beamforming, on the enhancement in data rate, has been evaluated. The optimal algorithm is selected based on the measurement setups for HBC transmission. The various scenarios and parameters that affect the obtained data rate are also evaluated. Simulation and measured data have been compared in several studies to enhance algorithm performance. Moreover, parameters that considerably affect the achieved data rate are identified.

## 5.2. COMPARISON OF THE PERFORMANCE OF ALGORITHMS

CAP systems achieve higher data rates than conventional communication systems. The target data rate can be attained by developing high-performance, low-complexity algorithms. In this study, the WMMSE and VSINR algorithms are compared. The relationship between WSR and weighted MMSE was determined using the WMMSE algorithm, in which the routine was iterated between the WMMSE transmit filter and MMSE receive filter [23] until the local minimum was obtained. The algorithm was also applied to a cellular system compatible with the measurement scenario in this study. [36] proposed the VSINR maximization algorithm, in which the weight coefficients were adapted to the original proposed scheme of VSINR [44] to produce a desired WSR maximizing point. This updated VSINR algorithm was applied in this study. The WMMSE algorithm can be applied in full cooperative and interference channel scenarios, whereas VSINR is intended solely for interference channels. The performances of the i.i.d. and measured channels were distinguished. The simulation results indicated that the VSINR algorithm is superior to WMMSE but with nonsignificant difference until the signal-to-noise ratio (SNR) exceeded approximately 15 dB. The VSINR algorithm functioned much better than the WMMSE algorithm at SNR of at least 20 dB. The data rate achieved using the VSINR algorithm at SNR of 20 dB was approximately 9% higher than that obtained by the WMMSE algorithm. Moreover, the former algorithm functioned better than the latter in the measured channels. The results show that the median obtained using VSINR was approximately 10% higher than the median achieved by the WMMSE algorithm in the user case. Additionally, both algorithms resulted in lower data rates in the measured channels than those achieved with the simulation results in the two scenarios.

This outcome is normal because of the various degrading parameters, such as the effect of different handsets. These variations cause dissimilar power imbalances or correlations among links or different distances from BSs. Data acquired from i.i.d. Approximately 19% reduced rayleigh to the measured channels for both algorithms at SNR of 20 dB in the user case.

### 5.2.1. BRANCH POWER RATIO (BPR)

The channels were assumed to be independent and identical distributed (i.i.d) Rayleigh channels during the simulation. The system was streamlined to two cells, that is, each cell contained one BS and one user. Two transmitter antennas were connected to each BS and one receiver antenna to each user.

Diverse assumptions were tested by approximating the experimentally measured data to simulate the channels to evaluate the behavior of the algorithm in more representative situations. Channel models were used to generate correlated channels because this process facilitates the simulation of the effect of correlation between channels [92]. Moreover, an imbalance of power was generated between the channels from each transmitter antenna of the same BS and those from the receiver antenna. This imbalance is called the BPR. The effect of BPR on this particular algorithm (WMMSE) will be discussed in the next section.

BPR is defined using Eq. (5-1), as follows:

$$BPR = \frac{E[|h_{n,m}|^2]}{E[|h_{n,\acute{m}}|^2]} \; m \neq \acute{m} \quad \textit{Equation} \qquad \textit{5-1}$$

where $h_{n,m}$ is the entry of $\mathrm{H}_{\mathrm{k}}^{\mathrm{b}}$or other links.

The capacity in the simulation scenario when BPR was 0 dB or 10 dB between links [Eq. (5-1)] is illustrated in Figure 5-1. The channels were uncorrelated, and BPR was the only alternating factor in this step. The capacity was reduced by approximately 18% at SNR of 15 dB compared with the ideal case.

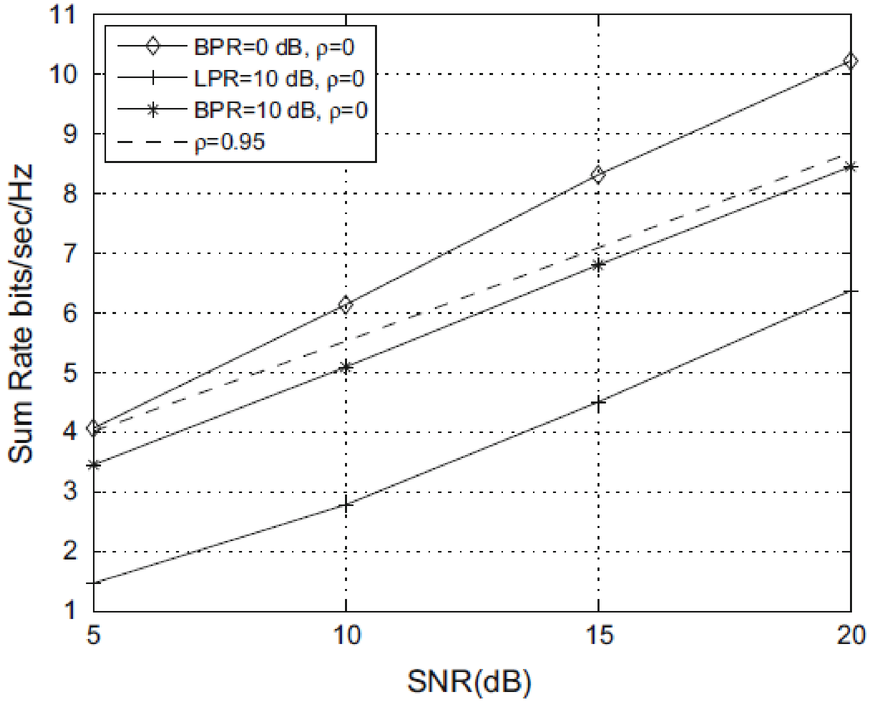



*Figure 5-1: Capacity of simulated channels with different BPR and LPR values [73]*

### 5.2.2. LINK POWER RATIO (LPR)

The effect of LPR on the capacity was also evaluated. The LPR is the variation in the power of different links from each BS to each receiver, as follows:

$$LPR = \frac{E[\|\boldsymbol{H}_{k,i}^{b}\|^2]}{E[\|\boldsymbol{H}_{k,\acute{\imath}}^{b}\|^2]}\ i \neq \acute{\imath} \quad \text{Equation} \qquad 5\text{-}2$$

where $H_{k,i}^{b}$ represents the channel matrix from one BS to one user (k is the index for distinct users, and i is used for different BSs), and $\|H_{k,i}^{b}\|^2$ denotes the Euclidean norm of H. This equation is also valid for $H_{k,i}^{a}$ in the second cell.

Changes in LPR with the WMMSE were determined by applying the same process. In this case, less power existed in the desired link (between BS1 and user1) than in the interfering link [between BS2 and user1 (Eq. 5-2)]. The capacity decreased by approximately 45% when power between the desired link and the interfering link differed by 10 dB (Figure 5-1). The sensitivity of the algorithm to the imbalanced links was also determined. This value is beneficial in elucidating the variations in data rates obtained with measured channels.

## 5.3. ANALYSIS OF MEASURED DATA CONSIDERATIONS AND ASSUMPTION

Several assumptions and parameters were investigated according to the performance of the algorithms to analyze the measured data accurately. The most critical elements for HBC transmission were ultimately established.

### 5.3.1. CHANNEL NORMALIZATION

Various methods were applied to normalize the channel for diverse scenarios based on the different parameters investigated for the capacity.

#### 5.3.1.1 Normalization to a reference handset

Variations in the power levels from two BSs should be preserved. Thus, the mean power received by the reference handset in all free space measurements from one BS was computed. The effects of BPR, correlation of algorithms, diverse power levels from different BSs, handsets, and fading information was observed during normalization, which is determined as follows:

$$h_{n,m}^{norm}(g) = \frac{h_{n,m}(g)}{\sqrt{\frac{1}{NMG}\sum_{n,m,g}\left|h_{n,m}^{ref}(g)\right|^2}} \qquad 5\text{- }3$$

where $M=2$ is the number of transmitter antennas, $N = 1$ is the number of receiver antennas, $G = 1200$ is the number of samples in each measurement, $g$ is the time index, $h_{n,m}$ is the channel coefficients from $n^{th}$ receiver antenna to the $m^{th}$ transmitter antenna, and $h_{n,m}^{ref}(g)$ is the channel for the reference handset in free space.

#### 5.3.1.2 Normalization to each individual measurement

The power collected by receiver antennas and all transmitters from each measurement were averaged. The BPR, correlation, and fading information were preserved. However, handset efficiency and the difference caused by the handsets and the relative body loss effect caused by the users were lost during normalization, which is determined as follows [92]:

$$h_{n,m}^{norm}(g) = \frac{h_{n,m}^{meas}(g)}{\sqrt{\frac{1}{NMG}\sum_{n,m,g}\left|h_{n,m}^{meas}(g)\right|^2}} \qquad 5\text{- }4$$

where $h_{n,m}^{meas}(g)$ represents the channels for each measurement.

#### 5.3.1.3 Normalization to each link

In this process, each channel link in each measurement was normalized. This process eliminated the effect of BPR and determined the effect of only correlation in the capacity. The normalization was determined as follows:

$$h_{n,m}^{norm}(g) = \frac{h_{n,m}^{meas}(g)}{\sqrt{\frac{1}{G}\sum_g \left|h_{n,m}^{meas}(g)\right|^2}} \qquad 5\text{- }5$$

where each coefficient of the channel is divided by the square root of the mean power received by antenna $n$ from the corresponding transmitter antenna. The mean was obtained from 1200 positions.

### 5.3.2. ALGORITHM PERFORMANCE WITH MEASURED CHANNELS

The results obtained using the measured data in the algorithms are achieved at SNR of 20 dB. Approximately more than 1980–2160 measured data were assumed for user case, whereas 456–462 were used for free space. Two classes were considered by the results, while users were involved in the measurement and with the free space case. Superior performance was exhibited by the VSINR algorithm in the measured channels in both scenarios compared with WMMSE. This result is consistent with the simulation results.

The VSINR resulted in approximately 10% higher median than the WMMSE algorithm in the user case. This value is almost similar to the results when both algorithms utilized i.i.d. Rayleigh channels. The results from the two algorithms showed approximately similar variations. This characteristic was due to the efficiency of the handsets or power imbalance between links, among others. The results show that the two algorithms possessed the same sensitivity to the tested parameters. Moreover, lower data rates were acquired by both algorithms using the measured channels than the simulation results in both scenarios. This result was expected because of the degradation parameters, such as the effect of different handsets, which resulted in the different power imbalance or correlation between links or varying distances to the BS. Both algorithms resulted in ~19% reduction in data rate from i.i.d. Rayleigh to measured channels at SNR of 20 dB in user case. The mean values of the measured results were compared with those of the simulated results. Higher data rate (0.5 bits/s/Hz in median value) was observed in free space than in the user case in both algorithms, as the influence of distinct bodies of the user is removed in free space. The body of a user reduces the achieved mean power value at the handsets from 0 dB to 10 dB [70].

Figure 5-2 presents the capacity of the channels as obtained from the measured data. Boxplots were utilized to investigate the manner by which the WMSSE algorithm works in a real propagation environment. Channels were normalized to the reference handset using Eq. (5-3). The capacities of distinct pairs of handsets were computed, and the results included all grips, users, movements, and orientations.

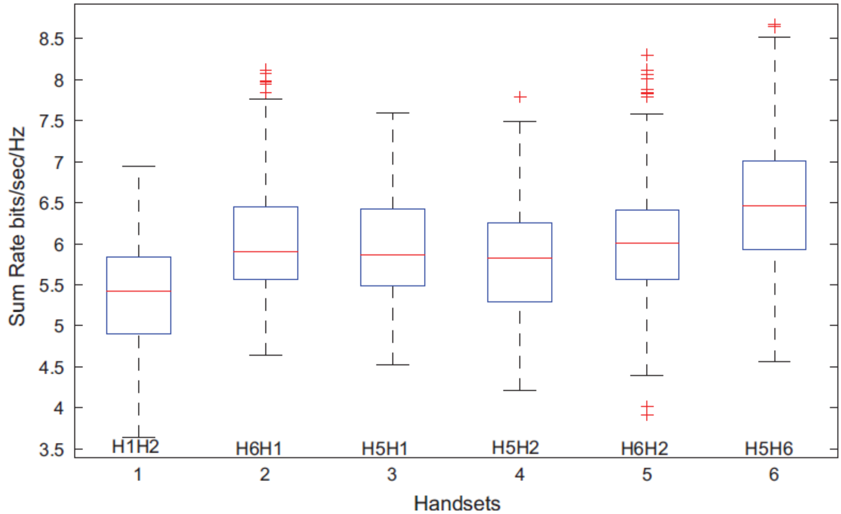



*Figure 5-2: Capacity of measured channels for different sets of handsets using WMMSE algorithm [62]*

Each box represented approximately 330 to 360 successful measurements. The experimentally achieved rate was generally lower than that obtained with ideal channels because of the effect of fading, correlation, antenna efficiency, BPR, and other factors in the "real channels". [73] shows that the mean value over the median values achieved is 5.9 bits/s/Hz, which illustrates a reduction of approximately 29% in capacity compared with those in the ideal channels, with parameters q = 0, and LPR = BPR = 0 dB. Utilizing handsets 1 and 2 resulted in minimum capacity, while handsets 5 and 6 exhibited otherwise. The median capacities of these two pairs differed by approximately 1 bit/s/Hz. The discrepancy was elucidated by subdividing each boxplot into different boxes to illustrate the various orientations, positions, and normalizations as shown in, Figure 5-3, Figure 5-4, and Figure 5-5 respectively.

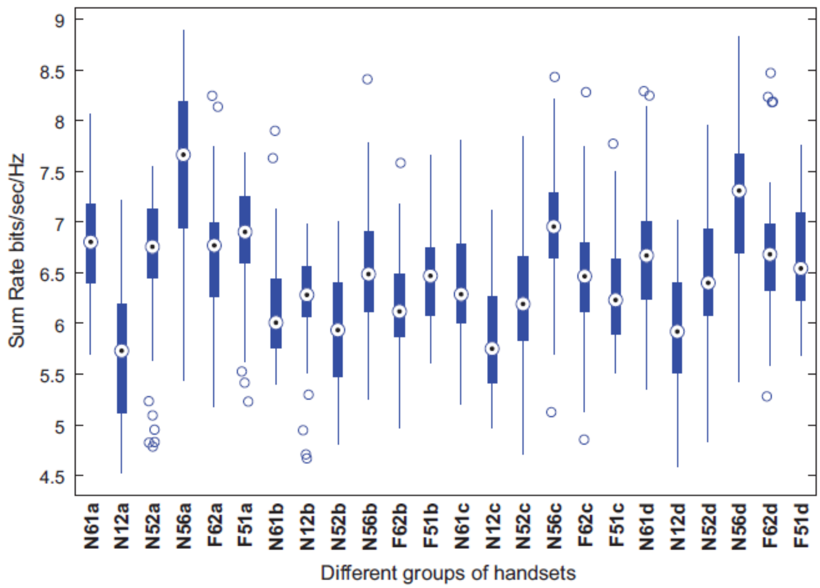



*Figure 5-3: Capacity for free space normalization [73]*

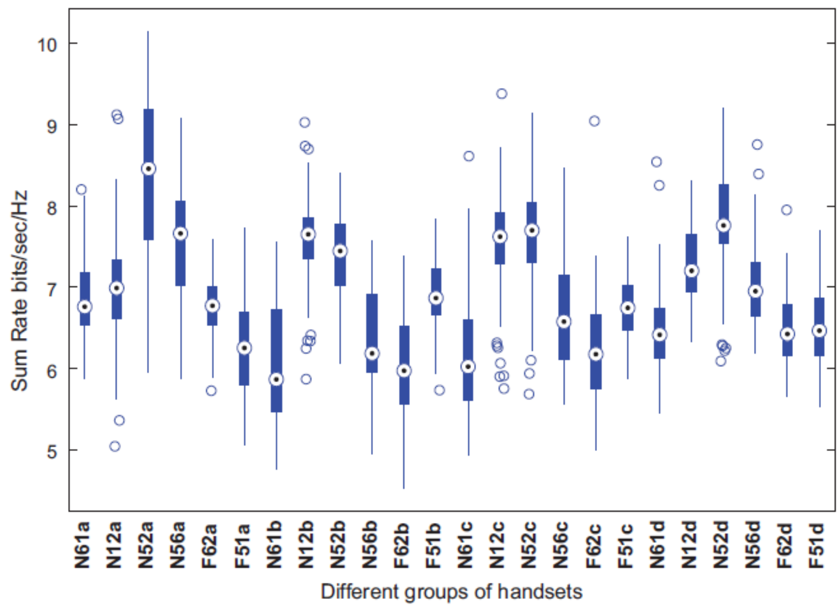



*Figure 5-4: Capacity to each measurement normalization [73]*

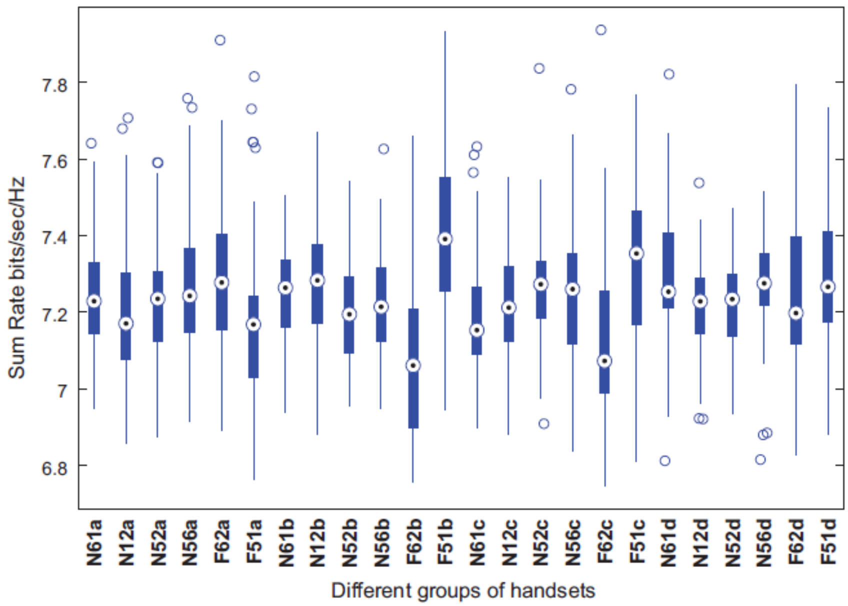



*Figure 5-5: Capacity for link normalization [73]*

## 5.4. DIFFERENT INVESTIGATED SCENARIOS

The performance of the algorithms was investigated using different scenarios and assumptions and the measured data.

### 5.4.1. APPLICATION OF WMMSE ALGORITHM TO DETERMINE THE EFFECT OF NEAR–FAR SCENARIOS ON THE CAPACITY

The position and potential orientation of user movements are demonstrated in Figure 5-6. Each small square had an area of 1 m$^2$. Random back and forth motion was performed by users in each square during each measurement. The arrows from A to D in Figure 5-6 shows that the orientations of the movements in one square differed from those in the other squares.

Each handset moved from one square to another during each measurement. The orientation of the handset changed with respect to the BSs.

The influence of correlation or interference on the capacity was explored by investigating the near and far scenarios. In the latter scenario, handsets were located at neighboring squares, whereas the handsets were at opposite squares in the former scenario. Figure 5-6a shows that H6 and H1 were proximate to each other, but H6 and H2 were far from each other. The capacity of each pair of handsets at each measurement time was evaluated.

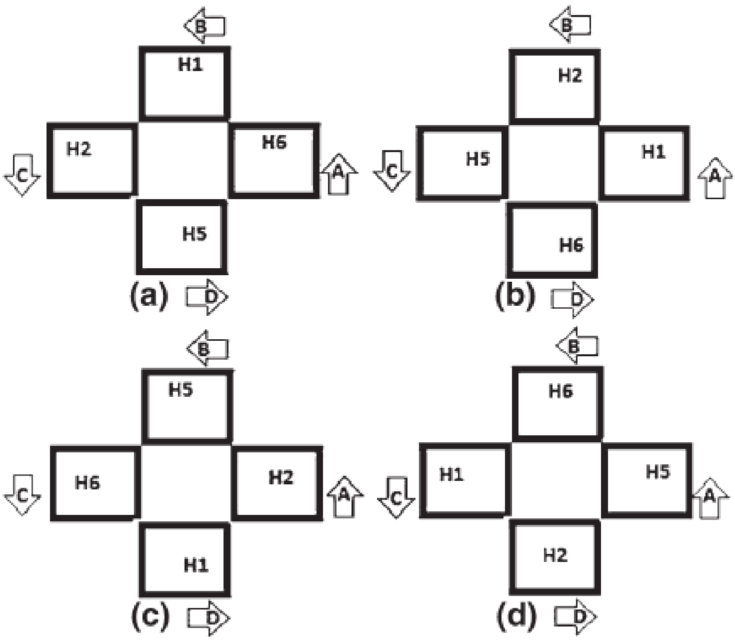



*Figure 5-6: Orientation of user movements in measurement room [73]*

All measurement results are presented as boxplots in Figure 5-3, Figure 5-4, Figure 5-5, and Figure 5-7. Figure 5-7 illustrates the influence of distance on capacity. Each box represented 960 and 480 different measurements of the near and far cases, respectively. The average was computed over different grips and different users. Contrary to the hypothesis that closer handsets would acquire lower data rate because of the interference between channels, the results from the measured channels showed otherwise. All factors that would result in undesirable results were retained in the first normalization. The results show that the capacities obtained in both the near and far scenarios provided the same median and whisker tails. The medians of the near and far cases differed by approximately 0.5 bits/s/Hz, and the interval of the data also varied when the influence of handset efficiency was eliminated during the second normalization. This result is contrary to the expected result. Meanwhile, the influence of correlation was maintained in the third normalization, and the near and far cases showed similar values and behavior of the capacity.

This normalization produced less variable capacities compared with other normalization procedures. The results show the manner by which the BPR and handset efficiency affected the capacity. Moreover, the near and far cases are shown to obtain much more similar capacities compared with each other when the influences of imbalanced channels and handset efficiencies were eliminated.

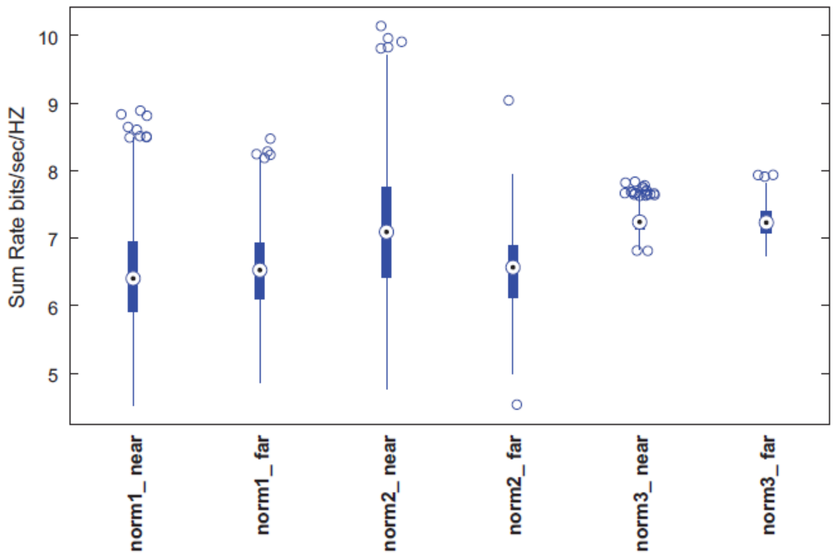



*Figure 5-7: Capacity for all normalization in all near far scenarios [73]*

The capacity generally was not considerably affected by the distance between handsets. However, every pair of handsets was further evaluated to elucidate the factors that may have contributed to the discrepancies in the obtained data rates.

### 5.4.2. APPLICATION OF WMMSE ALGORITHM TO DETERMINE THE EFFECT OF ORIENTATION ON THE CAPACITY

Figure 5-6 shows the pattern of movement of the users when the handsets were diversely oriented with respect to the BSs. Closer insight into the influence of the handset pairs is necessary to elucidate the effect of the orientation. Figure 5-3, Figure 5-4, and Figure 5-5 illustrate in detail the capacity of each pair of handsets. A total of 60 different measurements for the cooperative capacity for two handsets were included in each boxplot. The WMMSE algorithm involved different grips and users. Varying boxes were considered for the different pairs of handsets. The positions of the pairs of handsets were altered after six boxes.

The X- axes in all figures were explained as follows. N61 represents H6 and H1, and similarly, for other pairs, N and F indicate the near and far scenarios, respectively. The second indices, from a to d, in Figure 5-6a–d refer to the positions and orientations of handsets. The handsets were investigated by pair to investigate the effect of orientation. For example, handsets 6 and handset 2 remained far from each other while moving between squares, which indicate that their orientation toward each other was maintained. We hypothesized that the capacities should vary throughout these movements to a small extent. The results are consistent with this hypothesis as shown by F62a–F62d in Figure 5-3, Figure 5-4, and Figure 5-5. Other pairs of handsets in different normalizations showed similar results. Therefore, orientation towards different BSs could vary the capacity.

### 5.4.3. APPLICATION OF WMMSE ALGORITHM TO DETERMINE THE EFFECT OF CORRELATION ON THE CAPACITY

The correlation entries of all H channels in Figure 3-7 were computed similar to that in the simulations to check the correlation of the measured channels. For each pair of handsets, each boxplot in Figure 5-8 included the mean of the absolute values of the correlation coefficients of all links. Figure 5-8 shows that the medians of the correlations slightly deviated from each other, and the absolute values of the correlation coefficients also varied. These results also elucidate Figure 5-5, in which correlation was the only factor remaining after normalization. Thus, correlation and capacity showed direct relationship. Capacity declined at high correlation and vice versa. F62c showed the relation between correlated channels and capacity and had the highest median of the correlation (Figure 5-8) but the lowest median capacity (Figure 5-5). However, the medians of the capacity did not remarkably differ during the third normalization, in which the difference between the maximum and minimum medians was only 0.4 bit/s/Hz. Furthermore, the medians of the correlation were not significantly different. Therefore, correlation was not responsible for the variation in the capacities obtained during the first and second normalization procedures. The algorithm was very sensitive to the variation in the power level in the channels. Thus, capacity could be more remarkably affected by BPR than correlation, if BPR is the only difference between the second and third normalizations.

### 5.4.4. APPLICATION OF WMMSE ALGORITHM TO DETERMINE THE EFFECT OF BPR AND HANDSET EFFICIENCY ON THE CAPACITY

More remarkable variation in the handset capacity was observed during the third normalization than in the first and second normalizations (Figure 5-3, Figure 5-4, and Figure 5-5). BPR was included in the first and second normalizations but not in the third process. The BPR for each handset was computed using Eq. (5-1) to investigate the effect of BPR on the capacity. Figure 5-9 depicts the scatter plot which shows the mean of the absolute BPR for each pair of handsets in the near and far cases compared with the value of the capacity obtained by the second normalization using in Figure 5-4. Although the BPRs of the pairs of handsets varied widely, the BPR mostly ranged between 4 dB and 8 dB. No evident direct relation was found between capacity and BPR in the plot. The results are inconsistent with the simulation results, in which BPR of 10 dB caused changes of <2 dB in the capacity at SNR of 15 dB. Therefore, the measured results shows that changes in the capacity should be even <2 dB if BPR reaches 8 dB. The BPR showed its particular influence on the capacity in the various scenarios but with low effect due to small BPR.

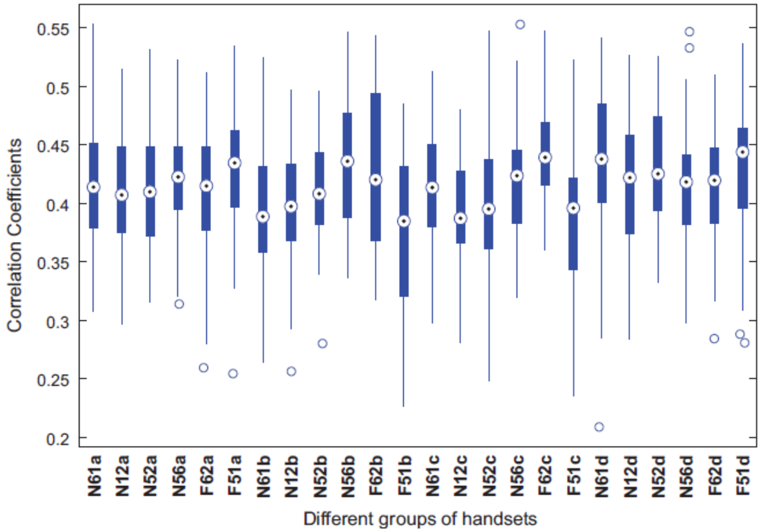



*Figure 5-8: Correlation for each sets of handsets [73]*

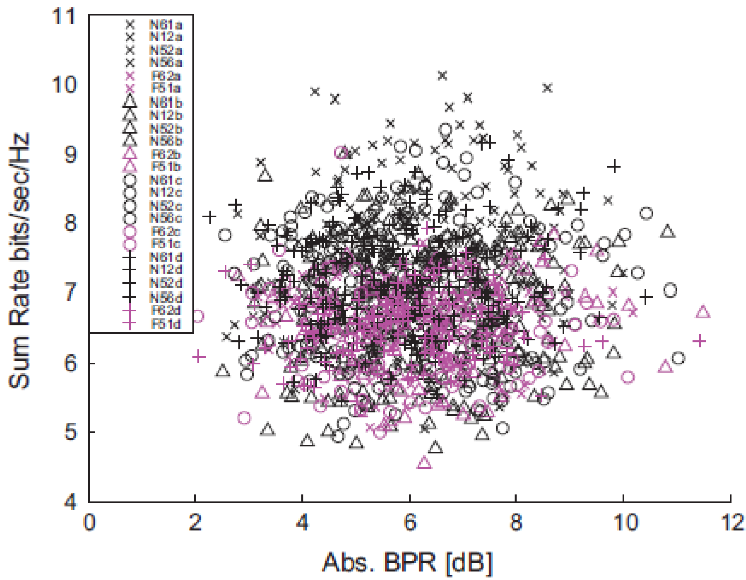



*Figure 5-9: Scatter plot of median values of capacities from second normalization versus absolute BPR of different pairs of handsets [73]*

Other factors, such as handset efficiency, were also found to contribute toward higher data rate such that the influences of distance, orientation, and correlation may have become occluded. The results from the first normalization indicated that N56a–N56d showed the highest mean capacity among all other handset combinations in the near scenario. This result indicated that this pair of handsets exhibited the highest handset efficiency among all pairs because distance, orientation, and correlation did not evidently magnify the capacity in our scenario. Moreover, N56a–N56d differed from other pairs only in handset efficiency.

Handset efficiency is discussed in more detail in [93]. The results of the calculated MEG for each handset showed that H5 and H6 gained more power than H1 and H2. This result is also shown in Figure 5-2, in which the H5–H6 pair was observed to acquire higher data rate than the H1–H2 pair. Considering the median value, which is the measure of [93], a 3.5 dB difference was observed between the worst and best cases, which were the MEGs of H1 and H6, respectively.

### 5.4.5. APPLICATION OF VSINR ALGORITHM TO DETERMINE THE CAPACITY OF DIFFERENT GRIPS

The SNR was fixed to 15 dB in all measurements. The obtained sum rates or capacities of the different grips of HSs were computed and presented using VSINR algorithm at LB and HB. The results showed the sensitivity of the algorithm to the various grips, and the investigation was beneficial in elucidating the performance and behavior of the algorithm at distinct frequencies using the measured channels.

The capacities of the different grips at HB frequency are shown in Figure 5-10. Approximately between 403 and 420 different values based on successful measurements for each grip were used to plot each box plot. Similar variations in the results were found. Lphr showed the maximum median among all measurements, while phr and lrth show the minimum values.

The maximum and minimum values differed by approximately 0.4 bit/s/Hz. Similar results but at LB frequency are shown in Figure 5-11. The capacities of the various grips showed the same tendencies. Lphr and lrth showed the maximum median of 8.6 bits/s/Hz, while the rest showed the minimum value of 8.3 bits/s/Hz. These results showed that distinct frequencies exerted no significant effect on the capacity of the different grips. The mean of the medians at low frequency was generally approximately 1.7 bits/s/Hz higher than at high frequency. Other parameters, such as correlation, should be investigated further to explain these discrepancies.

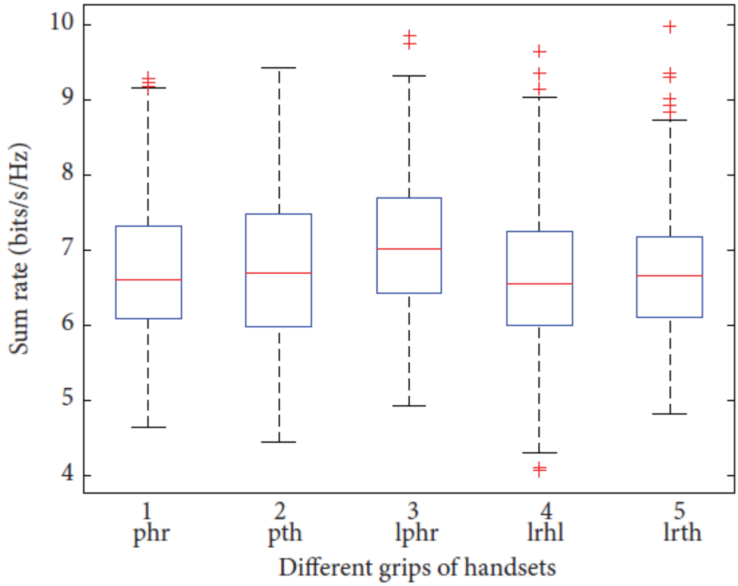



*Figure 5-10: Capacity of different grips at high band using VSINR algorithm [94]*

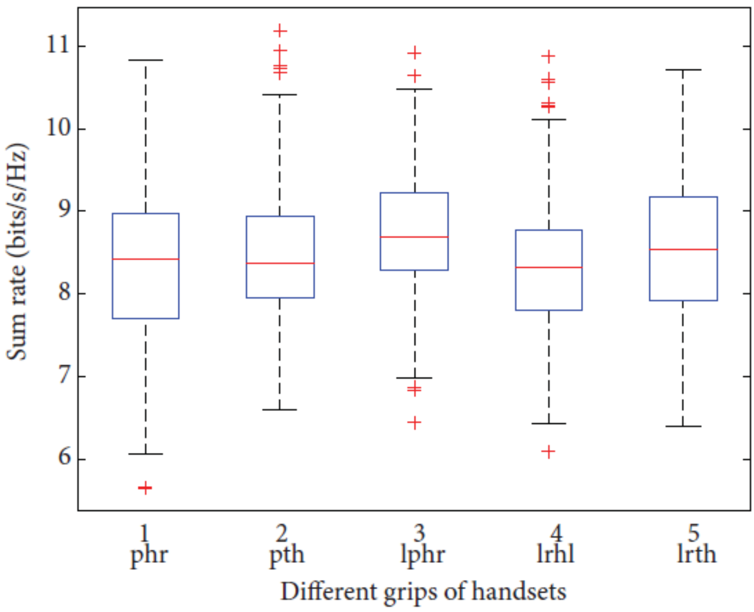



*Figure 5-11: Capacity of different grips at low band using VSINR algorithm [94]*

### 5.4.6. APPLICATION OF VSINR ALGORITHM TO DETERMINE THE EFFECT OF CORRELATION ON THE CAPACITY

The correlation was plotted for the desired and interference links at LB and HB. Each desired or interference link has two entries based on our setup. These entries are channels from each antenna at the user toward each antenna at each BS.

First, the correlation coefficients between channels from each BS toward each HS were computed. The calculated mean of these coefficients was assumed as the correlation for the desired link. The same procedure is applied for the interference links, but for the links from BS1 towards HS2 and vice versa. No obvious differences in the median values were found in the correlation for each of the grips as shown in Figure 5-12 and Figure 5-13 for high and LB, respectively. The results are consistent with those shown in Figure 5-10 and Figure 5-11, while no significant differences were found in the medians of the capacities of the different grips.

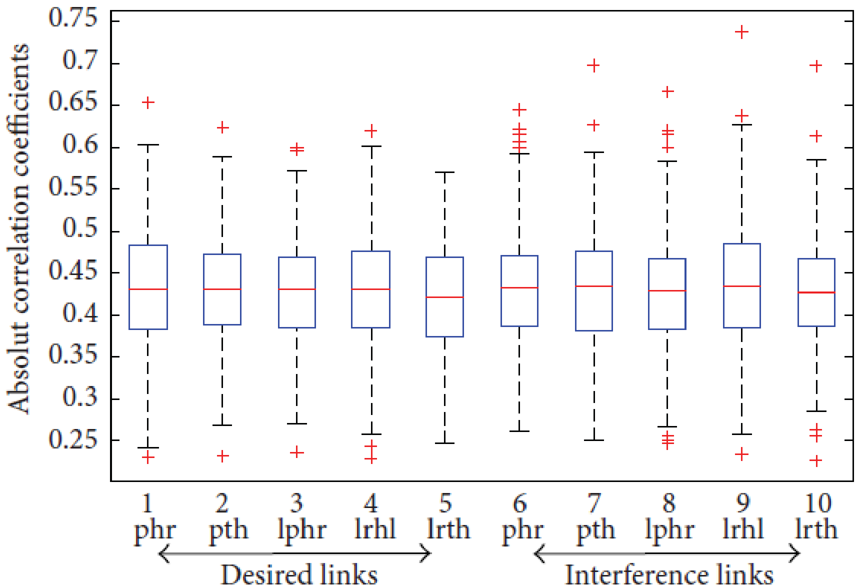



*Figure 5-12: Correlation coefficients for different grips at high band [94]*

However, comparison of the means of the medians of the LB and HB show that the LB had lower correlation at approximately 0.1 than HB, although the channels were not very correlated. However, the absolute values of the correlations remarkably varied, which distinctly affected the capacity. The scatter plot was presented to evaluate the relation between correlation and capacity. The scatter plots for correlation versus capacity for the desired and interference links according to the different grips at HB are shown in Figure 5-14 and Figure 5-15 respectively.

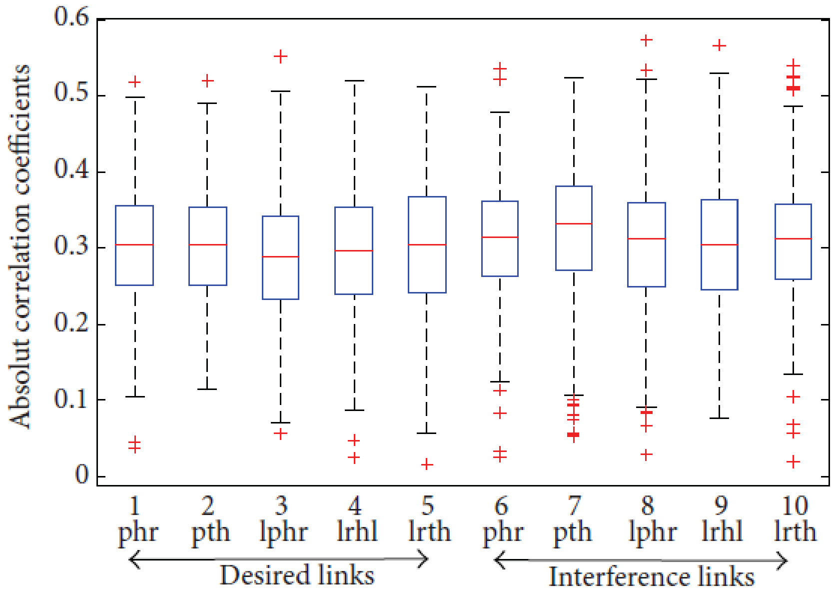



*Figure 5-13: Correlation coefficients for different grips at low band [94]*

The plots showed the wider distribution of the desired links in correlation with the interference links. However, Figure 5-14 and Figure 5-15 also showed no solid pattern in the changes in the capacity based on correlation. The tendency in the LB frequency was similarly investigated, and the results are shown in Figure 5-16 and Figure 5-17. The desired and interference links showed the same correlation distribution, and no strong links were found between changes in the correlation based on capacity. A wider range of correlation in LB than HB was found when these four figures were compared. At LB, correlation varies from 0 to 0.5 and showed most aggregation at approximately 0.4, whereas that at HB, the variation was from 0.2 to 0.7, with aggregation at 0.45.

Scatter plots for correlation versus capacity for HB and LB in the desired and interference links are shown in Figure 5-18 to present a clearer perspective. However, the effect of each grip is not shown in these results. Capacity considerably declined as correlation increased. LBs (yellow and blue stars) showed lower correlation and higher capacity regardless of desired or interference links. This result could elucidate the discrepancies in capacities in Figure 5-12 and Figure 5-13.

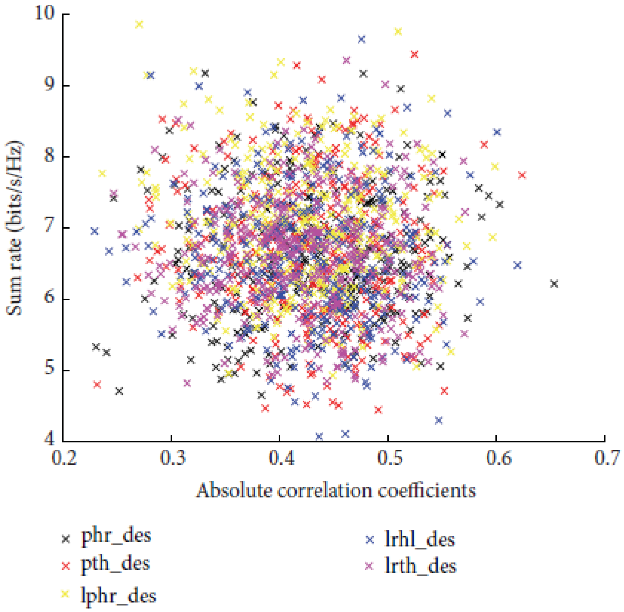



*Figure 5-14: Scatter plot: capacity versus correlation for desired links at high band [94]*

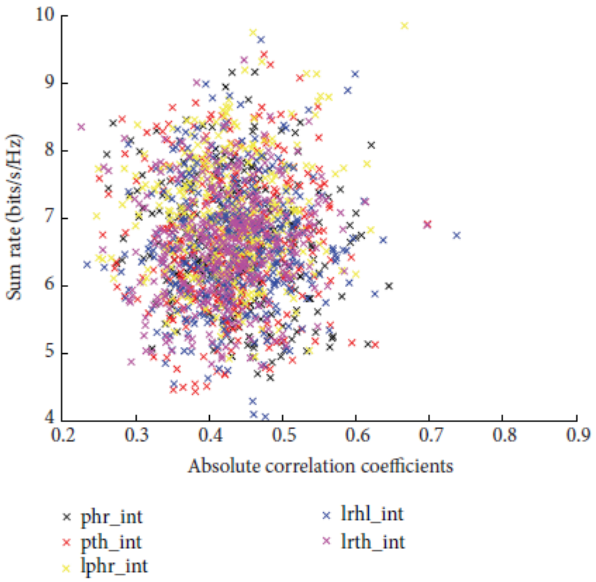



*Figure 5-15: Scatter plot: capacity versus correlation for interference links at high band [94]*

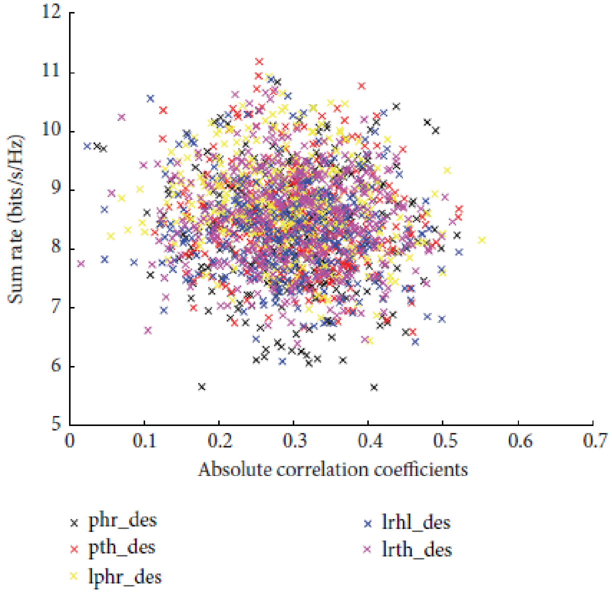



*Figure 5-16: Scatter plot: capacity versus correlation for desired links at low band [94]*

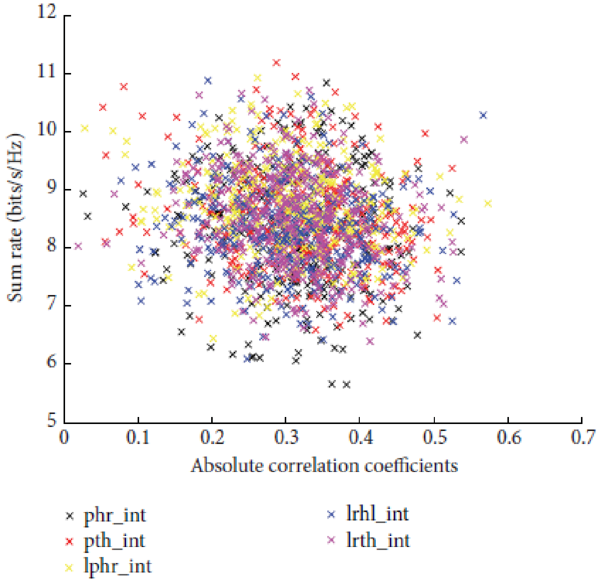



*Figure 5-17: Scatter plot: capacity versus correlation for interference links at low band [94]*

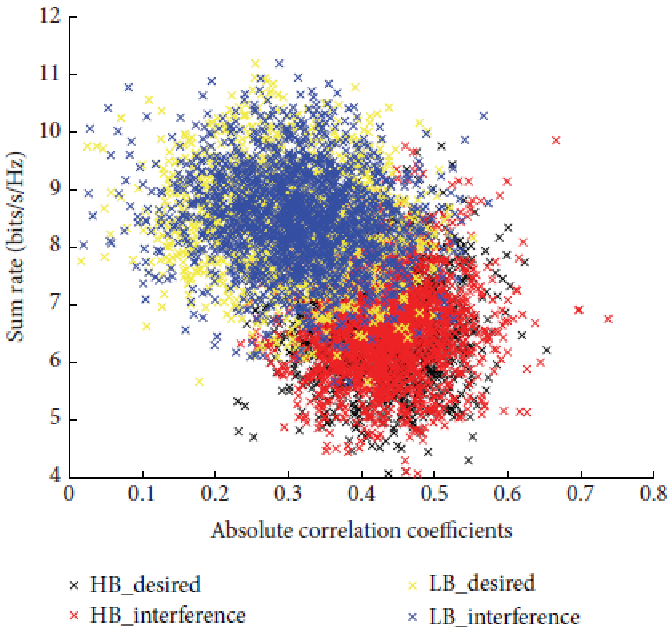



*Figure 5-18: Scatter plot: capacity versus correlation for desired and interference links at low and high band [94]*

## 5.4.7. APPLICATION OF VSINR ALGORITHM TO DETERMINE THE EFFECT OF LTE FREQUENCY BANDS ON THE CAPACITY

The performance of the proposed algorithm using measured data was evaluated at different frequencies for the application of the HBC transmission. The SNR was fixed at 15 dB, and over 2520–2592 measured data were used to plot the results for each handset pair. Figure 5-19 illustrates the data rate for the following scenarios:

(1) both BSs function at either HB or LB
(2) BS1 and BS2 function at LB and HB, respectively
(3) BS1 and BS2 function at HB and LB, respectively
(4) the first antenna of each BS functions at LB
(5) the second antenna of each BS functions at HB

The maximum and minimum data rates were recorded when both BS1 and BS2 functioned at LB and HB, respectively. A 1.7 bit/s/Hz difference was observed in the median data rates of both scenarios. Combining these bands regardless of BS resulted in almost the same values and enhanced the data rate by 13%. This enhancement could be attributed to the performance of HB. The last two scenarios also presented increased data rate (median value of 8.4 bits/s/Hz). It shows transmitting at LB could gain better data rate for HBC purpose, HB may be more crowded for transmitting that huge amount of data. The alternative could be unlicensed LTE bands for the use of HBC transmission.

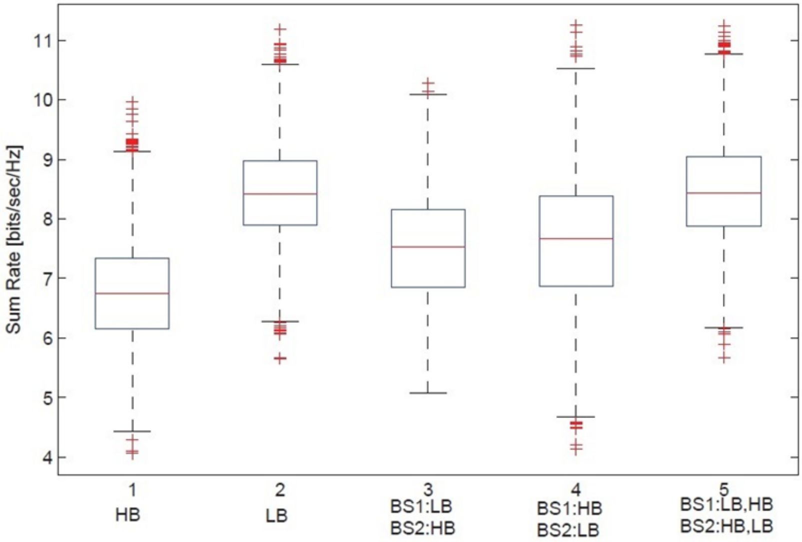



*Figure 5-19: Measured results for WMMSE with regards of different frequencies [88]*

## 5.5. SUMMARY AND CONCLUSIONS

In conclusion, the capacities of the different systems were measured to determine the influence of cooperation on capacity. Cooperation is defined as the case where two BSs can cooperate to send signals to users, and CSI is shared between BSs. The well-known WMMSE algorithm was applied to a multicell scenario and implemented in MATLAB to determine the capacity. Several methods were used to simulate the channels to imitate the real scenario. Capacity, which was more sensitive to correlation than to BPR, was obtained by the algorithm.

Three normalization methods were performed to plot the capacity from the measured data. Compared with the ideal channels, the first normalization yielded a 29% lower capacity for the measured channels. These discrepancies could be explained by parameters, such as correlation, distance between handsets, power imbalance, handset efficiency, and orientations of handsets with respect to BS. These parameters could be observed in real cases and negatively affect capacity.

The influence of distance and orientation of the handsets on capacity were also determined. Large distances between handsets did not necessarily result in lower achieved data if the handsets were highly efficient and suitably oriented toward the

BSs. Finally, the reproducibility of the measurement was investigated, and the results showed that more than 70 % of the measurements were reliable.

The two algorithms were compared using the i.i.d. Rayleigh channels and measurement data from the measurement campaign conducted by the Aalborg City Center. The following results were obtained:

1. The VSINR algorithm was superior to the WMMSE in simulation, with a difference of 0.8 bits/s/Hz at SNR of 15 dB, which is more significant at higher SNRs.
2. In the user case, the VSINR algorithm gained ∼10% more data rate in both simulation and measurement results compared with the WMMSE algorithm.
3. In the user case, both algorithms declined at the same percentages in gaining data rate from i.i.d. Rayleigh channels to measured channels (∼19%). This conclusion is valid for the current assumptions. Thus, the VSINR algorithm is beneficial in cases with single antenna at the receiver. WMMSE algorithm could be used when a MIMO scenario was established. However, the latter algorithm exhibited worse performance at high SNRs and higher computational cost compared with the former because of the root-searching process applied in the latter algorithm.

The behavior of the algorithm at varying frequencies with measured channels was investigated in this work. The following results are shown:

1. The highest capacity was achieved in LB (median=8.6 bits/s/Hz).
2. The algorithm was not very sensitive to the different grips of handsets.
3. Overall channels were more correlated at HB, although no highly significant difference was found between the LBs and HBs (approximately 0.1). The discrepancies resulted in higher capacity at LB.

When the signals at LB exhibited better penetration (i.e., they passed through objects, e.g., walls, with less attenuation), these signals could lead to higher data rate in the inner environments, where the measurements were conducted. The penetration loss was computed for both bands for the indoor scenario, which is very close to the presented scenario in this work.

Moreover, LB signals showed better penetration and better passage through objects than HB signals. Thus, working at LB to establish a setup for HBC transmission leads to a higher data rate, better coverage, more penetration, and lower cost.

# CHAPTER 6. APPLICATION ON THE HBC CONCEPT

The main outcome of this thesis is explained in this chapter. The main goal is to answer the basic but important question of how the huge amount of data achieved by sampling of different senses should be transmitted in a reliable and efficient way. This thesis provides the answer for this question, also the other possible solutions and technologies like using millimeter waves, 5G, or LTE unlicensed have been discussed in this chapter for further investigations and contributions.

## 6.1. INTRODUCTION

HBC has been defined, and requirements to apply this concept were discussed in chapter 4. HBC is established to primarily sample, digitize, transmit, and decode the optic, auditory, olfactory, gustatory, and tactile senses of humans. Feasible solutions for data transmission in HBC when abundant data should be transmitted were investigated using reliable wireless techniques.

A novel CAP for cooperative BS algorithm for HBC transmission is proposed, and its performance was investigated by measuring data at two LTE standard frequencies (776 MHz and 2300 MHz). The measured results show good agreement with simulated ones, indicating the applicability of the proposed algorithm. Enhanced performance of the proposed algorithm was observed at 776 MHz than at 2300 MHz because of the low interference and correlation at 776 MHz. The LTE-unlicensed (5 GHz) frequency has also been suggested for HBC usage because of the high spectrum and wide coverage at this frequency.

## 6.2. HBC AND CURRENT WIRELESS SYSTEMS ACCORDING TO PHYSICAL LAYER

Successful transmission of human bond information through a certain communication medium could be achieved if the following tasks are performed:

- Sampling of the physical subject
- Digitization and quantification of the sample to be transmitted
- Encryption of data at an appropriate security level
- Compression of data to comply with certain standards
- Transmission of data to the cloud or receiver, and
- Retrieval of data at the receiving side

These tasks should be investigated in detail. Thus, the HBC transmissions at various options or scenarios that can facilitate optimal data transmission, highest data transmission rate, and minimal information loss were investigated.

MIMO exhibits higher data transmission rate than SISO. Thus, the spectral efficiency and reliability of wireless communication systems are improved using the much developed MIMO.

Recent transmissions have increasingly applied multi-user MIMO or MU-MIMO to improve the communication capabilities of multiple independent radio terminals. MU-MIMO is frequently considered an extension of multiple access space division. Thus, this process facilitates the simultaneous access of multiple users to the same channel, thereby maximizing the system capacity. MU-MIMO suggests spatial degrees of freedom and diverse applications/versions to the users.

MU-MIMO presents numerous advantages but requires additional hardware, such as antennas and processing equipment, and consumes much bandwidth to acquire channel state information.

The different requirements for MU-MIMO should be satisfied before CAP architecture can be implemented. Each BS should possess channel state information to facilitate the optimal performance of CAP. Communication quality can also be improved by CAP with high throughput and excellent quality of service (QoS).

These parameters are vital in HBC transmission, and application of reliable and high-performance techniques is beneficial in the transmission of bulk data. In this case, an ideal system that can fulfil the requirements for HBC transmission is provided by CAP.

However, the application of CAP is limited by interferences, high cost, and requirement for a complex algorithm. Optimal techniques for HBC transmission have been explored, and an actual propagation environment has been used to test the proposed CAP algorithm by measuring data.

## 6.3. WMMSE ALGORITHM AND ITS APPLICATION IN HBC

WMMSE algorithm for HBC transmission is proposed in this study. The results of the WMMSE algorithm plotted in [88]. using ideal channels showed a sum rate of 8.3 bit/s/Hz at SNR of 15 dB. Thus, measured results in actual propagation environment showed that the experimental rate was less than that obtained with ideal channels because of fading, correlation, antenna efficiency, BPR, and other factors in the real channels. The mean of the medians achieved in [88] is 5.9 bits/s/Hz, indicating an approximately 29% reduction in capacity compared with ideal channels. Thus, good results are obtained compared with those from similar algorithms. The proposed algorithm outperformed many algorithms. However, more data rate is required to transmit human senses.

Among the five senses, only the audio and video signals have been transmitted to date. Vast bandwidth is required for transmission because of the huge bulk of data to be sent and received. Numerous methods and algorithms have been proposed to compress audio and video signals to decrease the required bandwidth in every transmission. These developments meet the requirements for audio and video transmission. These methods should also be applied for transmitting the other senses. Compressing signals of the other senses is apparently easier because these signals are sampled first. Thus, the required bandwidth can be remarkably reduced by proper adjustment of the sample rate. When a data set is prepared for transmission, the proposed algorithm with enhanced reliability can transmit the data to complete HBC transmission demand.

## 6.4. LTE STANDARD WITH WMMSE ALGORITHM AND HBC APPLICATION

The performance of the proposed algorithm was evaluated using measured data at varying frequencies. The maximum and minimum data rates were recorded when both BS1 and BS2 functioned at LB and HB, respectively. A difference of 1.7 bits/s/Hz was observed in the median data rates in both scenarios. Almost similar results were obtained when these bands were combined regardless of BS, and the data rate increased by 13%. These phenomena can be attributed to the performance of HBC. The last two scenarios also showed an evident increase in data rate (median value of 8.4 bits/s/Hz). The interference from the RF devices and high traffic of spectrum at 2300 MHz could have caused such difference.

This limitation is resolved by introducing unlicensed LTE to increase the efficiency of utilizing unlicensed spectra. LTE in the unlicensed spectrum (LTE-U), which was originally developed by Qualcomm, is proposed for 4G LTE radio communication technology in the unlicensed spectrum, such as the 5 GHz band used by dual-band Wi-Fi equipment. LTE-U may be an alternative to carrier-owned Wi-Fi hotspots [95].

LTE carrier aggregation is utilized in LTE-U to deploy the secondary carrier in the unlicensed band and maintain the primary carrier on the traditional licensed band. The 5GHz unlicensed spectrum in the US is divided into three different bands with diverse RF requirements, as follows:

- U-NII-1 (5150–5250 MHz)
- U-NII-2 (5250–5725 MHz)
- U-NII-3 (5725–5850 MHz)

Ericsson uses the term license-assisted access (LAA) to describe a similar technology. LAA is the result of the third-generation partnership project (3GPP) to standardize operation of LTE in Wi-Fi bands. This technology applies a contention protocol, namely, listen-before-talk (LBT), mandated in some European countries to coexist with other Wi-Fi devices on the same band. The final determination of the requirements of LBT by the 3GPP is still undergoing standardization [95].

The advantages of LAA to secure Wi-Fi are as follows:

- Increased coverage
- Extended range and improved performance in 5 GHz compared with Wi-Fi
- Increased Capacity
- Downlink throughput gains over Wi-Fi
- Co-existence that benefits all users
- Fair co-existence among LAA, LTE Wi-Fi link aggregation, and Wi-Fi with improved performance for all users sharing the same 5 GHz channel

The proposed technology would be a reasonable solution to reduce the interference in spectra and improve performance of algorithms to achieve enhanced data rate, which is required for HBC transmission.

## 6.5. CHARACTERISTICS OF MILLIMETER-WAVE (MM-WAVE) FOR HBC IMPLEMENTATION

Mm-waves assigned to the electromagnetic spectrum correspond to radio band frequencies in the range of 30–300 GHz, with wavelengths of 10 mm to 1 mm. These waves are longer than the infrared waves or X-rays but shorter than radio waves or microwaves. Mm-waves are used for various applications, such as transmission of large amounts of data, cellular communication, and radar, because of their high frequency and propagation characteristics.

More rapid and highly reliable communication is expected to be highly demanded. Annual mobile traffic is expected to exceed 291.8 exabytes (EB) by 2019 [96]. The monthly mobile data traffic is forecasted by CISCO to increase from 2.5 EB in 2014 to 24.3 EB in 2019 [97]. Meanwhile, Nokia and Samsung predict a 10,000-fold increase in traffic on wireless networks by 2020 with virtually no latency for content access [98] and [99].

Larger spectral channels are the primary advantage of using mm-wave carrier frequencies. For example, channels with 2 GHz of bandwidth could be expected using unlicensed mm-wave band at 60 GHz. Larger bandwidth channels indicate higher data rates, and these rates are the most remarkable advantage of mm-wave spectrum.

Massive MIMO is a promising technique for 5G cellular networks. High throughput has been reported to be feasible using a large number of BS antennas through simple signal processing in massive MIMO networks. Massive MIMO offers to remarkably enhance the efficiency of spectral and energies and the robustness of a system. The transmitter and receiver in a massive MIMO system are equipped with numerous (typically tens or even hundreds) antenna elements. Massive MIMO with mm-waves is recommended to overcome the difficulties in achieving higher data rate. Less energy of an antenna is captured by a smaller wavelength because of path loss and other factors. Moreover, higher noise power and lower SNR are indicated by larger bandwidths. Massive MIMO aids the mm-waves to resolve these problems and obtain higher data rate. Hence, the extra advantages presented by large antenna arrays in a system should be explored.

New techniques for MIMO communication signal processing are needed because of the use of large antenna arrays of transmitters and receivers and combined with radio frequency and mixed-signal power constraints. Transceiver algorithms with low complexity have become important because of the required wide bandwidths. Hence, exploiting techniques, such as compressed sensing for channel estimation and beamforming, presents much potential.

Mm-wave has diverse precoding and combining because of the following factors.

- Parameters have to be configured because of the distinct arrays. Different algorithms are required at this stage to explore the analog and digital parameters. Thus, the resulting algorithms are dependent on architecture.
- Analog precoding and combining is used for the receiver to encounter the channel. Thus, intertwined channel and analog beamforming is suggested by the setup, resulting in a challenging estimation of the channel.
- The utilization of largely close-spaced arrays and large bandwidths has resulted in increased sparsity and structure in the channel. Thus, structures that could be exploited by signal processing algorithms are generated.

Mm-waves are extensively applied to various areas, such as wireless local and personal area networks in the unlicensed band, 5G cellular systems, vehicular area and ad hoc networks, and IoT and HBC technologies because these waves enhance the transmission of huge amount of data.

## 6.6. 5G AND HBC

Fifth Generation Mobile System (5G) is introduced to achieve high data rate, low latency, low power consumption, etc. This technology is a great pace in wireless technology development to achieve the ultimate wireless communication.

Many studies are being performed to discuss the future of 5G technology. This technology is projected to increase the bandwidth, QoS, usability, and security, decrease delays and cost of services, reduce battery consumption, and enhance reliability of the communications, among others. The architecture of 5G is highly advanced such that this technology can be easily implemented by service providers.

Inter-cell interference, traffic management, multiple services, security and privacy, and standardization are some factors that limit the application of 5G. These limitations should be resolved before the implementation of 5G technology in 2020. The academe and industries should exchange their results to achieve the ultimate and promised 5G system.

Speed up to 1 Tbit/s, less than 1 ms latency, almost 10% network coverage, 1000× reduction in power consumption, deep indoor coverage, 10-to-100 connected devices, and 100× average data rate are expected in the 5G technology. The application of 5G is analogous to the fulfillment of a vision. Users could expect unified global standard, network availability anywhere any time, Wi-Fi global zone, etc. Thus, 5G wireless technology offers the capability of online games being played by players across the world opening new experiences, automatic driven cars, which can remarkably aid in transportation system, providing remote health care, assist the elderly, and enhance video conferencing to be closer to reality as if the conversing persons are in the same room.

HBC is one of the most inspiring applications of 5G. The 5G technology can be used to achieve this concept as long as it supports very high data rates. HBC transmission requires very fast connectivity and huge capacity to connect people worldwide with all their senses. This transmission has altered the concept of connectivity and access. HBC, which connects people to the digital world, is an integral and highly significant aspect of 5G networks.

Current technologies do not offer the best solutions to deploy HBC communication and connectivity, because HBC requires higher reliability, vast capacity, faster broadband, and connectivity, among others. Thus, 5G, which utilizes mm-waves, could open HBC transmission to the new era of wireless communication.

## 6.7. SUMMARY AND FUTURE WORK

The current and future wireless technologies for HBC application were discussed to introduce a new standard of quality of life and quality of human communications. The HBC would address the need for proper communication among individuals, with the prospect of transmitting and receiving signals from all five senses through wireless technology. HBC provides the satisfaction of people when they perceive themselves in an environment with power to sense other people, share their feelings with others, and receive proper feedback from others with all their five senses.

The implementation of HBC is planned to be conducted in several levels. The first level is the physical layer and the requirement for data transmission in communication technology. An algorithm for CAP technology with enhanced performance is proposed for HBC transmission [88]. Simulated and measured data are used to explore the behavior of the algorithm using various parameters, scenarios, and setups.

Much studies and investigations from the academe and industry, such as medical doctors and wireless technology engineers, are required to implement HBC in an actual setting. The use of LTE – U, mm-waves, and 5G is discussed to enhance the performance of algorithms for high data rate transmission. HBC is predicted to be functional beyond 2020.

# CHAPTER 7. CONCLUSIONS AND FUTURE OUTLOOKS

This chapter presents the conclusions and intended future scope of the research expressed through this thesis.

## 7.1. CONCLUSIONS

The transmission of HBC, which covered five human senses, namely, optic, auditory, olfactory, gustatory, and tactile senses, was explored in this study. Thus, broadcasting MIMO, cooperative MIMO, and the LB and HB under LTE standard were investigated. Important parameters that influence the performance of the proposed algorithm were investigated by evaluating the simulation results using the measured data. The results showed that the two sets of data were consistent.

The first basic steps of the advantages and disadvantages of the cooperative broadcast MIMO over the non-cooperative one with and without precoding techniques and the concepts of full and semi-cooperation between base stations have been investigated in first two papers, which have not been mentioned in the chapter 5 and also can be found in the references in [80] and [81]. In both assumptions, measured data have been used for evaluation of the results. The influence of beamforming is also investigated in those works. The outcomes lead to choose CAP system with MMSE precoding techniques for the rest of the work.

Three normalization methods were applied to determine the capacity for the measured data using the WMMSE algorithm. The normalization, which considered all parameters, yielded a 29% reduced capacity for the measured channels compared with the ideal channels. Parameters, such as correlation, distance between handsets, power imbalance, handset efficiency, and diverse orientations of handsets with respect to BS, could explain such discrepancies. The capacity could be adversely influenced by these parameters, which are found in real situations.

WMMSE and VSINR algorithms were compared using the i.i.d. Rayleigh channels and measured data obtained from the measurement survey of the Aalborg City Centre. The following results were obtained:

1. The VSINR algorithm outperformed the WMMSE algorithm during the simulation with a difference of 0.8 bits/s/Hz at SNR of 15 dB. Higher SNR levels showed more significant differences.

2. Approximately 10% higher data rates were observed in the measured and simulation results using the VSINR algorithm than the WMMSE algorithm under the user case.
3. Similar declines (~19%) in the achieved data rate were observed in both algorithms from i.i.d. Rayleigh channels to measured channels in the user case. Such conclusion is valid for the current conditions.

In conclusion, the VSINR algorithm is recommended for cases with single antenna at the receiver. By contrast, WMMSE algorithm can be used in a MIMO scenario. However, the root-searching process in the latter algorithm resulted in its worse performance at high SNRs and higher computational cost.

The behavior of cooperative BSs based on the achieved data rate was investigated using VSINR algorithm at different LTE frequencies with measured channels. The following results were obtained:

1. The LB yielded the maximal data rate (median= 8.4 bits/sec/Hz).
2. Capacity increased by 13% from solely HB scenario when data transmissions at LB and HB were combined.
1. 3- HB channels were generally more correlated than the LB channels. The higher the number of correlated channels could explain the lower data rate at HB.

Thus, working at LB resulted in higher data rate, improved coverage, higher penetration, and lower cost to establish the system. At high frequency, combining LB and HB could yield enhanced results without influence from cost and complex design.

Finally, the issues during transmission of huge data for HBC application were resolved. The data were assumed to be sampled, quantized, and prepared for transmission. Hence, transmission was conducted using the CAP system because of its excellent performance. The proposed algorithm demonstrated an improved performance and achieved excellent data rate using the ideal and measured channels. This algorithm also produced reliable and rational outputs for HBC transmission. The ideal possible LTE standard frequency for transmitting huge data was also determined. Minimizing interference created femtocells for enterprises and urban areas, improved coverage, and ascertained highly reliable communication. Thus, the use of the LTE-U standard for HBC applications is highly recommended.

## 7.2. FUTURE SCOPE

The implementation of HBC requires several parallel studies and investigations from diverse organizations and researchers, such as medical doctors and wireless technology engineers, to establish the actual HBC concept. Utilizing LTE–U, mm-waves, and 5G could enhance the performance of algorithms for high data rate transmission. HBC is predicted to be functional beyond 2020.

One of the possible paths to continue on the HBC and its implementation is proposed in [56] as the concept of Knowledge home. The Knowledge home is a virtual home where the knowledge of HBC is shared and accessible for the users. Like a society or enterprise environment with the knowledge of all five human sense to be transmitted. In addition to that, the power of sensing the feelings and transmitting them will be added to the Knowledge home as a second layer of the Knowledge home. The details were provided in [56]. It is mentioned: “The Knowledge Home is expected to be implemented in two levels. The first level as introduced in [55], encompasses Human Bond Communication technology. The final level adds up Human Feeling Identification and Transmission to the Home for processing data and communicating effectively.”

In addition, the whole concept of Knowledge Home and Human Bond Communication should be implemented at different layer of network, which had been reconstructed and optimized for transmitting this huge amount of data safe and reliable. Here, the need of a comprehensive platform has been seen. In this work, the physical layer for HBC transmission has been studied, and the solution for optimization for enhanced data rate, low interference and reliable communication has been proposed. The future work tries to point out the challenges in designing the security and standardization for HBC communication including in the CONASENSE platform [52]. CONASENSE promises a universal platform and principles from physical to network layer for optimizing, developing and improving the current wireless communication technology to the future wireless communication technology. The new set up should address the challenges of implementing the HBC idea. It is clear that CONASENSE combines diverse organizations, industries and researchers to make this dream to the reality.

Finally, the need for a new business model for HBC transmission should be addressed for the future of the wireless communication. Due to rapid development of HBC, it is obvious that a new business model should be defined for this huge changes, which will be expected after first implementation of the HBC in the real market. The investigation on the business opportunities of HBC development and later proposing different solutions such as persuasive business model concept and their abilities to design a comprehensive prototype for HBC technology is another problem, which will be discussed in this work [53], [54].

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# CURRICULUM VITAE

# CV

Maryam Rahimi was born in 1979 in Tehran, Iran. She has done her bachelor in Electronics Engineering at Mazandaran University, Iran in 2001. In 2001, she started working in a Behnam khodro company as a service technician. The main duties were testing and giving technical support, installing measurement machines like Titrators, Viscosity etc., help and guide customers to use the machine, routine visits of machines for checkups like calibration etc., fault detection and maintenance in the case of failure of machines, and technical phone support and discussion with customers. In 2004, she joined Yekke Taz company as a sale engineer with duties as providing pre-sales technical assistance and product education, and after-sales support services and supporting technical presentations and demonstrating how a product meets client needs.

In 2005, she moved to Malaysia to pursue her M. S. in Microelectronics Engineering at Putra Malaysia University. Her project was about design and simulation of Micro electro mechanical inductor and varactor and design and simulation of VCO oscillator (RF circuit design) using ADS software.

In 2010, she moved to Denmark to start her PhD in wireless communication at Aalborg University. Her research was mainly involving: planning the measurement campaign, analyzing real measured data & channel propagation, using MATLAB and C++ programming for analyzing data, algorithm development, and antenna design.

In 2016, she joined CTIF section in Aalborg University as Research Assistant with focus on: millimeter Wave research and investigation, 5G and future of wireless communication, and Human Bond Communication (HBC) and physical layer. From September 2016 she has joined to RTX A/S as a Project Engineer with duties on: indoor Positioning and UWB, LTE Standards, and femtocells, and SW developing.

Maryam has done some research projects during her academic activities as following:

- Analysis of Measured Channels, Channel Propagation, Cooperative MIMO Capacity, 2010-2014
- Design of MEMS Inductor and Varactor for Low Noise VCO, 2005-2008
- Design and Development of Radio Frequency (RF) Front-end for a Wireless Receiver or Transceiver, project of ministry science, 2008-2009
- Conducting Bachelor Student's Researches on Design of Voltage Generator, Mixer and LNA, 2007- 2009
- Reviewing some papers from International Journal of Electronics

She also won the one year license of the CoventorWare software for the best proposal in 2006. She is main author or co-author of more than 15 journal and conference articles.

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| Title: | Performance of Human Bond Communications using Cooperative MIMO Architecture |
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Has the article/manuscript previously been used in other PhD or doctoral dissertations?

No ☒ Yes ☐ If yes, give details:

The PhD student has contributed to the elements of this article/manuscript as follows:
A. Has essentially done all the work
B. Major contribution
C. Equal contribution
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| Title: | Human Bond Communications from a Business Perspective |
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# CONTRIBUTED ARTICLES

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# Performance of Human Bond Communications Using Cooperative MIMO Architecture

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**Abstract** Humans have significantly improved their quality of life using modern communication technologies. Earlier, human bond communication (HBC) was introduced to the community as a new concept of transmitting five humankind senses. This paper proposes a method for the HBC transmission to transmit massive amounts of data is available due to HBC transmission demands by implementing cooperation among several base stations in a MIMO architecture to promote the performance of the system. The findings of this work are evaluated by conducting simulation tests in ideal channels and by performing measurements at different frequencies in actual propagation environments. The proposed algorithm facilitates data transmission via HBC by improving the performance and data transmission rate of the cooperative access point system.

**Keywords** HBC · MIMO · Cooperative base stations · LTE · Physical layer

## 1 Introduction

As an essential component of human life, effective communication allows people to share information, exert their influence upon others, establish a beneficial society that is dominated by rules, and express their emotions. Accordingly, several communication methods have emerged along the years to help mankind achieve these objectives.

Communication has a long origin that can be traced back to the Stone Age, during which people communicate with one another by drawing on cave walls. The advancements in technology have eventually allowed people to communicate with one another wirelessly and in real time through text, voice, and video messaging. Such advancements persistently

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develop as humans continue to pursue their ambitions; the same level of determination has driven the advancements in science and technology that we enjoy today. As a crucial factor that drives man toward his communication goals [1, 2], the concept of human bond communication (HBC) posits that the five human senses, namely, optic, auditory, olfactory, gustatory, and tactile, can also be transmitted wirelessly, thereby allowing humans to characterize and share information about subjects the way they perceive them in real life. In HBC, humans select and interpret a physical subject using their five senses, compose a dataset using their obtained information, transmit the same information using a suitable communication tool, and obtain the transmitted information on the receiving end.

Apart from examining the transmission level of HBC, this work also reviews the literature on the implementation of the novel cooperative access point (CAP) system, in which several connected access points coordinate their respective functions. The performance level of this system has been assessed in previous studies based on information theory [3–6]. Somekh et al. [7] even showed that the CAP system could outperform conventional networks by over 10 times.

This study proposes a novel algorithm for HBC transmission and evaluates its performance by measuring data at two long term evolution (LTE) standard frequencies (776 and 2300 MHz). The measured results show favorable agreement with the simulated ones, thereby supporting the suitability of the proposed algorithm. The proposed algorithm demonstrated a better performance at 776 MHz than at 2300 MHz because of the low interference and correlation at the former. This work also proposes the LTE-unlicensed (5 GHz) frequency for HBC usage because of its high spectrum and wide coverage.

The rest of this paper is organized as follows. Section 2 describes HBC and its proposed architecture. Section 3 presents the physical layer requirements and design considerations of this system. Section 4 proposes the algorithm for HBC transmission. Section 5 describes the measurement process and setup. Section 6 presents the results. Section 7 concludes the paper and proposes directions for future work.

## 2 Architecture of the HBC System

HBC outperforms the existing communication systems in terms of its architecture. Figure 1 illustrates the components of HBC, including (1) sense transducers or senducers that convert stimuli into electrical signals for further processing, (2) the human bond sensorium

**Fig. 1** An overview on HBC architecture system

(HBS) that collects and processes the information from senducers to enhance their perceptibility, and (3) a human perceivable transposer (HPT).

## 2.1 Senducers

Senducers resemble the human senses and collect a subject in accordance with the human sensory domain. This device comes in the form of a capsule/shell that contains the following elements:

- sensing transducers that interpret the collected subject in the five human sensing domains
- intelligence systems that enhance the sensing process and the perceptibility of the subject
- radios that transmit data between HBS and senducers through a communication link

Senducers possess the same level of intelligence as their sensing domains. These devices avoid errors by reducing human involvement in the process as much as possible, which can also allow the system to interpret a subject with minimum chances of fading and the least amount of possible deviation. Senducers may be classified as either collective or distributive based on their applicability.

Collective or co-located senducers have also been termed as "unoducers" because they come equipped with a single sampling device with several transducers in a single monolith. Distributive senducers, which may either be used for individualistic sensing or comprise a chain of unoducers, achieve extensive sensing by evaluating the subject panoramically.

## 2.2 HBS

In the sensing process, the senducers accumulate all the required data and transmit them to a distant location. Given that material sensing can only be accomplished by physically approaching the subject, HBS provides senducers with a common node to which the latter can send their collected information. Senducers must also come equipped with an energy saving mechanism considering that they perform the subject sampling and transduction. A large part of the information processing task is assigned to the HBS.

Apart from ensuring a holistic communication, HBS guarantees the integrity, security, authenticity, and reliability of the data that are being transmitted from one point to another (Fig. 2).

## 2.3 HPT

Using HPT, the information sent by HBS is transposed in a format that is perceptible to humans and is then transformed into stimuli that can be sensed by an observer. These stimuli can be produced in two ways as follows:

- in brain-to-brain transmission, one person directly sends the data to another. This method is most useful in situations where an individual communicates with disabled people or when parents teach their children on how they can become aware of their feelings
- in device-to-device transmission, the sensor directly sends the data to a data center or a smartphone. This method is most useful when attending to health- or safety-related concerns

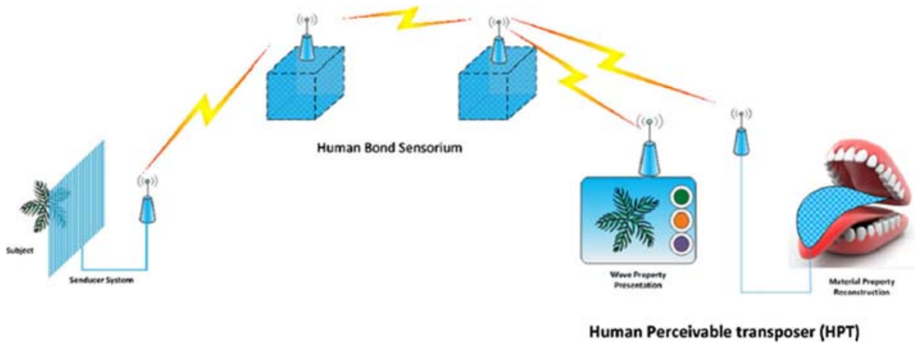



**Fig. 2** Human bond sensorium architecture [2]

The proposed HBC architecture improves the entire data transmission process beginning from the sending of data to their reception. The following section proposes several techniques for HBC transmission.

## 3 Physical Layer Requirements of HBC

The following tasks must be achieved to transmit human bond information successfully through a certain communication medium:

- the physical subject must be sampled
- the sample to be transmitted must be digitized and quantized
- the data must be encrypted at an appropriate security level
- the data must be compressed to comply with certain standards
- the data must be transmitted to the cloud or receiver
- the data must be retrieved at the receiving side

The aforementioned requirements must be investigated in detail. Accordingly, this work focuses on the HBC transmission level and on various options or scenarios that can facilitate data transmission with the best performance, highest data transmission rate, and minimal information loss.

Given its higher data transmission rate than Single-Input-Single-Output (SISO), Multiple-Input-Multiple-Output (MIMO) has been developed in many years to enhance the spectral efficiency and reliability of wireless communication systems.

Multi-user MIMO or MU-MIMO has been increasingly adopted in recent transmission to improve the communication capabilities of multiple independent radio terminals. Often considered an extension of space division multiple access, MU-MIMO allows multiple users to access the same channel at the same time, thereby exploiting the maximum system capacity. MU-MIMO also offers these users with spatial degrees of freedom as well as different applications/versions.

Despite its many advantages, MU-MIMO requires the use of additional hardware, such as antennas and processing equipment, as well as the consumption of additional bandwidth to acquire channel state information.

The CAP architecture cannot be implemented without satisfying the various requirements of MU-MIMO. Each base station (BS) must possess channel state information to help CAP achieve an optimum performance. CAP can also improve communication quality by offering high throughput and excellent quality of service.

All of the aforementioned parameters are vital in HBC transmission, and adopting reliable and high-performance techniques can help transmit a large amount of data. In this case, CAP provides an ideal system that can fulfill the requirements for HBC transmission.

However, CAP often encounters interferences, have high cost, and require an algorithm with a complex design. Previous studies have attempted to find the best techniques for HBC transmission and tested the proposed CAP algorithm by measuring data in an actual propagation environment.

## 4 Proposed Algorithm for CAP

To achieve excellent performance, HBC transmission uses a cooperative Base Station (BS) MIMO as its architecture. Both the transducer and receiver are equipped with more than one antenna, and each terminal has more than one transducer to transmit the sampled data to the cloud or receivers.

Given its simplicity and excellent performance, HBC transmission employs the weighted sum–minimum mean square error (WMMSE) algorithm for MIMO broadcast as proposed in [8]. This work implements the extension of the WMMSE to fit the CAP scenario to be used for HBC transmission as follows [9].

The work considers a multi-cell system that comprises two cells with $K$ BSs and $K$ users, with each BS only serving a single user. Figure 3 illustrates the system setup. Numerous cells may apply the same formula. Each BS is equipped with an $M$ transmitted antenna, while each receiver is equipped with $N$ received antennas. The channel matrices $\mathbf{H}_k^b \in \mathbb{C}^{[N \times M]}$ and $\mathbf{H}_k^a \in \mathbb{C}^{[N \times M]}$ represent the wireless channels between BS $k$ and user $k$ in cells $b$ and $a$, respectively. The signal that is transmitted from cell $b$ is computed as $X^b = \sum_{k=1}^{K} \mathbf{B}_k^b d_k^b = \mathbf{B}^b b^d$, where $\mathbf{B}_k^b \in \mathbb{C}^{[N \times M]}$ is a precoder matrix for each BS and $\mathbf{B}^b = \left[\mathbf{B}_k^b, \ldots, \mathbf{B}_K^b\right] \in \mathbb{C}^{[M \times KN]}$ is observed in all the pre-coders of cell $b$.

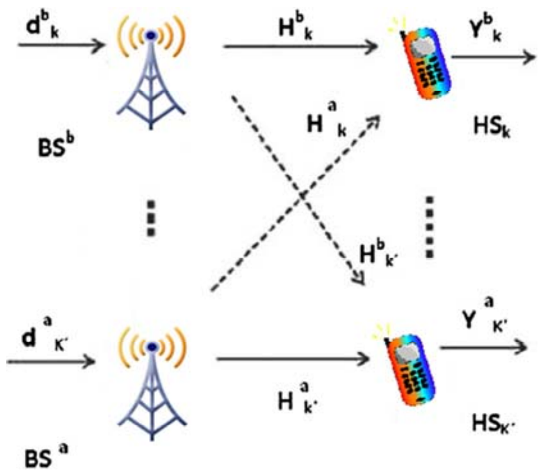



**Fig. 3** System model of CAP technology

The transmitter and receiver has $N$ data streams, where $N \leq M$. $d_k^b$ represents the complex vector of data streams where $d_k^b \in \mathbb{C}^{[N\times 1]}$, $d^b = \left[d_k^b\boldsymbol{T}, \ldots, d_K^b\boldsymbol{T}\right] \in \mathbb{C}^{[KN\times 1]}$ represents the data for all users in cell $b$, and $d^T$ denotes the transposition of vector $d$. The above definitions are also applicable for $\mathbf{B}_k^a$ and $d_k^a$ for cell $a$. In this case, the signal received by user $k$ in cell $b$ can be formulated as follows:

$$Y_k^b = \mathbf{H}_k^b\mathbf{B}_k^b d_k^b + \mathbf{H}_k^b \sum_{i=1, i\neq k}^{K} \mathbf{B}_i^b d_i^b + \mathbf{H}_k^a \sum_{k=1}^{K} \mathbf{B}_k^a d_k^a + n_k^b, \tag{1}$$

where $n_k^b \in \mathbb{C}^{[N\times 1]}$ is a standard circular white Gaussian noise vector with a covariance of $\mathbf{R}_{nknk} = \mathbb{E}\left[n_k n_k^H\right] = \mathbf{I}_N, n_k^H$ denotes the conjugate transposition of $n_k$, and $\mathbb{E}\left[n_k n_k^H\right]$ denotes the expected value of $\left[n_k n_k^H\right]$. The first, second, and third terms in Eq. (1) represent the desired signal of the user, the intra-cell interference or undesired signal at user $k$ that is transmitted from a BS inside cell $b$ that includes user $k$, and the inter-cell interference where user $k$ receives an unwanted signal from a neighboring cell. Each block is assumed to have constant channel matrices. Both the transmitter and receiver sides know the channel state information, and the system supports the assumption, $\mathbb{E}\left[d_k d_k^H\right] = \mathbf{I}_N$. The transmit vectors observe the following power constraint:

$$\mathbb{E}\left[X^{bH}X^b\right] = \sum_{k=1}^{K} \mathrm{Tr}\left(\mathbf{B}_k^b\mathbf{B}_k^{bH}\right) \leq E_{tx}^b, \tag{2}$$

where $E_{tx}^b$ denotes the total transmission power of each BS in cell $b$, while $\mathrm{Tr}\left(\mathbf{B}_k^b\mathbf{B}_k^{bH}\right)$ represents the trace of the matrix. The WMMSE algorithm and the scenarios that have been considered in the simulation analysis are described as follows.

Based on the minimum mean square error (MMSE) criterion, the WMMSE algorithm computes the transmit filter $\mathbf{B}^b$ that can optimize the achievable data rates of all users in cell $b$ as well as relates the weighted sum-rate with the weighted MMSE in the MIMO broadcast channel [8]. WMMSE has been extended to the MIMO interference channel in [10]. As an extension of [8, 10], this work modifies WMMSE to fit the multi-cell cooperative MIMO scenario.

The achievable data rate for user $k$ in cell $b$ can be computed as follows [8]:

$$R_k^b = \log\det\left(\mathbf{I}_k + \mathbf{B}_k^{bH}\mathbf{H}_k^{bH}\mathbf{R}_{v_k v_k}^{-1}\mathbf{H}_k^b\mathbf{B}_k^b\right), \tag{3}$$

where $\mathbf{R}_{v_k v_k}$ computes for the noise and interference covariance matrix at user $k$ as follows:

$$\mathbf{R}_{v_k v_k} = \mathbf{I}_k + \sum_{i=1, i\neq k}^{K} \mathbf{H}_k^b\mathbf{B}_i^b\mathbf{B}_i^{bH} + \mathbf{H}_k^a\mathbf{B}_k^a\mathbf{B}_k^{aH}\mathbf{H}_k^{aH} \tag{4}$$

A new term is added at the end of Eq. (4) to extend the interference matrix proposed in [8]. This newly added is also added in the other equations to address inter-cell interference.

As shown in [8], the MMSE receives filter $\mathbf{A}_k^{b,MSE}$ at user $k$ as follows:

$$\mathbf{A}_k^{b,MSE} = \mathbf{B}_k^{bH}\mathbf{H}_k^{bH}\left(\mathbf{H}_k^b\mathbf{B}_k^b\mathbf{B}_k^{bH}\mathbf{H}_k^{bH} + \mathbf{R}_{v_k v_k}\right)^{-1} \tag{5}$$

After implementing the received filter $\mathbf{A}_k^{b,MSE}$, the MMSE matrix for user $k$ is computed as follows [8]:

$$\mathbf{E}_k^b = \left(\mathbf{I}_k + \mathbf{B}_k^{bH}\mathbf{H}_k^{bH}\mathbf{R}_{v_k v_k}^{-1}\mathbf{H}_k^b\mathbf{B}_k^b\right)^{-1} \tag{6}$$

To maximize the weighted sum rate problem, the following cost function is defined:

$$\begin{aligned} &\arg \min_{\mathbf{B}_1^1,\ldots,\mathbf{B}_k^C} \sum_{k=1}^{K}\left(u_{R_k^b}\mathbf{R}_k^b + u_{R_k^a}\mathbf{R}_k^a\right) \\ &\text{s.t.} \sum_{k=1}^{K}\mathrm{Tr}\left(\mathbf{B}_k^b\mathbf{B}_k^{bH}\right) = E_{tx}^b \forall b \end{aligned} \tag{7}$$

$\mathbf{R}_k^a$ is added as a new term in Eq. (7) following the same procedure applied for $\mathbf{R}_k^b$. Equation (7) is expressed using Lagrange's formula and derived with respect to $\mathbf{B}_k^{b*}$ and $\mathbf{B}_k^{a*}$, with the latter denoting the conjugate of $\mathbf{B}_k^a$. The derivation must then be compared with the following derivation of the WMMSE problem:

$$\begin{aligned} &\arg \min_{\mathbf{B}_1^1,\ldots,\mathbf{B}_k^C} \sum_{k=1}^{K}\mathrm{Tr}\left(\mathbf{W}_k^b\mathbf{E}_k^b + \mathbf{W}_k^a\mathbf{E}_k^a\right) \\ &\text{s.t.} \sum_{k=1}^{K}\mathrm{Tr}\left(\mathbf{B}_k^b\mathbf{B}_k^{bH}\right) = E_{tx}^b \forall b \end{aligned} \tag{8}$$

where $\mathbf{W}_k^b \in \mathbb{C}^{[N\times N]}$ and $\mathbf{W}_k^a$ denote the weight matrixes for user $k$ in cells $b$ and $a$, respectively. After comparing these gradients, the MSE weights must be adjusted as follows:

$$\mathbf{W}_k^b = u_k^b\mathbf{E}_k^{b-1}\text{and} \tag{9}$$

$$\mathbf{E}_k^b = \left(\mathbf{H}^{bH}\mathbf{A}^{bH}\mathbf{W}^b\mathbf{A}^b\mathbf{H}^b + \mathbf{H}^{aH}\mathbf{A}^{aH}\mathbf{W}^a\mathbf{A}^a\mathbf{H}^b + \lambda^b\mathbf{I}\right)^{-1}\mathbf{H}^{bH}\mathbf{A}^{bH}\mathbf{W}^b, \tag{10}$$

where $\mathbf{W}^b = \mathrm{diag}\{\mathbf{W}_1^b,\ldots,\mathbf{W}_K^b\}$ and $\mathbf{A}^b = \mathrm{diag}\{\mathbf{A}_1^b,\ldots,\mathbf{A}_K^b\}$ are matrices that comprise diagonally aligned blocks that are equivalent to the weight matrix. These blocks also receive the filters that correspond to each user. The channel links in $\mathbf{H}^b = \left[\mathbf{H}_1^{bT},\ldots,\mathbf{H}_K^{bT}\right]^T$ connect each BS to each user within the same cell. The method proposed in [11] is used to calculate the Lagrangian multiplier. To address inter-cell interference, the term in the parentheses is added in Eq. (10).

Following the procedures proposed in [7], the beam formers and MSE weights are continuously optimized until they are converged to a fixed point. The algorithm is applied using the assumed initial value for $\mathbf{B}_k^b$. The same assumed value is used to compute the received filter and weight matrix $\mathbf{W}_k^b$ as shown in Eqs. (5) and (9). The values of $\mathbf{A}_k^b$ and $\mathbf{W}_k^b$ are then computed using Eq. (10), and the results are used to update $\mathbf{B}^b$. These steps are performed continuously until the aforementioned parameters converge to the local minimum of the main problem.

## 5 Measurement Campaign Setup

A measurement campaign was performed at an urban macro cellular environment at the heart of Aalborg, Denmark to identify several parameters that can influence the capacity of cooperative MIMO when different LTE standard frequencies and HBC transmission scenarios are considered. In other words, the proposed algorithm is applied in a real propagation environment to assess the influence of its performance on HBC transmission.

To take into consideration the cooperation among different BSs, two BSs were installed at two unique positions in the measurement scenario. A compromise between high capacity and coverage is achieved in this scenario. The first BS (BS1) was placed 13 m above and 150 m away from the measurement area to generate high capacity channels, while the second BS (BS2) was placed 500 m away and 60 m above the measurement scenario to improve the coverage of the cellular system. Each BS has two Low-band (LB) and two High-band (HB) transmit antennas, which were measured simultaneously and centered at 776 and 2300 MHz, respectively. This work only focuses on the HB antennas, which were selected based on the LTE standard frequency bands.

The adopted measurement setup replicated the transmission method that is being applied in actual situations to measure the transmission from both BS1 and BS2 to four different users. The reliability of the adopted measurement methods was tested by analyzing and repeating some of the adopted measurements.

Located on the third floor of the Aalborg university building in the center of Aalborg, the measurement room had no windows that faced any BS to block the influence of line of sight. Four 1 m $\times$ 1 m squares were drawn on the measurement room floor in which the users moved back and forth during the measurement process. The movement pattern of the users was called LA. Figure 4 shows some setup environments of the measurement campaign.

Ten handsets equipped with two antennas in LB and another two antennas in HB at different positions were also designed. Only four handsets that shared the same type of antennas, namely, H1, H2, H5, and H6, were examined in this work to avoid artifacts that may arise from the differences in antenna types. An optical fiber was used instead of coaxial cables to connect each handset to the sounder because the electromagnetic properties of coaxial cables may affect these relatively small devices. The same setup also provides a highly realistic measurement of these handsets that can closely reflect their actual usage. An optical unit was also designed and installed in typical handset [12].

A plastic frame that resembles the outer casing of a mobile phone was used to cover each handset to prevent the printed circuit boards from being touched by the users. These handsets are further described in [13]. Eight users participated in the measurement process to determine how different bodies affect the receive antennas. Each participating user tested and handled the selected handsets by either touching their antennas or placing their fingers far from the receive antennas. This setup can also reveal how the performance of the HBC system may be affected by different users and types of grips.

The mean power of each selected reference handset as measured in all free space measurements from one BS was computed to maintain the differences in the power levels of BS1 and BS2. The following normalization procedure highlights the influence of several factors, including branch power ratio, correlation, different power levels from different BSs, different handsets, and fading information:

$$h_{n,m}^{norm}(g) = \frac{h_{n,m}(g)}{\sqrt{\frac{1}{NMG}\sum_{n,m,g}\left|h_{n,m}^{ref}(g)\right|^2}}, \tag{11}$$

where $M = 2$, $N = 1$, and $G = 1200$ denote the number of transmit antennas, receive antennas, and samples in each measurement, $g$ denotes the time index, $h_{n,m}$ denotes the


**Fig. 4** Measurement campaign setups, **a** measurement room, **b** base station 2, **c** base station 1

channel coefficients from the nth receive antenna to the *m*th transmit antenna, and $h_{n,m}^{ref}(g)$ represents the channels for a certain handset in the free space.

## 6 Results and Discussions

The results are discussed in three parts. First, the proposed algorithm with simulated ideal i.i.d. Rayleigh channels will be evaluated in terms of its performance. Second, after implementing the measured channels in the algorithm and to facilitate the analysis of HBC transmission behavior, this work will investigate how the parameters from the real propagation environment can affect the performance of the proposed algorithm. Third, to improve the system for HBC transmission, this work will assess the behavior of the algorithm by measuring data at different LTE bands. The significance and the effects of these findings on the fulfillment of HBC transmission requirements are also discussed. In the analysis of the measured channels, this work assumes a signal-to-noise ratio (SNR) ranging from 15 to 20 dB.

### 6.1 Simulation Results

Following the measurement setup mentioned above, the simulation assumes two users and two BSs. One receive antenna and two transmit antennas are installed on each BS. Figure 5 shows the simulation results of the WMMSE algorithm for i.i.d. Rayleigh fading channels. The WMMSE algorithm results are also plotted to extend the applicability of this algorithm for cellular networks. To achieve a fair result, the algorithm has a fixed sum-rate weighting coefficient of 1. Figure 5 shows that a sum rate of 8.3 bit/s/Hz has been achieved at SNR = 15 dB using the aforementioned setup.

### 6.2 Measurement Results

Figure 6 presents the results that are obtained at SNR = 20 dB when six combinations of handsets are considered. The presented boxplots are plotted over 1980–2160 and 456–462 measured data (i.e., handset pairs, grips, and user movements) for the user and free space cases, respectively. The measurement results for each case are presented separately, and some variations are observed in the outcomes of both algorithms. Such differences may be attributed to the influence of handset efficiency or the power imbalance among different links. These findings indicate the sensitivity of the algorithm to the aforementioned parameters.

### 6.3 LTE Frequency

This section evaluates the performance of the proposed algorithm using measured data at varying frequencies. The results for each handset pair are plotted over 2520–2592 measured data. The SNR in all scenarios was fixed at 15 dB. Figure 7 shows the data rate for the following scenarios:

1. both BSs working at either HB or LB
2. BS1 and BS2 working at LB and HB, respectively
3. BS1 and BS2 working at HB and LB, respectively
4. the first antenna of each BS working at LB
5. the second antenna of each BS working at HB

The highest and lowest data rates were recorded when both BS1 and BS2 were working at LB and HB, respectively. The median data rates in both scenarios showed a 1.7 bits/s/Hz

**Fig. 5** Simulation results for WMMSE algorithm with i.i.d channels

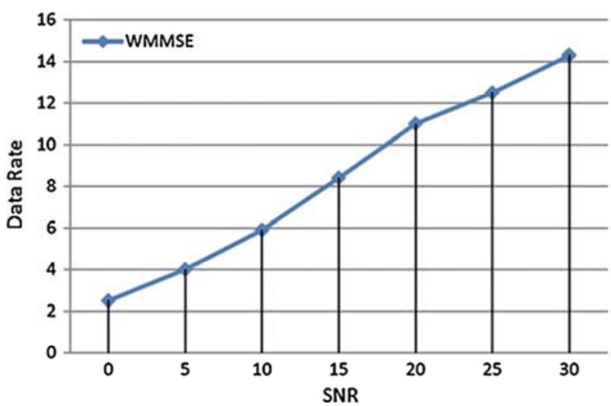
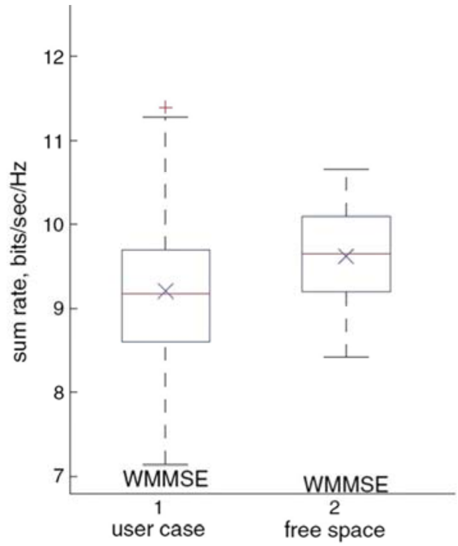


Fig. 6 Measurement results of WMMSE algorithm with and without users' influence



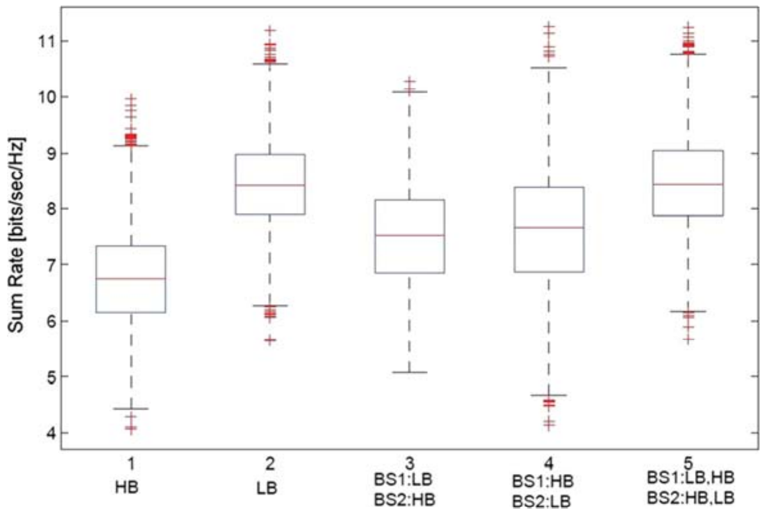




Fig. 7 Measured results for WMMSE with regards of different frequencies

difference. Combining these bands regardless of BS yields almost the same results and increases the data rate by 13%, which can be attributed to the performance of HB. An obvious increase in data rate (median value of 8.4 bits/s/Hz) was also observed in the last two scenarios.

## 6.4 HBC Results

Figure 5 shows the suitability of the proposed algorithm for HBC application. Two transducers, with each transducer equipped with two antennas, must be installed to transmit data to a receiver that is equipped with either one or two antennas. A reasonably high data rate is recorded when these two transducers cooperate with one another.

Figure 6 shows the performance of the proposed algorithm when using measured data and when applied in an actual HBC transmission scenario. Specifically, the proposed algorithm reported a 30% decrease in its performance yet managed to achieve an acceptable data rate. Installing the transducers at the proper positions and using these devices as wearable transmitters can reduce the influence of the user on the performance of the proposed algorithm. Determining the optimal position of antennas for HBC transmission may improve the results of the algorithm.

To investigate effectively the designs of the network or the network service provider, the performance of the proposed algorithm at low and high LTE bands is also examined. As shown in Fig. 7, the performance of the algorithm at 2300 MHz is much worse than that at 776 MHz, and such difference may be attributed to the interference with other RF devices and the high traffic at 2300 MHz. Using LTE-U at 5 MHz than at 2300 MHz may help address this situation, create femtocells, and improve network coverage at crowded areas.

## 7 Conclusions and Future Work Directions

As its primary objective, this work attempts to solve the issues encountered in the transmission of huge data for HBC application. These data are assumed to be sampled, quantized, and ready to be transmitted. To fulfill this objective, this work employs the CAP system because of its excellent performance. At ideal and measured channels, the proposed algorithm demonstrates an improved performance and achieves an excellent data rate. This algorithm also produces reliable, rational outputs for HBC transmission. This work also attempts to determine the ideal possible LTE standard frequency for transmitting huge data. By reducing interference as much as possible, creating femtocells in enterprises and urban areas, improving coverage, and guaranteeing a highly reliable communication, this work highly recommends the use of the LTE-U standard for HBC applications.

Future studies may evaluate the performance of the proposed algorithm at the LTE-U band by conducting measurements at 5 GHz and adopting the aforementioned measurement setup. The proposed algorithm is also expected to generate excellent outcomes at such frequency because of the excellent coverage and low interference in LTE-U, thereby making this algorithm highly reliable and efficient for HBC applications.

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# Achieved Data Rate of Cooperative MIMO in Measured Channels

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**Abstract** This paper evaluates the achieved data rate of a cooperative Multiple Input Multiple Output (MIMO) system in real measured channels. The achieved data is computed according to an iterative algorithm, which determines the linear transmit and receive beamforming filters that maximize the sum-rate. This method allows us to design the transmit filter with a simple algorithm. The Channel State Information (CSI) of all channels is assumed to be known at the transmitters, and cooperation between (BSs) in sharing the CSI is considered. MIMO channels in different scenarios were measured in a typical propagation environment using two BSs and four handsets, similar to smartphones, held by different users. Users were located at different distances from each other, and at different orientations with respect to each other. We computed the received data rate for four different groups of handsets at a fixed SNR of 15 dB. Using the algorithm, we investigated how the experimental and theoretical capacity is influenced by cross-correlation between the individual user linkages arising from one antenna at the BS, and by imbalance in the power of the different linkages. The system performs best when the handsets are separated by at least 1 m. Furthermore, both in theory and in practice, the algorithm is more sensitive to power imbalance rather than cross-correlation.

**Keywords** Cooperative BSs · Correlation · Branch power ratio · MMSE beamforming · Measured channels · Cooperative capacity

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## 1 Introduction

The ability of MIMO systems to provide continuous service to mobile users, and enhance the performance of systems such as Quality of Service (QoS), has attracted much research interest [1]. Among different limiting factors on the performance of the MIMO system [2], interference from MIMO base stations or mobile terminals is the main limitation to achieving the promised capacity of MIMO networks [3, 4]. The Cooperative Access Points (CAP) system was introduced to reduce intercell interference effects; its influence on the capacity of the cooperative MIMO has been discussed in [5].

Using CAP systems in wireless communication improves the quality (Bit-Error Rate or BER) and the maximum data rate (bits/s) of the communication. CAPs also allow for a direct gain in multiple access capacity, proportional to the number of access points. Moreover, they allow the spatial multiplexing gain at the BS to be obtained without the need for multiple antenna terminals [6, 7].

Beamforming for downlink multicell MIMO systems is a possible solution for the interference problem and may further improve the capacity and system performance of CAP technology [8–10]. Linear transmission techniques, because of their simplicity in comparison with non-linear ones, have attracted the most interest from researchers [11–14]. Minimum Mean Square Error (MMSE) beamforming is an optimal precoder for the case where the receive antennas outnumber the transmit antennas [15].

Among the different proposed algorithms, the Weighted sum-Minimum Mean Square Error (WMMSE) algorithm is of greater interest because of its simplicity and high performance, and also because it works on MIMO systems, while most proposed algorithms are for the MISO case. The WWMSE algorithm iterates between beamformers and MSE weights, converging to a local minimum after a few iterations. The initial value for the beamformer is a matched filter, which aids in the simplicity of the algorithms [16]. The well-known algorithm has been extended to cellular MIMO systems in [16], and the theoretical results have a good agreement with the proposed scenario. This allows us the use of this algorithm to analyze measured data arising from cellular MIMO systems.

On the other hand, studies on multiuser and cooperative MIMO systems in the real measured channels [17–19] have investigated the advantages of the cooperative MIMO case versus the non-cooperative case. These studies also discuss the how the CAP capacity is influenced by parameters such as correlation, delay, and fading in the measured channels. However, the studies did not address the difference in performance between the algorithms versus the ideal and measured channels.

The present study applies the extended algorithm to a cooperative multicell MIMO system in a real propagation environment. The algorithm automatically takes into account the effect of parameters such as fading, correlation, branch power ratio, different handsets and different distances, which are present in the real environment. We compare the performance of the algorithm using ideal and measured channels. While it is possible to manually generate correlated channels or imbalanced links and use them in the algorithm, to investigate the effect of the different parameters on its behavior, the advantage of using measured data is that it includes many other parameters, which would not be present in the manually-generated data. These parameters may include antenna-blocking effects from the user's body by different handset grips. By using experimental data, we can investigate whether such parameters affect the performance of the algorithm, and to what extent. The outcomes of this study could aid in designing better systems or proposing more efficient algorithms.

The main objectives of this investigation are:

1. Extending the algorithm to a cooperative base station scenario. By evaluating the extended algorithm using ideal and measured channels, we wish to answer the crucial question of how the WMMSE algorithm works in a real propagation environment, where the measured channels could either be very similar to the ideal channels, or differ by being correlated or not always following Rayleigh distributions. The present study thus provides a valuable link between the theory and real-world applications of these systems.
2. Influence of the separation distance between handsets. In the near and far scenario, we compare the data received from closer handsets (near case) to that received from further ones (far case). Comparing the two sets of data reveals whether correlations are present in the near case.
3. Introducing a power imbalance between channels in the near and far scenario. This experiment investigates whether a power imbalance affects the rate of data collection and/or transmission.

This paper is organized as follows. Section 2 describes the system model, describing the extended WMMSE algorithm and investigated scenarios in the simulated mode. Section 3 explaines the measurement setup considering different scenarios, users and handsets. Section 4 shows different steps of data analysis in terms of different normalizations. Section 5 demonstrates results and discusses different scenarios and effective parameters on the results and finally Sect. 6 concludes the paper.

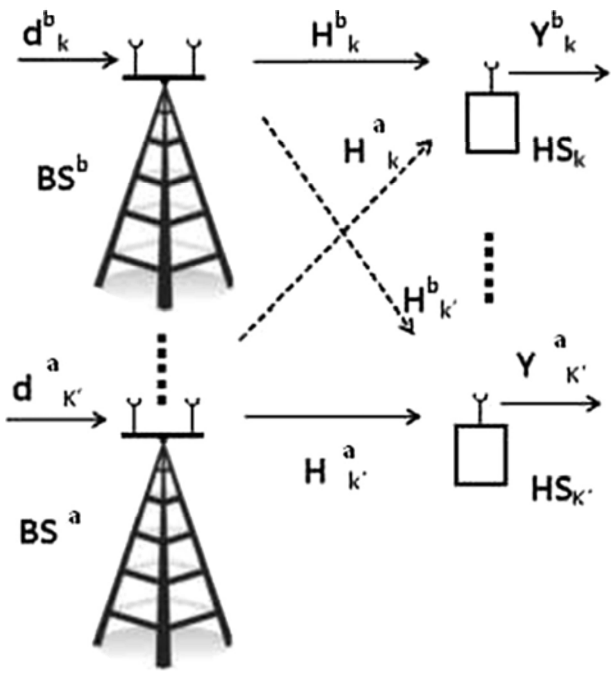


**Fig. 1** MIMO scenario

All of the measured results were obtained from a statistically significant number of measurements. The median and variance of different sets of data were plotted to provide a fair comparison between different scenarios. Henceforth in this manuscript, for simplicity we will refer to the capacity, instead of the data rate.

## 2 System Model

A multi-cell system with two cells, each with $K$ base stations and $K$ users, where each BS serves its user (one user) has been considered. Figure 1 shows the setup of this work. The formulation can be extended to more cells straight forward. Each base station has $M$ transmit antenna and each receiver has $N$ receive antennas. The channel matrix $\mathbf{H}_k^b \in \mathcal{C}^{[N\times M]}$ is the wireless channel between base station $k$ and user $k$ in cell $b$. And the channel matrix $\mathbf{H}_k^a \in \mathcal{C}^{[N\times M]}$ is the wireless channel between base station $k$ in cell $a$ (the second cell) and user $k$ in cell $a$. The transmitted signal from cell $b$ is shown as $X^b = \sum_{k=1}^{K} \mathbf{B}_k^b d_k^b = \mathbf{B}^b d^b$. In this equation $\mathbf{B}_k^b \in \mathcal{C}^{[M\times N]}$ is a precoder matrix for each base station and $\mathbf{B}^b = [\mathbf{B}_1^b, \ldots, \mathbf{B}_K^b] \in \mathcal{C}^{[M\times KN]}$ is all precoders of cell $b$. The number of data streams in the transmitter and the receiver equals $N$, when $N \leq M$. In addition $d_k^b$ is the complex vector of data streams by dimension of $d_k^b \in \mathcal{C}^{[N\times 1]}$ and $d^b = [d_1^b T, \ldots, d_K^b T]^T \in \mathcal{C}^{[KN\times 1]}$ is all data for all users in cell $b$, when $d^T$ denotes transpose of vector $d$. The same definition can be used for $\mathbf{B}_k^a$ and $d_k^a$ but for cell $a$, so the received signal at user $k$ in cell $b$ is:

$$Y_k^b = \mathbf{H}_k^b \mathbf{B}_k^b d_k^b + \mathbf{H}_k^b \sum_{i=1, i\neq k}^{K} \mathbf{B}_i^b d_i^b + \mathbf{H}_k^a \sum_{k=1}^{K} \mathbf{B}_k^a d_k^a + n_k^b \tag{1}$$

where $n_k^b \in \mathcal{C}^{[N\times 1]}$ is a standard circular white Gaussian noise vector with covariance $\mathbf{R}_{nknk} = \mathbb{E}[n_k n_k^H] = \mathbf{I}_N$, $n_k^H$ represents the conjugate transpose of $n_k$ and $\mathbb{E}[n_k n_k^H]$ is the expected value of $[n_k n_k^H]$. The first term in the Eq. 1 is desired signal for the user. The second term describes the intra-cell interference. Intra-cell interference is an undesired signal at user $k$ transmitted from one of the BSs inside the cell $b$, where user $k$ located in. The third part represents the inter-cell interference, which means user $k$ received an unwanted signal from a neighbor cell. The channel matrices are assumed constant for the duration of each block. Moreover the CSI is known in both transmitter and receiver side. In addition the assumption of $\mathbb{E}[d_k d_k^H] = \mathbf{I}_N$ is valid for our system. The transmit vectors obey the power constraint:

$$\mathbb{E}[X^{bH} X^b] = \sum_{k=1}^{K} \mathrm{Tr}(\mathbf{B}_k^b \mathbf{B}_k^{bH}) \leq E_{tx}^b \tag{2}$$

and $E_{tx}^b$ is the total transmit power for each base station in cell $b$ and $\mathrm{Tr}(\mathbf{B}_k^b \mathbf{B}_k^{bH})$ is the trace of the matrix.

The formulation of the WMMSE algorithm and different scenarios, which have been considered in the simulation analysis, will be described in the next steps.

## 2.1 WMMSE Algorithm

The WMMSE algorithm is to compute the transmit filter $\mathbf{B}^b$, which maximizes the sum of achievable rates of all users in cell $b$. The algorithm is based on the MMSE criterion, and establishes a relation between weighted sum-rate and weighted MMSE in the MIMO Broadcast Channel (BC) [16]. The algorithm was extended to the MIMO Interference Channel (IFC) in [20]. In this work we use the algorithm for the multi-cell cooperative MIMO, which is straight forward extension of the work in [16, 20].

For this case the achievable rate for user $k$ in cell $b$ is given as [16]:

$$R_k^b = \log\det\left(\mathbf{I}_k + \mathbf{B}_k^{bH}\mathbf{H}_k^{bH}\mathbf{R}_{v_kv_k}^{-1}\mathbf{H}_k^b\mathbf{B}_k^b\right) \tag{3}$$

where $\mathbf{R}_{v_kv_k}$ is the noise and interference covariance matrix at user $k$ and can be shown as:

$$\mathbf{R}_{v_kv_k} = \mathbf{I}_k + \sum_{i=1,i\neq k}^{K} \mathbf{H}_k^b\mathbf{B}_i^b\mathbf{B}_i^{bH}\mathbf{H}_k^{bH} + \mathbf{H}_k^a\mathbf{B}_k^a\mathbf{B}_k^{aH}\mathbf{H}_k^{aH} \tag{4}$$

which is the extension of the interference matrix from [16] with a new term at the end. The third term appears here due to inter-cell interference and will be added to the following equations as well.

Additionally the MMSE receive filter $\mathbf{A}_k^{b,MSE}$ at user $k$, which was shown in [16], is:

$$\mathbf{A}_k^{b,MSE} = \mathbf{B}_k^{bH}\mathbf{H}_k^{bH}\left(\mathbf{H}_k^b\mathbf{B}_k^b\mathbf{B}_k^{bH}\mathbf{H}_k^{bH} + \mathbf{R}_{v_kv_k}\right)^{-1} \tag{5}$$

The MMSE matrix for user $k$ after implementing the receive filter $\mathbf{A}_k^{b,MSE}$ is shown at [16] as:

$$\mathbf{E}_k^b = \left(\mathbf{I}_k + \mathbf{B}_k^{bH}\mathbf{H}_k^{bH}\mathbf{R}_{v_kv_k}^{-1}\mathbf{H}_k^b\mathbf{B}_k^b\right)^{-1} \tag{6}$$

Therefore the cost function for maximizing the WSR problem can be defined as:

$$\begin{aligned} &\arg\min_{\mathbf{B}_1^1,\ldots,\mathbf{B}_k^C} \sum_{k=1}^{K}\left(u_{R_k^b}\mathbf{R}_k^b + u_{R_k^a}\mathbf{R}_k^a\right) \\ &s.t. \quad \sum_{k=1}^{K}\mathrm{Tr}\left(\mathbf{B}_k^b\mathbf{B}_k^{bH}\right) = E_{tx}^b \forall b, \end{aligned} \tag{7}$$

The new term consists of $\mathbf{R}_k^a$ is added to the equation, which can be achieved from the same procedure like $\mathbf{R}_k^b$. The above optimization problem should be formulated in Lagrangian formula and the derivation of the function should be taken with respect to $\mathbf{B}_k^{b*}$ and $\mathbf{B}_k^{a*}$, while $\mathbf{B}_k^{a*}$ is the conjugate of $\mathbf{B}_k^a$. Afterwards this derivation should be compared to the derivation of the WMMSE problem, which is shown as below:

$$\begin{aligned} &\arg\min_{\mathbf{B}_1^1,\ldots,\mathbf{B}_k^{a,b}} \sum_{k=1}^{K} Tr\left(\mathbf{W}_k^b\mathbf{E}_k^b + \mathbf{W}_k^a\mathbf{E}_k^a\right) \\ &s.t. \quad \sum_{k=1}^{K}\mathrm{Tr}\left(\mathbf{B}_k^b\mathbf{B}_k^{bH}\right) = E_{tx}^b \forall b, \end{aligned} \tag{8}$$

when $\mathbf{W}_k^b \in \mathcal{C}^{[N\times N]}$ is the weight matrix corresponds to the user $k$ in cell $b$ and $\mathbf{W}_k^a$ is the same for cell $a$. Comparison between those gradients leads to find the equation to adjust MSE weights as:

$$\mathbf{W}_k^b = u_k^b \mathbf{E}_k^{b-1} \tag{9}$$

$$\mathbf{B}^b = (\mathbf{H}^{bH}\mathbf{A}^{bH}\mathbf{W}^b\mathbf{A}^b\mathbf{H}^b + \mathbf{H}^{aH}\mathbf{A}^{aH}\mathbf{W}^a\mathbf{A}^a\mathbf{H}^a + \lambda^b\mathbf{I})^{-1}\mathbf{H}^{bH}\mathbf{A}^{bH}\mathbf{W}^b \tag{10}$$

where $\mathbf{W}^b = \mathrm{diag}\{\mathbf{W}_1^b, \ldots, \mathbf{W}_K^b\}$ and $\mathbf{A}^b = \mathrm{diag}\{\mathbf{A}_1^b, \ldots, \mathbf{A}_K^b\}$ are block-diagonal matrices with blocks equal to the weight matrix and receive filter associated to each user respectively and $\mathbf{H}^b = [\mathbf{H}_1^{bT}, \ldots, \mathbf{H}_K^{bT}]^T$ contains all channel links from each base station to all users in the same cell. The lagrangian multiplier will be calculated by the method proposed in [21]. The second term in the parenthesis, which is new in this equation came from the inter-cell interference.

Finally as it has been described in [16] alternating between optimization of beamformers and the MSE weights until convergence to the fix point is applied. The iterating algorithm starts by initial value assumed for $\mathbf{B}_k^b$, and follows as below:

- The received filter and weight matrix $\mathbf{W}_k^b$ is computed based on initial assumption using Eqs. 5 and 9.
- $\mathbf{B}^b$ will be updated using calculated $\mathbf{A}_k^b$ and $\mathbf{W}_k^b$ in Eq. 10.

These two steps iterate until converge to the local minimum of the main problem.

### 2.2 Investigated Scenarios in Simulation Mode

For the purposes of simulation, we assumed that the channels are Independent and Identically Distributed (i.i.d) Rayleigh channels. The system was simplified to two cells, with each cell containing one BS and one user, while each BS has two transmit antennas and each user has one receive antenna. To investigate the behavior of the algorithm in more realistic scenarios, approximating the experimentally measured data, we tested several different assumptions in simulating the channels. Using channel models to generate correlated channels allows us to simulate the effect of correlation between channels [22].

We furthermore artificially generate an imbalance of power between the channels arising from each transmit antenna of the same BS, and those arising from the receive antenna, which is called Branch Power Ratio (BPR). The effect of the power imbalance on this particular algorithm will be discussed in the next section.

Equation 11 represents the definition of the BPR in this work:

$$BPR = \frac{\mathbb{E}[|h_{n,m}|^2]}{\mathbb{E}[|h_{n,\acute{m}}|^2]} \quad m \neq \acute{m}, \tag{11}$$

$h_{n,m}$ is the entry of the $\mathbf{H}_k^b$ or other links.

In addition, the difference in power of different links from each base station to each receiver called Link Power Ratio (LPR) and its effect on the capacity has been examined. LPR is defined as:

$$LPR = \frac{\mathbb{E}[\|\mathbf{H}_{k,i}^b\|^2]}{\mathbb{E}[\|\mathbf{H}_{k,\acute{i}}^b\|^2]} \quad i \neq \acute{i}, \tag{12}$$

$\mathbf{H}_{k,i}^{b}$ represents channel matrix from one BS to one user, when $k$ is the indices for different users and $i$ used for different BSs and $\|\mathbf{H}_{k,i}^{b}\|^2$ denotes Euclidean norm of $\mathbf{H}$. This equation is also valid for $\mathbf{H}_{k,i}^{a}$ in the second cell.

## 3 Measurement Setup

Measurement setup can be explained in three different categories such as measurement campaign details, handsets specifications and the chosen scenarios to be investigated in this work. More details about each category comes in the future steps.

### 3.1 Scenario and Setup

The measurements used in this work are described in [23]. Below a brief summary is given.

The measurement campaign was situated in an urban macro cellular environment in the center of the city of Aalborg, Denmark. The measurement scenario was designed to consider the cooperation between BSs. To fulfill this requirement, two base stations were installed at two different positions. The setup provides a compromise between high capacity and coverage because BS1 was assumed to provide high capacity channels, so it was located at 13 m height and 150 m away from the measurement area. BS2 was located at 500 m from the measurement building, but at a height of 60 m, to support more coverage in the cellular system. Each BS has four transmit antennas, two in the low band (LB) and two in the high band (HB) frequencies. Two bands were measured simultaneously. The (LB) and (HB) frequencies were centered at 776 and 2300 MHZ respectively. The two bands were chosen with respect to the Long Term Evolution (LTE) standard frequency bands. In this work we chose to investigate the HB frequencies.

The measurement setup was designed to closely resemble the transmission method that is applied in real situations, by measuring the transmission simultaneously from both base stations to four different users. Also, some measurements were repeated and analyzed to check the reliability of the measurement methods.

The measurement room was located on the third floor of the (AAU) building in the city center. The room has no windows toward any BS, which means (LOS) was blocked. In the room, four 1m by 1m squares were drawn on the floor. Users moved back and forth inside squares during the measurement time; this pattern of movement was called (LA). The measurement was performed with different handsets and users as follows.

### 3.2 Handsets and Users

Ten different handsets were designed and measured. Each handset had two antennas in the LB and two in the HB. Antennas were located in different positions in each handset. The present study focuses on only four of the handsets (H1, H2, H5 and H6), chosen because of the similarity in their antenna types. This selection is done to avoid artifacts arising from differences in the type of antennas.

Each handset was connected to the sounder via optical fiber, instead of coaxial cables, to prevent that the relatively small devices should be influenced by changes in the electromagnetic properties of the coaxial cables. This setup allows us to measure the handsets in a more realistic way, closer to their actual usage. The optical unit was designed to fit into a typical handset [24].

In addition, each handset was covered in a plastic frame, which resembles the outer casing of a mobile phone, to provide a more realistic scenario and prevent users from touching the Printed Circuit Boards (PCB) directly. More details about the handsets can be found in [23].

Moreover, eight different users were involved in this measurement to investigate the effects of different bodies on the receive antennas. Each handset was tested with different users and different grips. Different grips were applied by having the users either touch the antennas or hold the handsets in such a way that their fingers were far from the receive antennas. We thus measured how the different users and different grips influenced the performance of the system.

### 3.3 Investigated Scenario

To compute the capacity, we considered two BSs and two handsets at each measurement time. We selected two antennas at each BS and one single antenna per handset, all of which were working in narrow band at 2.3 GHz frequency. We assumed cooperation between BSs, meaning that the BSs shared channel knowledge and each BS could cancel out interference from the others.

Figure 2 illustrates the position and potential orientation of user movements. Each small square has dimensions of $1 \times 1\ \mathrm{m}^2$. Users moved randomly back and forth in each squares during each measurement. The orientation of the movements at each square differed from that of the movements at the other squares, as shown by the arrows from A through D in Fig. 3. During each measurement, each handset moved from one square to another, which changed the orientation of the handset with respect to the BSs.

The near and far scenarios were investigated to find the effect of correlation or interference on the capacity. In the near scenario, handsets are located at neighboring squares, and in the far scenario, the handsets are at opposite squares. For example in Fig. 3a, H6 and H1 are near to each other, but H6 and H2 are far from each other. The capacity of each pair

**Fig. 2** Measurement room

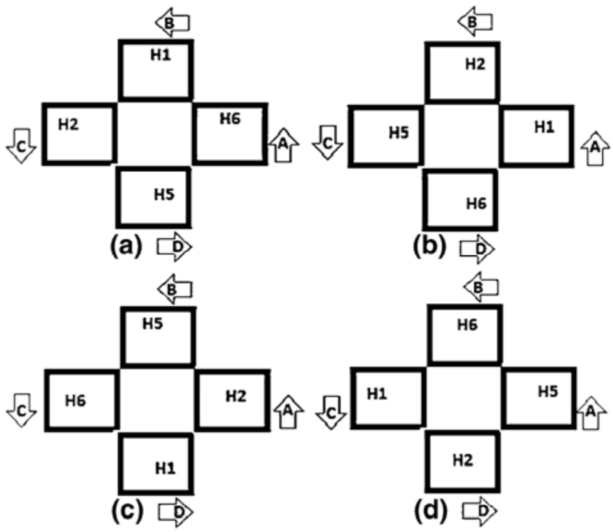


**Fig. 3** Near–far scenario

of handsets at each measurement time was examined and the results are discussed in Sect. 5.

## 4 Channel Normalization

There are different ways of normalizing the channel for different scenarios with respect to the different parameters we want to investigate in the capacity. In this section different normalization methods will be introduced.

### 4.1 Normalization to a Reference Handset

The difference between power levels from two base stations should be preserved. So the mean power received by the reference handset in all free space measurements from one base station is computed, in this normalization we can see the influence of:

1. Branch power ratio.
2. Correlation.
3. Different power levels from different base stations.
4. Effect of different handsets.
5. Fading information.

The equation for this normalization is:

$$h_{n,m}^{norm}(g) = \frac{h_{n,m}(g)}{\sqrt{\frac{1}{NMG}\sum_{n,m,g}|h_{n,m}^{ref}(g)|^2}} \tag{13}$$

where $M = 2$ is the number of transmit antennas, $N = 1$ is the number of receive antennas and $G = 1200$ is different samples in each measurement, when $g$ can be interpreted as the time index and $h_{n,m}$ is the channel coefficients from $n$th receive antenna to the $m$th transmit antenna and $h^{ref}_{n,m}(g)$ is the channels for the reference handset in free space.

### 4.2 Normalization to Each Individual Measurement

In this case, for each measurement, the power collected by receive antennas and all transmitters is averaged. The branch power ratio, correlation and fading information is preserved. However handset efficiency information and the difference due to the handsets, the relative body loss effect due to the users, are lost in the normalization [24].

$$h^{norm}_{n,m}(g) = \frac{h^{meas}_{n,m}(g)}{\sqrt{\frac{1}{NMG}\sum_{n,m,g}|h^{meas}_{n,m}(g)|^2}} \tag{14}$$

where $h^{meas}_{n,m}(g)$ represents the channels for each measurement.

### 4.3 Normalization to Each Individual Link

The normalization is applied to each channel link in each measurement. The reason of this kind of normalization is getting rid of the effect of the branch power ratio and see the effect of only correlation in the capacity. The normalization can be defined as:

$$h^{norm}_{n,m}(g) = \frac{h^{meas}_{n,m}(g)}{\sqrt{\frac{1}{G}\sum_{g}|h^{meas}_{n,m}(g)|^2}} \tag{15}$$

where each coefficient of the channel is divided by the square root of the mean power received by antenna $n$ from the corresponding transmitter antenna. The mean is taken over different 1200 positions.

## 5 Results and Discussion

Section 5 shows results from the WWMSE algorithm with both the simulated and the measured channels. The results from simulating the channels as i.i.d Rayleigh are shown first. The results using the measured channels are shown next, to compare the behavior of the algorithm when considering cooperation between BSs.

It should be noted that, in this work, the noise covariance at the receiver is normalized as follows: $\mathbf{R}_{n_k n_k} = \mathbf{I}_N$. The average energy of the desired channel $\mathbf{H}^b_k$ in Eq. 1 is $\sigma^{2des}_h$ and the average energy of the interference channel $\mathbf{H}^a_k$ in the same equation is $\sigma^{2int}_h$. The ratio of these two elements is assumed to be 0 dB in this work to investigate the behavior of the algorithm in its general case. The SNR is fixed to 15 dB when analyzing the measured channels.

### 5.1 Capacity of Simulated Scenarios

The achieved sum rate, or capacity, in different scenarios is investigated using Eq. 3. The results show the sensitivity of the algorithm to the different parameters, which helps to understand the performance of the algorithm with measured channels. Figure 4 shows the capacity of the ideal i.i.d channels in comparison with the correlated and power imbalanced

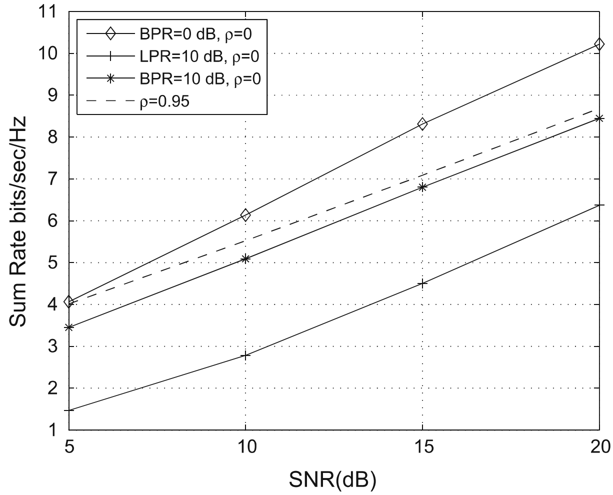


**Fig. 4** Capacity of simulated channels in different scenarios

channels. The effects of different parameters on the capacity, assuming i.i.d channels are shown as below.

### *5.1.1 Capacity of Correlated and Uncorrelated Channels*

In one scenario, a correlation coefficient of $\rho = 0.9$ between entries of all channels $\mathbf{H}$ in Fig. 1 is used. This means that each user receives data from the correlated channels, and all of the desired links and interference channels are correlated. This assumption yields insight into the behavior of the algorithm in the correlated channels, for comparison with the measured scenario.

As shown in Fig. 4 the achieved sum rate at $\mathrm{SNR} = 15\,\mathrm{dB}$ is 8.3 bits/s/Hz using channels with $\rho = 0$, while in the correlated case ($\rho = 0.9$), it is only 7 bits/s/Hz. This means that correlation reduces the capacity of the system by about 16 %. This reduction is consistent with previous observations, e.g. [25].

### *5.1.2 Capacity with Non-zero BPR*

The same figure shows the capacity in the simulation scenario when $\mathrm{BPR} = 0$ or 10 dB between links (Eq. 11). In this step, channels are uncorrelated and the BPR is the only alternating factor. The reduction of the capacity at $\mathrm{SNR} = 15\,\mathrm{dB}$ is about $18\,\%$ compared to the ideal case.

### *5.1.3 Capacity with Non-zero LPR*

The same comparison was performed in the case of changes in LPR with the WMMSE algorithm, where the desired link (between BS1 and user1) has less power than the interfering link [between BS2 and user1 (Eq. 12)]. In this case, if the difference in power between the desired link and the interfering link is >10 dB, the capacity decreases about $45\,\%$, which is shown in Fig. 4. This experiment investigates the sensitivity of the algorithm to the imbalanced links, which is useful for understanding differences in the values of the data rate obtained with measured channels.

### 5.2 Capacity of Measured Channels

Figure 5 presents the capacity of the channels obtained from measured data, using boxplots to investigate how the algorithm works in a real propagation environment. Channels are normalized to the reference handset using Eq. 13. The capacity for different pairs of handsets was computed, and the results include all grips, users, movements and orientations. Each box represents between 330 and 360 successful measurements. As can be seen in most cases, the experimentally achieved rate is less than that obtained with ideal channels, due to the effect of fading, correlation, antenna efficiency, BPR and other factors present in the real channels. The mean value over the median values achieved in Fig. 5 is 5.9 bits/s/Hz, which shows a reduction in capacity of around 29 % in comparison with the ideal channels, whose parameters are $\rho = 0$ and LPR $=$ BPR $= 0$ dB. The lowest values of the capacity were obtained with handsets 1 and 2, and the highest was obtained with handsets 5 and 6. The difference between the median capacity of these two pairs is around 1 bits/s/Hz. The reason for this variation is further explored by breaking each boxplot into different boxes which each represent different orientations, positions, and normalizations; the results are respectively shown in Figs. 7, 8 and 9 respectively.

### 5.3 Effect of Near–Far Scenarios on the Capacity

All measurement results (Figs. 6, 7, 8, 9) are presented as boxplots. In Fig. 6, which shows the effect of distance on capacity, every box represents 960 measurements of the near case and 480 different measurements of the far case. The average was computed over different grips and different users. Our expectation was that the closer handsets would achieve a

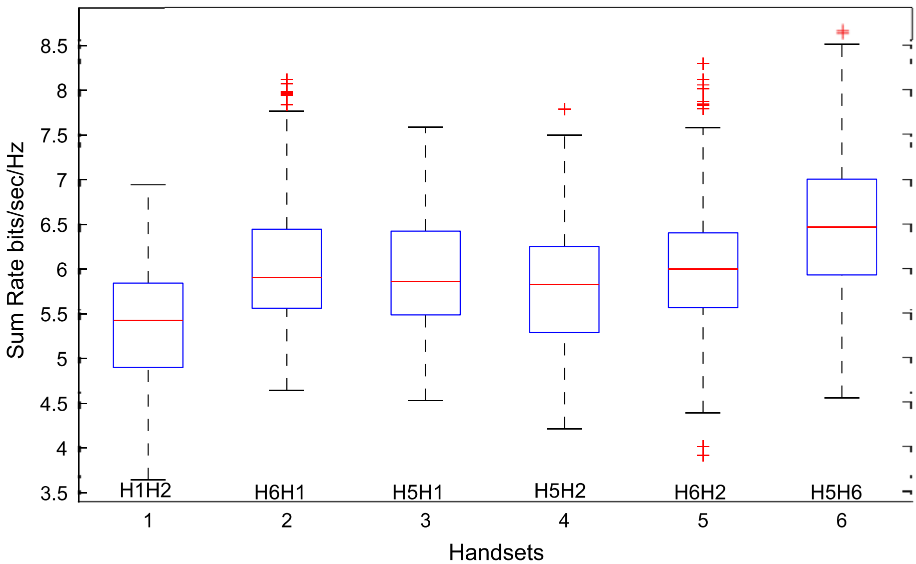


**Fig. 5** Capacity of measured channels

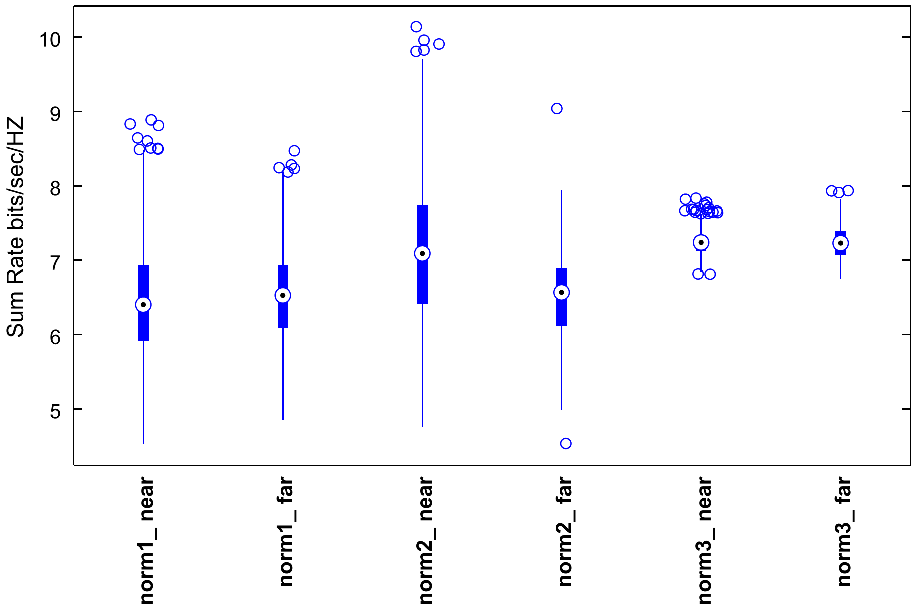


**Fig. 6** Capacity for all normalization in all near far scenarios

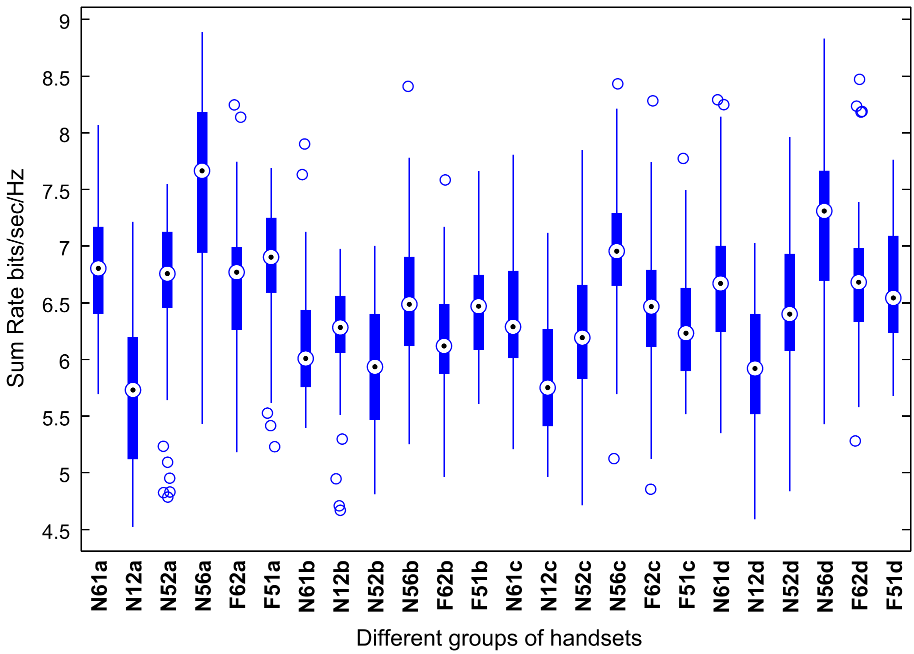


**Fig. 7** Capacity for free space normalization

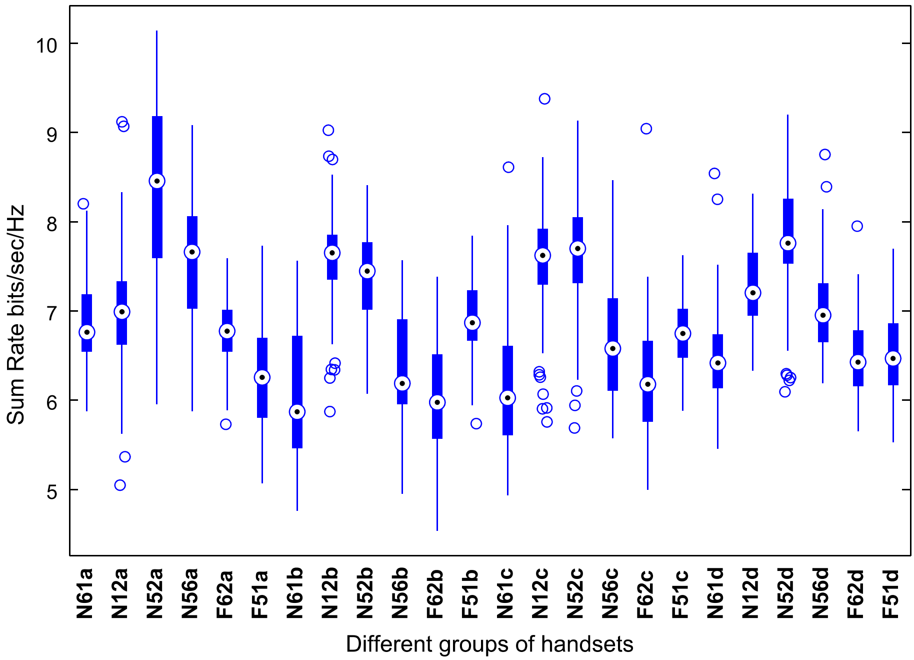


**Fig. 8** Capacity to each measurement normalization

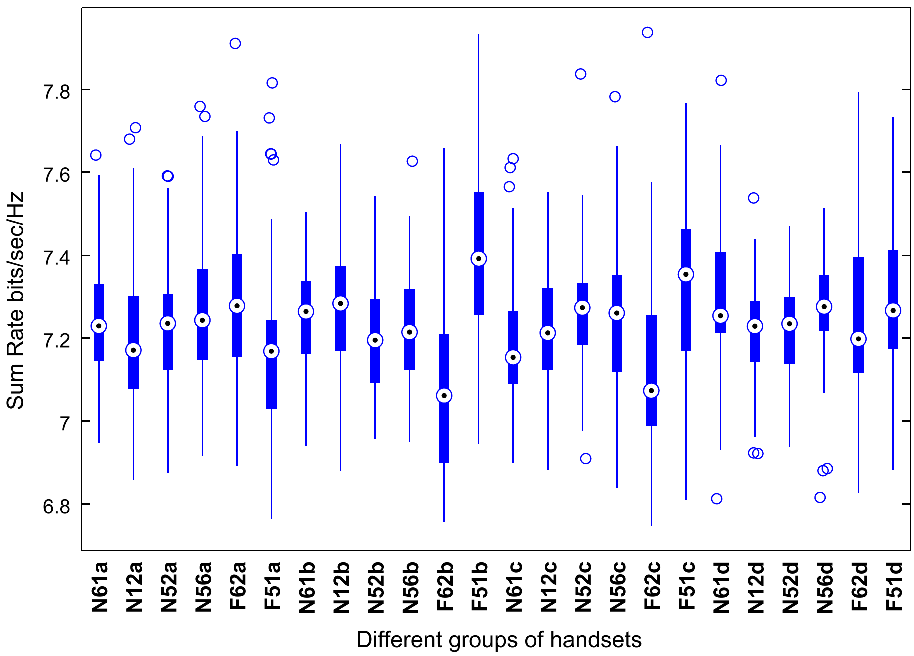


**Fig. 9** Capacity for link normalization

lower data rate due to interference between channels. However, the results from the measured channels do not follow this expectation. In the first normalization, which retains all the factors that could be detrimental, the capacity obtained in both the near and far scenarios achieves the same median and whisker tails. In the second normalization, when the effect of handset efficiency is eliminated, the median value of the near and far cases differs by around 0.5 bits/s/Hz, and the interval of the data also differs; this is contrary to our expectations. The third normalization maintains the effect of correlation, and the near and far cases result in almost the same values and behavior of the capacity. In comparison with other normalizations, this normalization produces less variation in the values of the capacities. The results shows how the BPR and handset efficiency affect the capacity, and suggest that when the effects of imbalanced channels and handset efficiencies are eliminated, the near and far cases achieve much more similar capacities compared to each other. Although the distance between handsets does not dramatically influence the capacity in general, we further investigated every pair of handsets to elucidate the factors that may contribute to differences in the achieved data rates.

## 5.4 Effect of Orientation on the Capacity

Figure 3 shows the results of measurement at different positions, where the handsets have different orientations with respect to the BSs. To elucidate the effect of the orientation, closer insight into the influence of the handset pairs is needed. Figures 7, 8 and 9 show the capacity of each pair of handsets in greater detail. Every boxplot includes 60 different measurements of the cooperative capacity for two handsets. using the WMMSE algorithm with different grips and different users. Different boxes are for different pairs of handsets; after six boxes, the pairs change their positions.

The X axis in all Figures can be explained as follows. N61 represents the pair of handsets H6 and H1, and similarly for other pairs, where N indicates the near scenario and F the far scenario. The second indices, from a to d, refer to the positions and orientations of handsets, shown in Fig. 3a–d, where the positions/ orientations of handsets are shown.

To investigate the effect of the orientation, we studied each pair of handsets individually. For example, handset 6 and handset 2 remained far from each other while moving between squares, which means their orientation towards each other remained constant. Our expectation in this case was that the capacities should vary throughout these movements, to a small extent; our observations support this expectation (check F62a–F62d in Figs. 7, 8, 9). Following other pairs of handsets in different normalizations leads to the same observation. Therefore, orientation towards different BSs can cause the capacity to vary.

## 5.5 Effect of Correlation on the Capacity

To check the correlation of the measured channels, the correlation was computed for entries of all channels $\mathbf{H}$ of Fig. 1 in a similar manner as was done for the simulations. In Fig. 10 each boxplot includes the mean of the absolute values of the correlation coefficients of all links, for each pair of handsets. As shown in Fig. 10, the median values of the correlations differ slightly from each other, and there also exist differences between the absolute values of the correlation coefficients. This also explains Fig. 9, when the correlation is the only factor remaining after normalization. As can be seen, correlation and capacity are directly related. Whenever correlation is high, capacity drops off, and vice versa. The relation between correlated channels and capacity can be seen in F62c, which has the highest median value of the correlation (Fig. 10) and the lowest median capacity

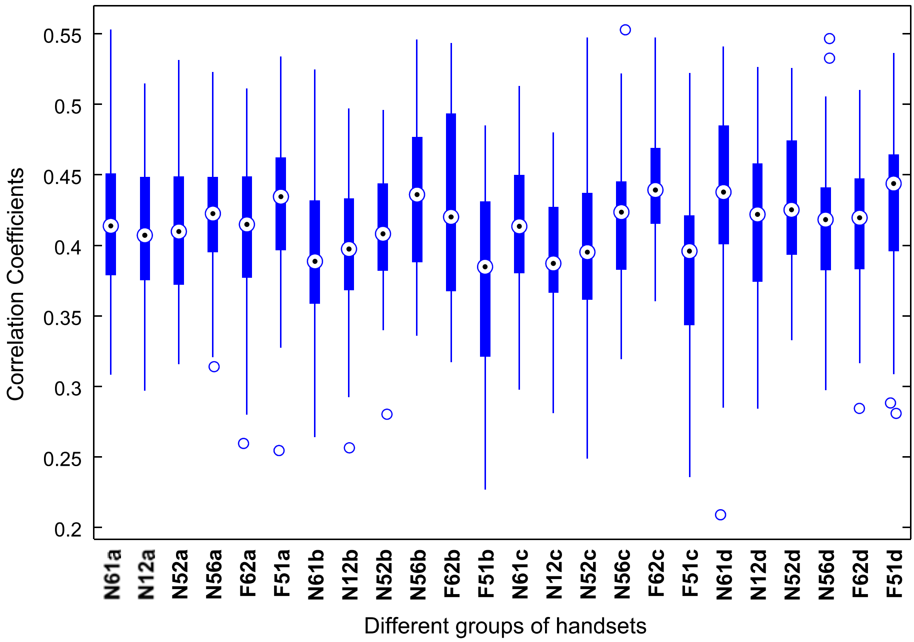


**Fig. 10** Correlation for each sets of handsets

(Fig. 9). However, it should be noted that the median value of the capacity does not vary greatly in the third normalization, where the difference between the highest and lowest median is only 0.4 bits/s/Hz), and the median values of the correlation are also not significantly different. Therefore, the variation in the capacities obtained by the first and second normalization cannot be caused by correlation. Because the algorithm is very sensitive to power level differences in the channels, the capacity could be affected to a greater extent by BPR, compared to correlation, as long as BPR is the only difference between the second and third normalizations.

## 5.6 Effect of BPR and Handset Efficiency on the Capacity

In the first and second normalizations, the handset capacity varies to a greater extent than in the third normalization (Figs. 7, 8, 9). BPR is included in the first and second normalization but excluded from the third. To investigate the effect of BPR on the capacity, the BPR for each handset was computed using Eq. 11. The scatter plot in Fig. 14 shows the mean value of the absolute BPR for each pair of handsets regarding the near and far cases, over the value of the capacity obtained by the second normalization using Fig. 11.

Although the BPR of different pairs of handsets varies widely, the BPR mostly remains between 4 and 8 dB. A direct relation between the capacity and the BPR was not evident in the plot. The results are in a good agreement with the simulation results from section A.2 of the paper, when the BPR of 10 dB causes changes of $<2$ dB in the capacity at SNR $= 15$ dB. Therefore, according to our observations from the measured results, if the BPR is up to 8 dB, the changes in the capacity should be even $<2$ dB. It can be concluded

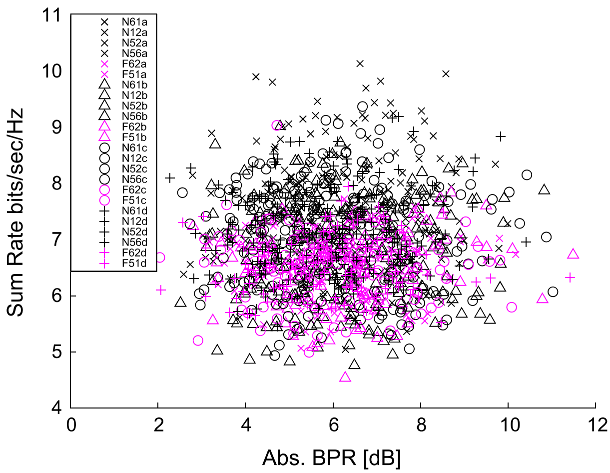


**Fig. 11** Scatter plot of median values of capacities from second normalization versus absolute BPR of different pairs of handsets

that the BPR has its own effect on the capacity in the different scenarios, but this effect is small because the BPR is small.

Further investigation shows that other factors contribute towards achieving a higher data rate, which can disguise the effect of distance, orientation and correlation. One of these factors is handset efficiency. In the first normalization, N56a–N56d has the highest mean capacity among all other handset combinations in the near scenario. Because we know that the distance, orientation and correlation do not play obvious roles in magnifying the capacity in our scenario, and that handset efficiency is the only difference between this pair and others, this result could be interpreted to indicate that the handset efficiency of this pair is higher than that of other pairs.

More details about handset efficiency are presented in the [26]. The (MEG) for each handset has been computed, and the results show H5 and H6 gain more power than H1 and H2. This also is shown in Fig. 5, while the H5H6 pair achieves a higher data rate than the H1H2 pair. Considering the median value, which is the measure of [26], there exists around a 3.5 dB difference between the worst and best case, which are MEG of the H1 and MEG of the H6, respectively.

## 6 Repeatability

The measure of comparison in this work is the cooperative capacity between two BSs and two HSs at each time point. In order to check the reliability of the measurement, it is important to investigate the reproducibility of the measurements in the same combination. Measurements were taken without any users holding the handsets, where the surroundings of the handsets were free from factors that could degrade the capacity. H6 and H5 were chosen to check the capacity. Around 72 % of 18 separate measurements varied from the mean value by <0.1 bits/s/Hz. Of these, 5 % were considered to be errors in data, which differed from the mean value by more than 1 bits/s/Hz. However, the errors could be due to noise in the measurement or changes in the measurement environment. In general, we can conclude that in most cases the measurements have a high degree of accuracy and few errors.

## 7 Conclusion

In conclusion, this study measured the capacity of different systems to determine how this capacity was influenced by cooperation, where two BSs can cooperate to send signals to users, and where the CSI is shared between BSs. To find the capacity, the well known WMMSE algorithm was extended to the multi-cell scenario and implemented in MATLAB. The channels were simulated in several different ways to approximate the real scenario. The capacity obtained by the algorithm is more sensitive to the correlation than to the BPR.

The capacity for the measured data was plotted with three different normalization methods. The first normalization yielded a 29 % lower capacity for the measured channels in comparison with the ideal channels. These differences can be explained by parameters such as correlation, distance between handsets, power imbalance, handset efficiency, and different orientations of handsets with respect to BS, all of which can be present in real situations and can negatively affect the capacity.

This paper also addresses how the distance and orientation of the handsets influences the capacity. We found that large distances between handsets do not necessarily result in lower data achievement, as long as the handsets have high efficiency and are positioned in a suitable orientation towards base stations. Finally, the reproducibility of the measurement was investigated; we found that more than 70 % of the measurements were reliable.

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*Research Article*

# On the Effect of Different Grips of Handsets on Data Rate in the Measured Channels

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The investigation on the achieved data rate of the cellular system considering different grips of handsets at different frequencies using measurement results of the measurement campaign—which was carried out in the city of Aalborg—is presented in this paper. The achieved data rate of the multiple-input single-output (MISO) interference channel is investigated. A typical propagation environment using two BSs and four handsets, like smart phones, held by four to eight different users was designed and multiple-input multiple-output (MIMO) channels in different scenarios were measured. In this paper, two BSs and two handsets at each measurement time are considered. The impact of the different parameters like correlation, different grips of handsets, and different long term evolution (LTE) frequency bands on the achieved data rate is investigated for different measurements. It could be concluded that the variations in the values of data rate are weakly associated with the different grips of handsets but more correlated with different frequencies.

## 1. Introduction

Cellular MIMO systems attract the interest of researchers due to providing continuous services to mobile users, enhancing system performance, and gaining higher data rate at the receiver [1]. The main limitation in achieving the promised capacity in the network MIMO is caused by interference from their own base stations or mobile terminals [2, 3]. Due to that limitation research on interference channels become a vital issue [4, 5].

To improve the capacity and system performance of cellular networks, beamforming for downlink multicell MIMO systems has been proposed as one of the most promising techniques to solve the interference problem [6–9]. Linear transmission techniques because of their simplicity in comparison with nonlinear ones have attracted the most interest from researchers [10–13]. Among different proposed algorithms, the VSINR algorithm has been chosen in this work to analyze the measured data due to the simplicity and high performance of the algorithm. The performance of the algorithm is validated with the real propagation environment, while measured channels are used. VSINR maximization algorithm proposed by [14] adapts the weight coefficients to the original VSINR proposed scheme [15] to achieve a desired weighted sum-rate maximizing point. The updated VSINR algorithm proposed by [14] is used in this work.

After implementing the proper algorithm to analyze the measured channels, different parameters and their effects on the achieved data rate are investigated in this work. The measurement was done at two different frequencies (776 and 2300 MHz) simultaneously with regard to the LTE standard. Different scenarios with respect to the low and high band were investigated to compare the performance of the system. This was done to find an answer to this important question about which frequency promises more data rate in the measured channels, which is a novel work in this field to the knowledge of the author.

On the other hand, many different scenarios have been considered in the measurement campaign. One of them is the investigation on the influence of different grips on the achieved data rate. Eight different users held the handsets during measurements. The users were instructed to hold the handsets with the predefined grips and walk forward and backward inside a square which is drawn on the floor. The effect of different grips in MIMO case has been studied for previous measurement campaign [16, 17]. In this work more grips added to the measurement scenarios and the effect of them on the performance of the algorithm will be discussed in the cellular network systems.

The last parameter which is investigated in this work is cross correlation between different links from the base stations to the users. The designed system works as each BS serves its user, so signals received by the second user are assumed as the interference. To investigate whether cross correlation between channels has any effect on the achieved data rate, the cross correlation between all links from each BS to each user is computed, which is called correlation for desired links, the same procedure is applied for the links from each BS to the second user and the correlation is called interference correlation. The effect of these values on the behavior of the algorithm will be shown in this work. This investigation is a new look through the effect of the correlation on the data rate, although there have been some studies on the effect of the correlation on the capacity of MIMO in previous measurement campaigns [18–20]. It should be noted that the effect of the other parameters such as fading, branch power ratio, different handset efficiencies, and different distances to the base stations is taken into account automatically, when the real environment is considered. These effects degrade the performance of the algorithm from simulation to the measurement. But the main focus of this paper is the investigation of the different grips, correlation, and different frequencies.

All results from measured data will be shown statistically utilizing a great amount of data. The median and variance of different sets of data have been plotted to have a fair comparison between different scenarios. Also from now on, we use the word "capacity" instead of achieved data rate for its simplicity.

## 2. Measurement Setup

*2.1. Scenario and Setup.* The measurements used in this work are described in [21] and a brief summary is given below.

The measurement campaign is situated in an urban macrocellular environment in the center of the city of Aalborg, Denmark. The measurement scenario has been designed to consider the cooperation between BSs. To fulfill this requirement, two base stations were installed at two different positions. The compromise of both high capacity and coverage has been provided in the setup because BS1 was assumed to provide high capacity channels, so it was located at 13 m height and 150 m away from the measurement area. BS2 was located at 500 m from the measurement building but at the height of 60 m to support more coverage in the cellular system. Each BS has four transmit antennas, two at low band and two at high band frequency based on LTE standards. Figure 1 shows the locations of the base stations. Two bands were measured simultaneously. An effective sounding bandwidth of about 5 MHz was used at the center frequency of 776 MHz. This band is subsequently referred to as the low band (LB). The high band (HB) was centered at 2300 MHz where an effective sounding bandwidth of about 100 MHz was used. The two bands were chosen to resemble the LTE bands in the 700–800 MHz and 2.3–2.6 GHz ranges, respectively. In practice, both the center frequencies and the bandwidths are compromises given the available equipment and unused frequency spectrum, resulting in the unequal bandwidths. In this work we chose both frequencies to investigate the performance of the algorithm at different frequencies.

Table 1: Handsets and antennas overview.

| Handset | Antenna number | Antenna location |
|---|---|---|
| H1 PDA | 1 | Top-center |
| | 2 | Bottom-center |
| H2 PDA | 1 | Top-right |
| | 2 | Bottom-right |
| H5 PDA | 1 | Top-right |
| | 2 | Top-left |
| H6 PDA | 1 | Top-right |
| | 2 | Top-center |

The measurement setup is very close to the transmission method, which will be applied in practice, since transmission has been measured simultaneously from both base stations to four different users.

The measurement room is located on the third floor of the Aalborg university (AAU) building in the city center. The room has no windows toward any BS, which means line of sight (LOS) was blocked. In the room, four 1 m by 1 m squares were drawn on the floor. Users moved back and forth inside squares during the measurement time. This pattern of movement is called local average (LA). The measurement was done with different handsets and users, which will be described in the next part.

*2.2. Handsets and Users.* Ten different handsets were designed and measured in this campaign. In this work we focus on four of them (H1, H2, H5, and H6). Table 1 gives an overview of the antenna types and locations of the antennas at different handsets for reference. All handsets have a size of 59 × 11 mm. All antenna types are mono and all handsets have antennas at low and high band. This group of handsets was chosen because they have similar types of antennas. This selection is done to avoid any unwanted differences in the results, which could be caused by the differences in the type of antennas. Each handset has two antennas in LB and HB. Antennas were located in different positions in different handsets.

Each handset was connected to the sounder via optical fiber instead of coaxial cables to avoid the effect of changes in the electromagnetic properties on small devices. This solution helps to measure the handsets in a more natural and realistic way. The optical unit was designed to be small enough to fit into a typical handset [19].

In addition, each handset was covered in a plastic frame, which is close to the material of mobile phones for a more realistic scenario and avoiding users to touch printed circuit boards (PCB) directly. More details about the handsets could be found in [21].

Five different grips were used in this measurement. In each case, the users placed their fingers in predefined

(a) (b)

Figure 1: Positions of base stations (a) BS2, (b) BS1.

markings on the handsets and held the handset in front of the body at an angle of about 45°. Five different grips of handsets are considered: portrait mode right hand only (phr); portrait mode two hands (pth); landscape mode, right tilt, right hand only (lphr); landscape mode, right tilt, left hand only (lrhl); landscape mode, right tilt, two hands (lrth). The grips are shown in Figure 2. Moreover, eight different users were involved in this measurement to investigate the effects of different bodies on the receive antennas. Each handset was tested by different users and different grips. Different grips were studied to measure each handset. This involved users touching antennas or holding the handset in a certain way, so that their fingers were far from the receive antennas. In this work we included the effect of different grips on the performance of the system.


Figure 2: Different grips of handsets.

*2.3. Investigated Scenario.* Two BSs and two handsets at each measurement time were considered to compute the capacity. Two antennas at each base station and one single antenna per each handset were selected, which all were working in narrow band at 2.3 GHz and 776 MHz frequency. Figure 3 illustrates the investigated scenario in this work. The BSs shared the channel knowledge and they canceled the interference from the other BS.

Figure 4 illustrates the position and potential orientation of movements of the users. Each small square has the dimension of $1 \times 1\ \mathrm{m}^2$. Users moved randomly back and forth in the squares during each measurement.

## 3. Data Analysis

In this section different steps for analyzing the measured data and the normalization method will be introduced.

*3.1. Channel Normalization.* There are different ways of normalizing the channel for different scenarios with respect to the different parameters, which we want to investigate in the capacity.

In this work, the difference between power levels from two base stations should be preserved. So the received mean power by the reference handset (H6) in all free space measurements from one base station is computed, in this normalization, we can see the influence of the following:

(1) branch power ratio,

(2) correlation,

(3) different power levels from different base stations,

(4) effect of different handsets,

(5) fading information.

The equation for this normalization is as follows:

$$h_{n,m}^{\mathrm{norm}}(g) = \frac{h_{n,m}(g)}{\sqrt{(1/NMG)\sum_{n,m,g} h_{n,m}^{\mathrm{ref}}(g)^2}}, \tag{1}$$

where $M = 2$ is the number of transmit antennas, $N = 1$ is the number of receive antennas, and $G = 1200$ is different samples in each measurement, when $g$ can be interpreted as the time index and $h_{n,m}$ are the channel coefficients from $n$th receive antenna to the $m$th transmit antenna and $h_{n,m}^{\mathrm{ref}}(g)$ are the channels for the reference handset in free space.

*3.2. Correlation.* To investigate the effect of correlation on the capacity, correlation coefficients between links from the measurement data are computed. The correlation is computed between desired links and interference links separately. Desired links mean direct links from each BS towards its user,

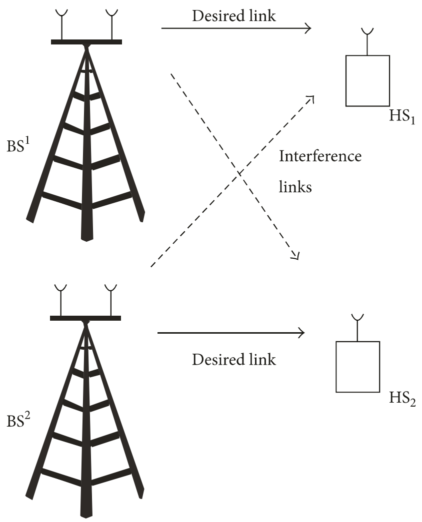


FIGURE 3: Investigated scenario.

FIGURE 4: Measurement room.

like BS1 serves user 1. Interference links are channels from each BS to the other user (BS1 to user 2 and vice versa). The links are shown in Figure 3. The correlation coefficients are calculated using the Pearson correlation coefficient equation as defined in [22].

*3.3. VSINR Algorithm.* The VSINR algorithm works for $K$ users and $K$ base stations scenario. But in this work, two users and two BSs are assumed for the simulation, with two transmit and one receive antenna for each. In the VSINR algorithm, nonweighted coefficients are assumed and the average WSR was computed. The results presented in [14] included weighted coefficients. It means that the VSINR algorithm used in this work was implemented for the reduced version of the original one and could have even better performance if we use the same assumptions as the reference. For example, using weight coefficients of $[3 \quad 1]$ leads to achieve data rate at SNR = 15 dB around 19 bits/sec/Hz [14], but it is 9 bits/sec/Hz in our assumption. The reason of having this assumption is for investigating the lower bound of the VSINR algorithm with the measured data. It is clear that having the same results as it is shown in [14] is straightforward.

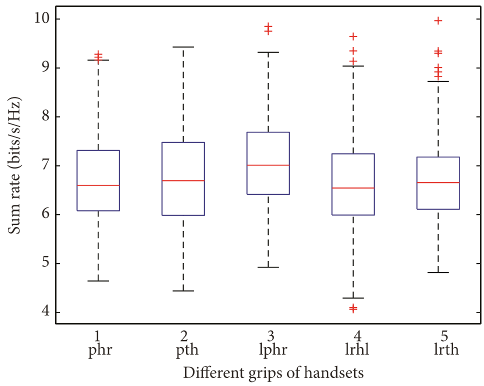


FIGURE 5: Capacity of different grips at high band.

## 4. Results and Discussion

*4.1. Capacity of Different Grips of the Measured Data Using VSINR Algorithm.* In all measurements the SNR is fixed to 15 dB. The achieved sum rate or capacity of different grips of HSs is computed and presented in this section using VSINR algorithm at low and high bands. The results show the sensitivity of the algorithm to the different grips and the investigation helps to understand the performance of the algorithm with the measured channels, as well as the behavior of the algorithm at different frequencies.

Figure 5 shows the capacity of different grips at high band frequency. Each box plot in the graph is plotted over a range between 403 and 420 different values based on successful measurements for each grip. As it is shown, the results have almost the same variations. The median of lphr is the highest among all of them and phr and lrth gained the lowest values. The difference between the highest and the lowest value is around 0.4 bits/sec/Hz.

Figure 6 presents the same results but at low band frequency. The same trends could be found in the capacities of different grips. The lphr and lrth have the highest median value of 8.6 bits/sec/Hz and the rest gained the lowest value of 8.3 bits/sec/Hz. It shows different frequencies do not have significant effect on the capacity of different grips. But in general the mean of the medians at low frequency is around 1.7 bits/sec/Hz higher than the mean of the medians at high frequency. More investigation on other parameters like correlation could explain these differences.

*4.2. Effect of Correlation on the Capacity.* The correlation is plotted for desired links and interference links as mentioned before at both frequencies. Based on our setup, each desired or interference link has two entries, which are channels from

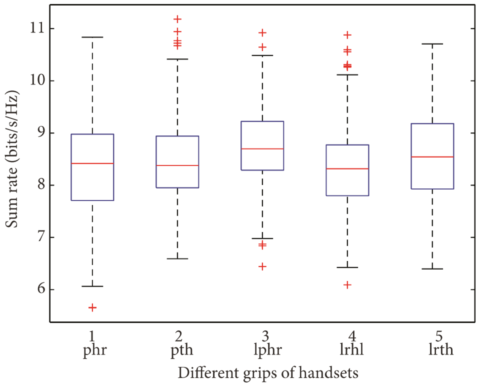


FIGURE 6: Capacity of different grips at low band.

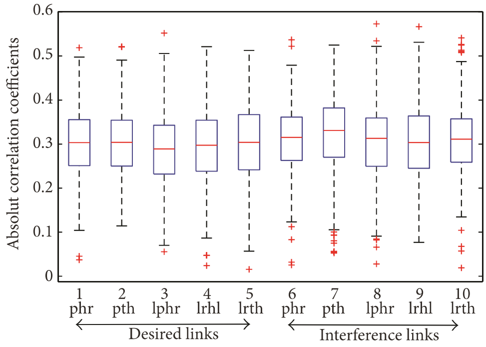


FIGURE 8: Correlation coefficients for different grips at low band.

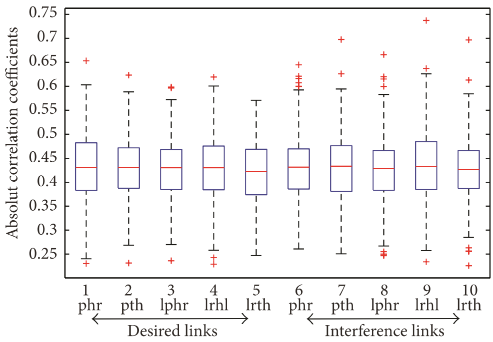


FIGURE 7: Correlation coefficients for different grips at high band.

each antenna at the user towards each antenna at each BS. The correlation coefficients between channels from each BS towards each HS are computed first. The mean of values has been calculated and assumed as the correlation for the desired link. The same procedure has been done for interference links, this time for the links from BS1 towards HS2 and vice versa.

Considering correlation for each of the grips, which are shown in Figures 7 and 8 for high and low band, respectively, there are no obvious differences in the median values. The results have good agreement with observations from Figures 5 and 6, while there were not significant differences in the median values of the capacities in terms of different grips. However, by comparing low and high band, we can see low band has lower correlation around 0.1 than high band based on the mean of median values, although in total, channels are not very correlated. On the other hand, the absolute values of the correlations have a wide variation, which affect the capacity individually. To investigate the relation between correlation and capacity, the scatter plot is presented.

Figures 9 and 10 show the scatter plots for correlation versus capacity for desired and interference links, respectively, in terms of different grips at high band. From the plots it is evident that desired links have wider distribution in correlation than in interference links. However, at both figures, the solid pattern of changes in the capacity with regard to the correlation cannot be found.

The same investigation is done for low band. Figures 11 and 12 show the results. The distribution of the correlation is the same for desired and interference links and again, strong links between changes in the correlation with regard to capacity could not be seen. Comparison of these four figures illustrates a wider range of correlation in LB than HB. As can be seen at LB, correlation varies from 0 to 0.5 with most aggregation around 0.4. At HB, the variation is from 0.2 to 0.7, with most of the values placed at 0.45. To present a more solid conclusion, Figure 13 is presented.

Figure 13 shows the scatter plots for correlation versus capacity for HB and LB in desired and interference links. The effect of each grip is not shown in these results. A pattern can be seen that capacity decreases dramatically with an increase in correlation. Regardless of desired or interference links, low bands (yellow and blue stars) have lower correlation and higher capacity, which can explain the differences of capacities in Figures 5 and 6.

*4.3. Repeatability.* The measure of comparison in this work is cooperative capacity between two BSs and two HSs at each time. In order to check the reliability of the measurement, it is important to investigate the repeatability of the measurements in the same combination. In this measurement the repeated data is available for free space, which means there is no user to hold the handsets. H6 and H5 are chosen to check the capacity. In 18 different measurements, around 72% of them have a difference to the mean value of less than 0.1 bits/sec/Hz. And 5% of them considered as error in the measurement, because they have a difference to the mean value of more than 1 bits/sec/Hz. However, the errors were attributed to noise in the measurement or some changes in the measurement environment. In general, we can conclude

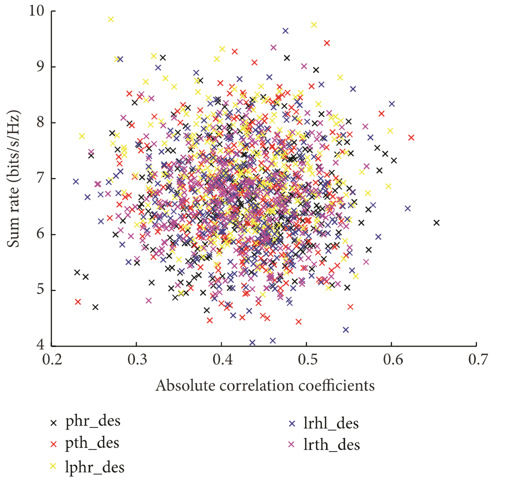


FIGURE 9: Scatter plot: capacity versus correlation for desired links at high band.

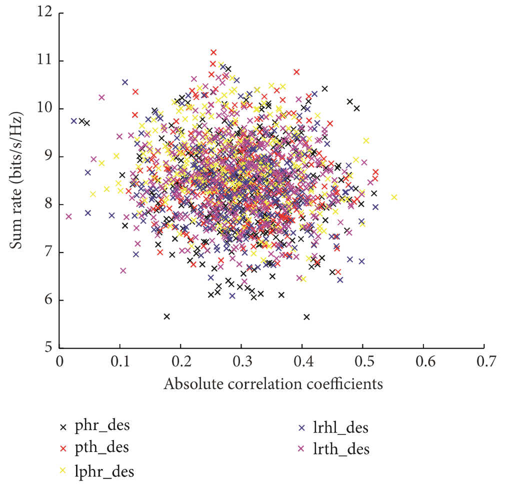


FIGURE 11: Scatter plot: capacity versus correlation for desired links at low band.

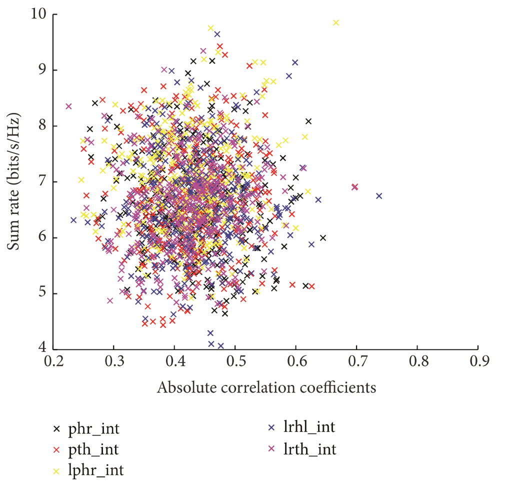


FIGURE 10: Scatter plot: capacity versus correlation for interference links at high band.

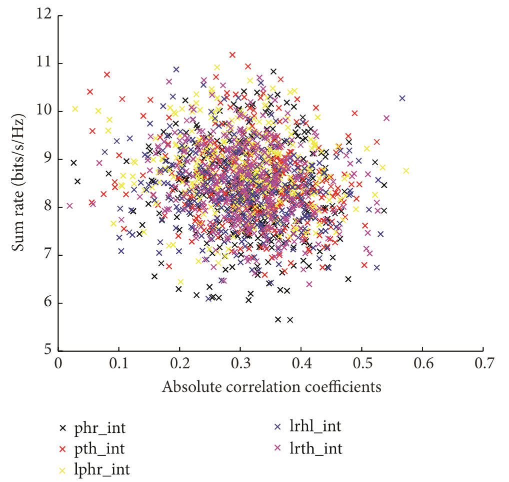


FIGURE 12: Scatter plot: capacity versus correlation for interference links at low band.

that the most cases are error-free and that the measurement was very accurate.

## 5. Conclusion

This work analyzed the results from a recent measurement campaign which was carried out in May 2011 in central Aalborg city. The main focus of the work was the capacity of the interference channels. To find the capacity, the VSINR algorithm was implemented in MATLAB using measured channels.

The behavior of the algorithm in different frequencies with measured channels was investigated in this work. The results show the following.

(1) The highest capacity was achieved in low band (the median is 8.6 bits/sec/Hz).

(2) The algorithm was not very sensitive to the different grips of handsets.

(3) Overall channels are more correlated at high band, although the difference between low and high band

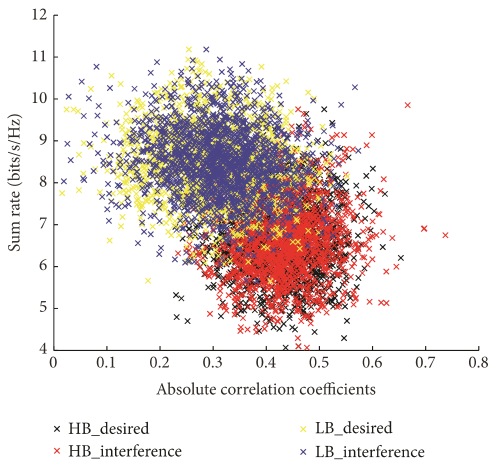


Figure 13: Scatter plot: capacity versus correlation for desired and interference links at low and high band.

is not very significant (around 0.1). These differences cause higher capacity at low band.

It should be noted that, as long as signals at low band have better penetration (meaning they pass through objects such as walls with less attenuation), they can lead to a higher data rate in inside environments, where our measurement was done. In [23] same analysis has been studied. The penetration loss is computed for high and low band for indoor scenario, which is very close to the presented scenario in this work. The results also confirm that low band signals have better penetration and they can pass through objects better than high band signals. The important highlight of this work is that working at low band leads to a higher data rate in addition to other advantages like better coverage, more penetration, and lower price to establish setup.

## Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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# CONASENSE as a Platform for the implementation of Human Bond Communication

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**Abstract**—This paper focuses on developing solutions for implementing the well-known concept of human bond communication (HBC) based on the comprehensive platform called CONASENSE (denoting communications, sensing, navigation, and services). The CONASENSE provides a platform for integrating the academia, industries, and researchers to create a long-term vision for the convergence of communication at a level that is more enhanced than that of current communication. This work mainly aims to define protocols, standards, and business models for the future of wireless communication beyond 2050 and beyond 5G. The main goal of this solution is to connect each person through all of his/her senses (HBC) in every activity (from agricultural and environmental to telehealth and remote navigation) via a reliable, fast, well-constructed wireless network. The requirements to reach this goal are high data rates, ubiquitous connectivity, and global networking. CONASENSE is a platform for addressing these challenges to realize the goal of HBC.

## 1 Introduction

The concept of human bond communication (HBC) was proposed by [1]. Owing to HBC, the five senses, namely, optic, auditory, olfactory, gustatory, and tactile, can be transmitted via wireless communication technology. HBC is a comprehensive approach of describing and transmitting the features of a subject in the way humans perceive them. The HBC concept covers several steps from sampling the physical subject, interpreting the sample into five sense domains, transforming these domains into a dataset, and using a compatible communication medium for transmitting the information to recovering the information at the receiving side. Predictions indicate that the end goal of HBC will be fully achieved by 2050, considering that several groups and institutes are currently working on different aspects of the concept [2].

Extensive research has been conducted on the vision and core technical enablers of the HBC paradigm. Several recent studies were discussed in [3]. In [4], the contributions of 3D optical vision, thermal vision, acoustic profiling, olfaction, and tactile sensing to remote inspection were discussed. Analytical solutions were also investigated. The authors proposed the use of a robot-mounted opto-thermal acoustic sensing system as a possible integrated system to gather data; this system could be the first step in HBC technology development.

Several investigations have also been conducted on the standards of future wireless systems to support the HBC architecture [5]. Management of security and privacy issues was also discussed in these studies.

One of the challenges in the HBC transmission is that olfactory, gustatory and tactile senses in contrast of optic and auditory are not wave based sensing and could not be analyzed based on wave properties. The transmission for these three senses needs more complicated solutions such as taking samples of material particles of the subject to be properly smeared along the neuron receptors for it to be accurately analyzed. Another method could be brain- to- machine transmission, which is developing rapidly recently.

Moreover, there have been some proposals and solutions for transmitting some senses such as touching [6]. the method is called Huggy Pajama and is a wearable system that provides physical interaction in remote communication. The product helps to reproduce the sense of touch and hugs between people. The system works by sensing the pressure variation by the module, digitize it and transmit this information via the Internet.

There is also another solution introduced for smell transmission by sampling and transmitting different aroma via phone. The system works like “A custom-made app allows you to take a photo of something and “tag” it with a few aroma notes (from more than 3,000 scents). These smells — which range in category from “Paris

Afternoon" to "Plantation" — are transferred via a pipe-like smelling station called an oPhone Duo and are controlled by a phone application" [7].

It should be mentioned, that any of these solutions could be developed and optimized to use for HBC transmission, it is obvious that more investigations and researches are also needed for more novel solutions of data sampling and transmitting.

The HBC system can be used in several applications, such as utilizing knowledge to assist handicapped people in any stage of the HBC system from sensing to transmitting data. Telemedicine and personal healthcare [8], dental and biological implant prosthesis for early warning performance [9], multi-business model innovation for future wireless technology as a platform for HBC technology [10], and the impact of network neutrality on futuristic innovation, particularly on HBC [11], are notable applications of HBC at present.

Achieving the final stage of transmitting all five senses demands a new definition in wireless communication technology in terms of architecture, security, mobility business model, and application services. The current work discusses how CONASENSE (denoting communications, sensing, navigation, and services) can provide a proper platform from the physical layer to the application layer and to support the idea of HBC. CONASENSE not only offers technical requirements for the future of wireless communication but also provides essential paths and solutions to reach the goal [12]. CONASENSE involves a wide range of novel converged services, applications, technologies, and business models.

The rest of this paper is organized as follows. Section II describes HBC, the requirements of different layers, and the design considerations and proposed architecture of this system. Section III introduces the CONASENSE platform for the HBC concept. Section IV presents the conclusions and proposed directions for future work.

## 2 HBC

As a holistic approach, the human bond communication (HBC) describes and transmits the features of a subject from the human perspective. This approach involves using the five senses in characterizing a physical subject into the information domain and actuating and transmitting the obtained information through a communication platform. This platform allows a physical subject to be understood by two HBC users who mutually agree in the way the subject is observed by individual users separately.

To successfully transmit human bond information through a communication medium, a system should be able to

- sample a physical subject,
- interpret such subject through the five human senses,
- transform the obtained information into a dataset,
- securely encapsulate the dataset by adding encryption and other security add-ons,
- compress the dataset for transmission through a highly efficient communication system,
- transmit the dataset through an appropriate communication medium, and
- obtain the transmitted information at the receiving side.

## 2.1 HBC Architecture

The architecture of HBC makes it superior to existing communication systems. Figure 1 shows the components of HBC, namely, (1) sense transducers or senducers that convert stimuli into electrical signals for further processing, (2) a human bond sensorium (HBS) that receives and converts the signals from senducers to make them perceivable by humans, and (3) a human perceivable transposer (HPT).

### 2.1.1 Senducers

Senducers function similar to the human senses and characterizes a subject from the perspective of the human sensory domain. This device takes the form of a capsule or shell and contains the following elements.

- Sensing transducers, which interpret a physical such subject through the five human senses
- Intelligence systems to enhance the sensing process and make the subject perceivable
- Radios for transmitting data between HBS and senducers through a communication link

Senducers exhibit the same level of intelligence as their sensing domains. They prevent errors by reducing human involvement, thus allowing the subject to be interpreted with minimum possibilities of fading and the least amount of possible deviation. Senducers can be categorized as collective or distributive depending on their applicability.

Collective or co-located senducers are also called “unoducers” because they contain a sampling device with several transducers in a single monolith. Distributive senducers achieve extensive sensing by evaluating the subject panoramically; these senducers may be used for individualistic sensing and may consist of a chain of unoducers.

### 2.1.2 HBS

Senducers gather the required data and transmit these data to a distant location during the sensing process. HBS provides senducers with a common node, to which the latter can send their collected information, considering that material sensing can be accomplished only by physically approaching the subject. Senducers must also possess an energy-saving mechanism to allow them to perform subject sampling and transduction. HBS is assigned a large part of the information processing task. HBS ensures holistic communication and guarantees the integrity, security, authenticity, and reliability of the data being transmitted (Figure 2).

### 2.1.3 HPT

The information transmitted by HBS is transposed in a format that is perceptible to humans through the use of HPT. The information is subsequently transformed into sensory stimuli, which can be produced in two ways as follows:

- Brain-to-brain transmission, in which a person sends information directly to another person. This method is commonly used by parents communicating with their children or by specialists communicating with disabled individuals.
- Device-to-device transmission, in which sensors directly send data to data centers or smartphones. This method is often used to address healthcare or safety concerns.

HBC is evidently an important advancement in wireless technology and requires numerous requirements to be fulfilled before actual implementation. Figure 3 shows four essential considerations for HBC implementation. A previous study [13] has already discussed physical layer improvements. The current work proposes to use a platform for the full implementation of the HBC concept. CONASENSE supports the HBC concept by providing diverse activities and services. This study comprehensively discusses security and standardizations and introduces the full options and possibilities that can be achieved with CONASENSE. The following section describes CONASENSE for HBC implementation.

# 3 CONASENSE

CONASENSE, a complete platform for future wireless communication, serves as a foundation for the HBC concept. CONASENSE aims to integrate the academia, industries, research centers, institutes, and organizations to achieve the convergence of communication, navigation, sensing, and services. Its main goal is to combine research innovations from domains to make them accessible to users and to support generalized user mobility. In particular, CONASENSE addresses the rapidly evolving and radically changing manner through which traditional communication and services are being used, demanded, and performed.

## 3.1 Security

Traditional security architectures protect audio information and data. They possess the following common security features.

- User identity management based on (U)SIM
- Mutual authentication between networks and users
- Hop-by-hop path security between communicating parties

Wireless communication in the future is expected to be service oriented. This expectation implies that special emphasis will be placed on security requirements that originate from services, thus leading to different security issues for different services. To fulfill the security which is needed for HBC, a new and flexible security architecture should be introduced [14]. Table 1 illustrates the security requirement for HBC in details. A flexible security architecture is required in this case to support and protect different services. New security and privacy implications in future wireless communication require at least four specifications, namely, new trust models, new service delivery models, an evolved threat landscape, and increased privacy concerns.

### 3.1.1 New trust models

Trust models change constantly. An example is the bring-your-own-device trend in enterprises. In the past, all user devices were assumed to be trustworthy because they were of the same type and were issued and managed by a corporate IT department. At present, users wish to use their personal devices instead, thereby posing threats by creating potential Trojan horses behind corporate firewalls.

New types of devices are expected to span a wide range of security requirements and simultaneously possess different security positions, such as industry automation control devices, shipping containers, vehicles forming entire capillary networks, tiny climate monitoring sensors, and next-generation tablets and smartphones. Existing trust models do not capture this evolving business and technological scenery. The trust model map must be redrawn to ensure that future wireless communication technology can support the requirements of new business models and to guarantee sufficient security. This task is one of the primary duties of CONASENSE contributors.

### 3.1.2 Security for new service delivery models

Cloud usage and virtualization emphasize the dependency on secure software and affect security. Software and hardware decoupling means that telecom software can no longer rely on the specific security attributes of a particular telecom hardware platform. Increased demands on virtualization with strong isolation properties arise when operators host third-party applications in their telecom clouds via execution on the same hardware as native telecom.

### 3.1.3 Evolved threat landscape

Hacktivists, underground economies, cybercrimes, and cyber terrorists arise due to the accessibility of new and wide values on the Internet. Attack resistance should be a design consideration in the creation of new wireless system protocols. Questionable authentication methods, such as the use of usernames/passwords, must be eliminated. Three authentication models could be simultaneously adopted in future wireless technology to address the requirements of different scenarios.

- Authentication by networks only

  Service authentication increases the costs incurred by service providers. Service providers can pay networks for service authentication for users to be able to access multiple services after completing a single authentication. This approach eliminates the cumbersome task of obtaining service grants repeatedly when attempting to access different services.

- Authentication by service providers only

  Meanwhile, networks may adopt proven authentication capabilities from vertical industries and exempt devices from radio network access authentication so that networks can reduce their operating costs.

- Authentication by networks and service providers

  A legacy model may be adopted for some services. Networks manage network access, and service providers handle service access.

### 3.1.4 Increased privacy concerns

Several recent news stories have reported mass surveillance allegations. Rogue base stations have been reported to track users in major cities. Personal data extraction without user knowledge has also been mentioned. The European Union has discussed the protection of personal data. This task is currently under review by standardization bodies, such as 3GPP and the Internet Engineering Task Force, and debated in many forums.

The user identifier(s) is a particularly sensitive asset. User privacy has been an important consideration since the emergence of 2G technology. However, the advantages of full international mobile subscriber identity protection do not appear to outweigh the complexity of implementing this measure.

## 3.2 Standardization

CONASENSE addresses the standardization of future wireless communication systems and considers various requirements, demands, and applications, such as HBC. The main challenges for standardization are shown below.

- Complexity of emerging users and usage scenarios
- Evolution from single-purpose wireless systems (mobile broadband) to a broad range of usage cases and requirements (e.g., range of IoT service and device types)
- Requirement for a scalable service experience regardless of the time and location at a reduced cost

CONASENSE primarily aims to avoid the "one standard fits all" concept. This aim indicates that multiple standard organizations are expected to define key building blocks for future wireless communication. Coexistence, integration, and harmonization across standards that complement one another must be highlighted to provide an ultimate experience. To allow new participants to play a key role, different standards and/or technologies may be required to address different usage cases and requirements. The new standards should address the following:

- services, including machine to machine, vehicle to anything, explosion of videos, proximity and context awareness, tactile Internet, and public safety;
- network architectures, including device-centric and device to device, dense and layered architecture, network function virtualization, and cloud radio access network;
- air interface pertaining to massive MIMO, advanced waveforms, and full duplex; and
- spectrum pertaining to flexible and dynamic spectrum sharing, new spectrum for access and backhaul, and mmWave.

Owing to the reliable platform provided by CONASENSE, different organizations can discuss, propose, and develop new standards for future wireless communication to fulfill demands and requirements.

## 3.3 Technology and business development

Business models for implementing an HBC system could be determined in different layers of the network such as network, security, and physical layers. This undertaking represents a substantial evolution in the scientific, industrial, and marketing fields. In this paper, we mention an abstract introduction of business model and marketing of HBC for physical layer and user level, the final version of this discussion will be discussed in tour future work.

Several novel business models can be applied in the physical layer, from the point of view of design to application and usage. Antenna, massive MIMO, cooperative algorithms, and software development (embedded and platform) are examples of system designs.

Huge alterations in terms of industrial products, such as those in featured in online marketing and electronic shopping, are forthcoming. For example, users can smell the perfumes that Amazon sells before ordering. Clothes sold online can be touched or felt. However, this massive amount of data need infrastructure that will handle various innovations. New aspects will also emerge, such as effective factors for organizations or companies that attempted to apply business models for HBC and marketing analysis for the implementations. This great changes in marketing can open a new gate to Internet of Things (IoT) market and industry, which we call it Internet of Being (IoB).

Figure 4 shows a picture of CONASENSE, which offers diverse activities and achievements. Research and global services are the main categories. Diverse activities are defined and supported by academic research and investigation, specialization, and technology innovation in the research category. The research area covers various fields, such as

- agricultural–environmental scenario: remote sensing, location, and communication;
- smart grids/ambient living scenario: sensing and communication;
- emergency scenario: location-based services, sensing, and communication; and
- telehealth scenario: remote sensing, location, investigation, and communication.

Moreover, CONASENSE generates technical documents and IPRs and makes global markets accessible to its contributors and other interested parties. CONASENSE can be utilized to develop business models and systems for various industries and startups. In summary, CONASENSE allows organizations, the academia, and other contributors to reach the goal of enhanced communication. The main definition involves the HBC concept so that a personal mobile device can gain a new dimension and become capable of the following:

- sense and communicate over radio,
- locate and communicate over radio, and
- act and communicate over radio.

In summary, the stages of implementing HBC system based on the CONASENSE platform could be described as following:

- Combining academia and industries in terms of goals and orientations of joint activities
- Introducing the research section in academic institution to conduct research and development parts of HBC implementation, academia could carry on:
  - All research tasks for the best solution on sampling data and digitization to be ready for transmission (mainly physical layer tasks)
  - Introduce and investigate new technologies, which are needed for developing the
  - HBC idea
  - Define new standards and study various requirements and demands for HBC transmission technology
  - Outline a new network system for network providers to support the required data transfer for HBC transmission purpose
- Introducing the industry section to cover marketing and technology implementation for HBC, industry could be involved in:
  - New access to the global market for the products based on HBC technology
  - Define and pursue the new business models for HBC system

Finally, different IPRs and many novel ideas are expected to be achieved during the procedure of investigation and implementation of the HBC technology in diverse domains and levels, which would be taken care of by CONASENSE platform.

## 4 Conclusions and future work

This work presents the role of CONASENSE as the main platform for the future of wireless communication. The main objective of discussing this idea is to address the requirements and challenges in implementing the HBC system. HBC is the foremost field of research for the future of wireless communication, and in general, the whole world. People in the near future require a more enhanced and efficient means of data transmission than just using video and audio. Sampling, transmitting, coding, and decoding of the five human senses are the essential demands of future communication. The implementation of the concept requires extensive research in many different organizations, industries, academia fields, and markets.

Moreover, a different layer of the network should be reconstructed or optimized for transmitting a large amount of data safely and reliably. In this work, the requirement for a comprehensive platform was identified. The physical layer for HBC transmission was studied, and a solution for optimization for enhanced data rate, low interference, and reliable communication was proposed. This study highlights the challenges in designing the security and standardization of HBC communication, including the CONASENSE platform. CONASENSE promises a universal platform and principles from the physical layer to the network layer for optimizing, developing, and improving the current wireless communication technology. The new setup should address the challenges in implementing the HBC idea. Clearly, CONASENSE combines diverse organizations, industries, and researchers to realize this goal.

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*Figure 1: The HBC architecture system overview*

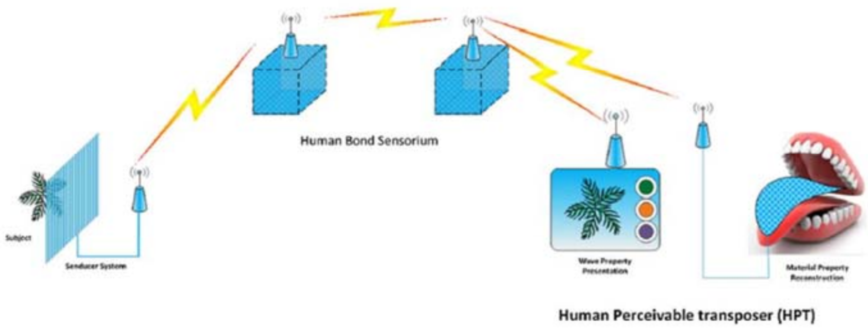


*Figure 2: Human bond sensorium architecture [2]*

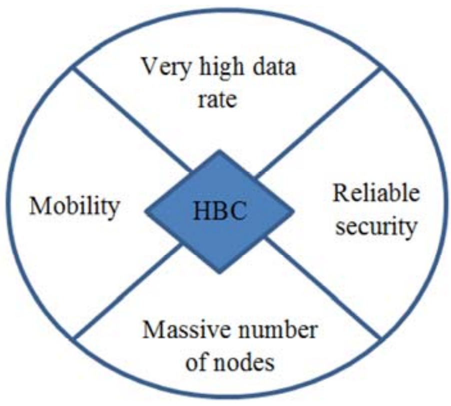


*Figure 3: Essential components of HBC to be considered in architecture design*

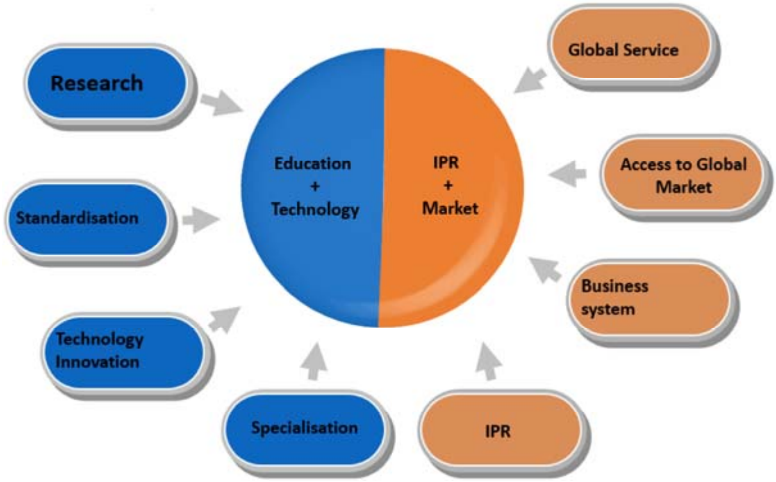


*Figure 4: CONASENSE snapshot, a wide range of novel converged services, applications, technologies and business models*

*Table 1: Summary of security requirement for HBC*

| Security requirement | Description |
|---|---|
| Confidentially | Personal data should be considered confidential at nodes, servers and transmission stages |
| Integrity | Destruction in data should be considered in all levels and user should be warned about it |
| Dependability | Retrievability of data should be possible all the time even after destruction |
| Scalability | Access controls should be scalable based on different load of nodes to avoid storage overhead |
| Flexibility | Nodes could be able to choose access points any time anywhere to transmit data |

# Human Bond Communication from a Business Perspective

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***Abstract*— Human bond communication (HBC) is a prominent idea in the scholarly world. Research on various elements of HBC range from sampling to transmission of the senses. HBC necessitates extensive development in relation to structures of networks and their physical and application. This work is driven by the necessity for a novel business model for an HBC system. Such a model must be defined within the context of an extensive area covering the substantial modifications necessary after implementing the HBC system in an actual market. This work concentrates on physical layer changes, network security, and marketing with the new features of HBC.**

***Keywords—HBC; Business Model; Network; Marketing***

## I. INTRODUCTION

A business model is a design through which a company or organization earns and profits from its operations [1]. Magretta [2] described such a model as one comprising a logical narrative explaining the types of customers, the things they value, and the method of earning income by providing customers the former. To sustain a business, four among the several core objectives to be realized are profitability, productivity, customer service, and growth. Accordingly, the intention for employing business models should be clarified. A business is established initially with a creative and impressive idea. The discussion in [3] emphasizes the role of a business model, which is to assist entrepreneurs in objectively evaluating the success rate of their business propositions. A recommendation should be transformed into a business concept through business modeling and planning before it can be realized. The success of a concept depends on a sound and optimum business model before its deployment in an actual market. The inadequacies of traditional models should be overcome, and innovation is critical for business models. The current models have considerable room for improvement. Business model innovation must put forward novel prospects and ensure sustainably effective and financially beneficial contributions that can meet customer needs. Regarding future communication technology (i.e., 5G), original offerings focusing on technology and services should take business model innovation into consideration to provide various rapid services. As a leading global supplier of telecommunication equipment, Ericsson reiterated the significance of innovative and creative business for 5G technology [4]. Ericsson emphasized in one of its reports that wireless industry players should come up with innovative business models for effective application of developing 5G technology. The telecommunication field has been witnessing various revolutionary improvements that pertain to the advancement of various technologies, user requirements, procedures, and rules. Network operators enjoy the advantage of establishing the necessary network infrastructure for cultivating subscriber relationships and guaranteeing business profitability, particularly revenue generation. Consequently, network operators must take into account a new perspective pertinent to novel business models. Such a requirement is due to the fact that 5G is developing as a next-generation communication technology that intends to provide big data, low latency, and reliable network services that can handle the continuous growth of wireless subscribers. At present, the enormous increase in the number of subscribers is disproportionate to the growing rate of revenue for wireless services providers. The need for innovative business models will drive market investors, leading telecommunication companies, and equipment manufacturers to question their profit-making strategies in delivering mobile and communication services. Network operators should concentrate on models independent of time, place, and people when considering the requirements of novel business approaches in connection to the future market [5]. The platforms that should be positioned and implemented are crucial in determining the successful application of new business models. Outdated mobile network platforms are inapplicable for flexible spectrum usage, and they cannot be implemented to mission critical or massive machine types of traffic as well. Rethinking, restructuring, and redesigning of the techniques involved in extant successful models of the universal implementation of ultra-broadband network platforms are required for developing and expanding wireless networks for huge data transmissions in the future of the wireless communication. Forthcoming communication networks will develop an ecosystem for innovation in technical and business aspects, wherein majority of network services are maximizing software use, thereby requiring flexible and responsive platforms. In addition, future wireless network will equip new industry players (e.g., vertical industries, new service providers, or owners and providers of infrastructure) to develop over-the-top network architecture and infrastructure. Given these possibilities, novel business models should support future wireless network infrastructure to highlight flexibility and programmability (e.g., advanced software embedded with artificial intelligence) and facilitate numerous services and user mobility conditions.

Research on HBC business models are in its initial stages. Previous studies propose several models, which are reviewed in the present work. Authors in [6] proposed three important business models according to service provider roles: asset, provider, and partner service provider (PSP). In the first business model, “asset” pertains to the various components of a network infrastructure operated for or on behalf of third parties that result in a service proposition. This model endorses the “anything as a service (XaaS)” concept, wherein X represents an infrastructure, network, or platform. Another characteristic is network infrastructure sharing between two or more service operators, and such a sharing is based on static/dynamic policies (e.g., congestion/excess capacity policies). The second business model refers to the service operator providing the best effort IP connectivity for retail and wholesale customers. Features, such as self-configuration options for customers or third parties, are provided for the enhancement of this business scheme. The third model recommends two variants for PSP. In one, the operator addresses end customers directly and offers integrated services according to their capabilities. In the other, partners (e.g., third parties) can extend offers directly to end customers, and network providers enhance such offers.

All in all, new business models should be taken advantage of to enable operators, service providers, investors, and equipment manufacturers for obtaining cost benefits. This current research seeks to serve end users of future communication networks, particularly in a small cell environment.

## II. CHALLENGES FOR HBC BUSINESS MODEL DESIGN

Identifying a comprehensive business model for an HBC system is accompanied with several challenges. These concerns involve needs and opportunities and managerial challenges related to internal team alignment (i.e., matching technology to the objectives of business developers). In addition, the means necessary to overcome the market maturity problem for a novel HBC technology should be figured out. We extend this view and identify three contemporary challenges of HBC, namely, object diversity, innovation immaturity, and unstructured ecosystems. The literature review and expert discussions on the Internet of Things (IoT) pinpoint these challenges. According to [7], these challenges focus on business ecosystem spheres, developer communities, and platforms in relation to forming IoT-based ecosystem business models.

### *A. Object Diversity*

The problem of object diversity lies in the difficulty of designing HBC business models due to the various types of connected objects and devices without recognized or emerging standards. An HBC system is a network of interconnected objects and humans, in which everything and every sense (from toothbrushes and sportswear to refrigerators and cars to feelings and smells) will exhibit online presence. Standardizing all interfaces within which these myriad of objects and concepts can connect to the Internet is extremely problematic on top of intricately difficult. Managers faces another challenge with regard to object diversity, that is, the virtually endless means to connect a thing, a business, and a consumer [8]. Possible business models are expanding continually. Recent estimates indicate that 10 billion devices are connected presently and 50 billion devices will be connected by 2020; however, over 99% of physical objects that may one day join the network remain unconnected [9]. These estimates suggest that an unprecedented number of objects will be part of the future Internet. In [10] noted that physical objects (“things”) are increasingly becoming available in the digital format, and these “virtual objects” have specific purpose, comprise a series of data, and can perform actions. They integrate with other applications and physical “things” and may require specific business logics.

### *B. Innovation Immaturity*

In this context, immaturity connotes the current “mess” of emerging technologies and components hindering HBC innovations from maturing into products and services. These technologies are yet to be standardized or modularized for wide usage, and, as such, they often require engineering work for coupling in another application area. Modularized objects are one of the prerequisites for an emerging market, and these objects include the “plug and play” characteristic of components. With coupling components, developers can experiment and create products and services for an HBC ecosystem and simultaneously learn from market experiences when designing business models. The technology adoption lifecycle model [11] recognizes five types of innovation adopters: innovators, early adopters, early majority, late majority, and laggards. The main challenge is to grow from early adopters to early majority because a business model must take into account the “scaling up” of a business. Early adopters are willing to tolerate innovation immaturity, whereas early majority rather evaluate and buy entire product lines, including the main product, ancillary products, and any related services [11].

### *C. Unstructured Ecosystems*

Unstructured ecosystems do not have defined underlying structures and governance, stakeholder roles, and value-creating logic. An emerging ecosystem may lack appropriate or required participants, for example, operators or potential customers. To pursue new business opportunities, other relationships in unfamiliar industries should be established or existing relationships must be extended. Doing either requires time, thus posing considerable challenge for managers. Ecosystem complexity is associated with the number of participants [12], and an early ecosystem represents an unstructured, chaotic, and open playground for participants. IoT is an early ecosystem, similar to the Internet when it was in its infancy. The Internet serves as the impetus for the incredible richness of rival and complementary business ecosystems that employ it in myriad ways. The ecosystem anchored around the Amazon Web Services, Google’s AdSense platform, the mashup ecosystem enabled by open APIs and open data are examples along with the many business ecosystems involving community-developed platforms. Therefore, principles that shape HBC business ecosystems through business model innovation are necessary as well. However, which one will become the significant yet evolving ecosystems in the HBC field and which participant(s) will become keystone players cannot be determined at this stage. Object/device suppliers, software infrastructure suppliers, suppliers of hosted solutions or smart services, operators, value-added service providers or full service integrators, data collectors/analyzers, or even an (open source) user community are all in the running. Rather than focusing on the key stakeholder(s), generating and capturing the value of the ecosystems should be emphasized. Unstructured HBC ecosystems drive the need for HBC-specific business model frameworks that help construct and analyze the ecosystems and business model choices and, at the same time, articulate this integrated value for the stakeholders.

## III. BUSINESS MODEL SCENARIO FOR HBC ARCHITECTURE

This section discusses distinct business model scenarios for installing an HBC system. Using our previous studies [13], [14] as basis, we determine the appropriate network, security, and physical layers required. In doing so, our present research represents a substantial evolution in the scientific, industrial, and marketing fields. This study concentrates on factors such as the network provider of the HBC and physical layer users.

### *A. Core Network Extension*

An HBC system is connected to the central network. The HBC system attempts to expand the central network along with small business partners related to network developers. The present network architecture platform can be reused multiple times and in multiple places for HBC purpose. In addition, the footprint of the ground network increases without additional costs. The connection footprint is attractive, and the services are substantially available from a user perspective. Accordingly, core network extension increases the average revenue per user and emphasizes both network health and revenue.

### *B. Network Operator*

A network operator should initially bridge enterprises to their customers. A successful HBC connectivity provider builds highly reliable and scalable networks for connecting the exponentially growing numbers of devices in a secure and cost-effective manner. Doing so entails providing the best services, platforms, and tools designed to manage HBC device connections. In addition to strengthening communications interoperability, operators should enhance stability, speed, security, and service quality by aiming to become the foremost choice of enterprises moving into a HBC system. Thereafter, enterprises of all sizes must face the challenge of working with numerous varied and complex connectivity technologies. An HBC connectivity provider must help address this complexity.

The next step is to become an HBC service enabler. At this stage, the portfolio is expanded to provide a range of technologies targeted at facilitating and accelerating the launch of HBC services for enterprise customers. Competition at this level is intense, driving providers to have the most agile platforms on the market. The providers must acquire new ecosystem partners quickly in addition to a flexible monetization engine to support any new business models, and superior analytics tools to understand the massive amount of HBC data generated.

A few telecommunication service providers take on the full responsibility of an IoT service creator, and this role can be extended to an HBC service creator in the future. At this stage, providers must create new E2E innovative services and pursue a direct go-to-market strategy maximizing newly found revenue streams. With this role comes the opportunity to target consumers, whether in a simple B2C fashion or in conjunction with an industry partner using a more articulated B2B2C model. Either as an IoT or an HBC service creator, operators should drive end-user experience. To do so, assessing the market carefully and understanding its opportunities and barriers are necessary. Operators must precisely choose which verticals to aim for with the new offerings. This role makes providers central players in dedicated vertical ecosystems, and they must transform to be successful by building the right delivery, distribution, and sales channels for the new verticals.

*C. New Trust Models for Security Purposes*

Trust models undergo constant change, such as the “bring-your-own-device” trend in enterprises. Before, user devices were presumed trustworthy because they had the same type and were provided and supervised by the information technology (IT) department of a corporation. Now, users prefer using their own devices, which jeopardizes enterprises because Trojan horses may be created behind extant corporate firewalls.

Device models are expected to cover extensive security requirements while possessing various security components. Industry automation control devices, shipping containers, vehicles that form entire capillary networks, tiny climate monitoring sensors, and next-generation tablets and smartphones are examples of such devices. The problem is that existing trust models lack evolving scenarios in the business and technological fields. To solve this problem, the trust model map should be revised to guarantee that future wireless communication technology can sustain the needs of new business models and promise adequate security.

*D. Securing New Business Opportunities*

HBC will change most existing industries and usher in a multitude of new business opportunities. The most interesting potential HBC applications are in the transport industry. When people can transmit through all their senses, the need for travel will be reduced. The same is true when people can experience traveling with more senses via wireless communication. The transformation toward the reality of connected vehicles occurs simultaneously as a result of developments in electrical and autonomous vehicles. In the future, connected vehicles may function similar to schools of fish or flocks of birds by using artificial intelligence (AI). AI will safely take over when connection to a network and other vehicles becomes lost because of a malfunction or as an attack (e.g., jamming).

Underneath a modern connected vehicle is a complex system with thousands of sensors and actuators. The internal workings also include a large code base across a set of embedded processors. Hardware and logical isolation are essential to address problems, including a breach in the infotainment system that cannot escalate into a breach in the steering system. Compatibility between different subsystems (e.g., brake pedals and brakes) can be maintained with firmware updates. The simplest solution is updating all subsystems at once. In case of failure, the updates can be rolled back. Transportation is one of the riskiest activities in everyday life at present, but nearly all automobile accidents can be possibly prevented through vehicle-to-vehicle communication. Although accidents caused by malfunctioning machines seem inevitable, development should not be impeded by fear.

HBC will also increase public safety. For instance, by integrating sensors and cameras into human bodies, vehicles can be forewarned about people crossing roads and tracks. HBC represents immense possibilities for increasing the safety of emergency response agencies along with the society they are sworn to protect. Emergency vehicles will automatically get free lanes, missing children will be easier to find, and both citizens and emergency personnel will be tracked during crises, such as fires and natural catastrophes. The critical nature of these functions requires strict authorization and transparency to prevent misuse or suspicion of misuse. Although certain aspects of surveillance may be necessary to public safety, privacy rights should be considered.

### *E. Physical Layer Market Models*

From the perspective of design to application and usage, many novel business models can be applied in the physical layer. Examples of system designs are antenna, massive MIMO, cooperative algorithms, and software development (embedded and platform).

Massive modifications in terms of industrial products, such as those featured in online marketing and electronic shopping, are imminent. For instance, users can smell perfumes sold at Amazon before ordering or clothes sold online. The problem lies in the infrastructure needed to handle the numerous innovations involved in this immense amount of data.

New features will also emerge, including factors effective for organizations or companies seeking to apply business models for HBC and marketing analysis for implementation. The succeeding sections discuss these features.

#### *1) Internal and External Factors*

Analysis of the HBC business model at the physical layer centers on identifying internal and external factors that are critical to achieve enterprise goals. The two major categories are as follows:

- Internal factors – r the strengths and weaknesses inherent to an organization
- External factors –the opportunities and threats presented by the environment outside an organization

Analysis views internal factors as either strengths or weaknesses. This view depends on their importance in relation to the objectives of an organization. Factors that possibly denote strengths with respect to one objective may be considered weaknesses (i.e., distractions or competition) for another objective. These factors may include personnel, finance, and manufacturing capabilities as well.

External factors involve changes in macroeconomic matters, technology, legislation, and sociocultural issues. Shifts in the marketplace or in competitive positions are also included. A matrix is often used to present the analysis results.

An analysis is among the numerous methods for categorization, and, as such, it has certain disadvantages. To illustrate, analysis may influence users to gather lists rather than consider the actual factors critical to achieve the objectives. This work uncritically provides the resulting lists and thus lacks precise prioritization (e.g., weak opportunities possibly balancing strong threats).

#### *2) Marketing for HBC*

An HBC system is a technological revolution that will affect everything people do. This system represents an enormous wave of new possibilities destined to change the current face of technology. HBC will give rise to interconnectivity between humans and things through wireless communication technology (each with their own unique identifiers), which in turn will connect objects, locations, animals, and people to the Internet. Direct transmission and seamless sharing of data will be possible through this connectivity. Basically, everyday devices can automatically exchange information over a network. HBC will also exert a substantial effect on people’s everyday lives because it will change data collection and traffic, weather, pollution, and environment monitoring. Although these expected developments are meaningful, they will merely be the tip of the iceberg in terms of the potential of HBC. The HBC system will have enormous impact on the way people do business, specifically marketing. The following examples highlight how HBC will transform the manner in which marketing is conducted.

##### *a) Easy Exchange of Data*

Data represents one of the most valuable commodities of any business. Enterprises can tailor their marketing efforts toward specific clients efficiently when they have access to information regarding how, where, and why products are purchased and used. Smart devices that can gather such data and send them to firms in real time can enable businesses to formulate informed marketing strategies and improve future sales. Customers can provide useful feedback instantaneously through an HBC system. Thus, firms can be made aware immediately if a specific product fails expectations and act promptly to resolve the issue.

##### *b) Instantaneous Customer Analysis*

An HBC system will perform beyond simply gathering and organizing client data when utilized in conjunction with a dependable customer relationship management tool. This system can analyze data efficiently and accurately and provide actionable results pertaining to consumer base. Such function present immense value for marketers because the buyers' chain of command is often long and decision making often takes much time. HBC devices can streamline this process by 1) helping consumers understand their purchase options, thus enabling them to maximize their time toward resolving issues, and 2) providing accurate information to encourage consumers to purchase.

*c) Predictive Social Media*

In the early years of Facebook and Twitter, most marketers were cynical about targeting these new "social media" sites. An HBC system can be optimized so that it can be used with social media. Such a system can enable automated posts and shares to be generated regularly by the devices themselves. Doing so paves the way for creating new online communities centered around users of particular devices. Marketers who can predict the development of these social communities and target their efforts toward such communities can reach potential customers who are unavailable before. With an HBC system coupled with social media, marketers can identify and maximize new emerging trends.

## IV. Conclusions

The challenges of designing business models for emerging HBC are the main focus of this research. This study recognizes the ongoing paradigm shifts toward ecosystem thinking, both in the discussion of platforms and the design of business models. Major problems that prevent companies from designing business models and monetizing the HBC have also been highlighted. These problems are object diversity, innovation immaturity, and unstructured ecosystems. Managers can overcome these challenges and design successful business models if they focus on the ecosystem approach of conducting business and utilizing business model design tools that take the ecosystem nature of the HBC into account. This research also considers the diverse requirements for HBC network design from a provider perspective. The requirements include the security of the system, the needs and development of physical layers and advancements of marketing based on HBC technology. This research illustrates the need for substantial improvements in all the discussed aspects after HBC system implementation and the manner in which these improvements and implementation can facilitate a substantial change in business model innovation in the future.

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# An Introduction to the Business Model for Human Bond Communications

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***Abstract*— The concept of human bond communication (HBC) has recently attracted the attention of researchers because of its possible role in revolutionizing future communication levels. HBC was rapidly established in the academe and among researchers. The current study centers on the market development and business modeling for HBC. HBC is also referred to as the "Internet of beings" because of its capability to analyze numerous fields and address modern communication techniques. Evidently, a novel business model should be developed to accommodate the expected massive modifications after the initial application of HBC in the actual market. Therefore, this study explores the possible opportunities in the field of business for HBC in various network layers.**

***Keywords—HBC; Business Model; Network; Marketing;***

## I. Introduction

A business model is simply defined as a design wherein a company or organization earns and profits from its operations [1]. Magretta [2] explained that a business model presents a coherent narrative that explains the types of customers, the things that they value, and the method of earning income by providing customers with such value. Profitability, productivity, customer service, and growth, among others, are only a few of the core objectives that should be achieved to maintain a business. Accordingly, we should be aware of the reasons for having business models. A business is initially built by having a creative and impressive concept. The discussion in [3] emphasized that a business model assists entrepreneurs perform an objective assessment of the possibility of success of their business propositions. Prior to the application and realization of a suggested notion, such notion should be turned into a business idea by means of business modeling and planning. Evidently, success lies with such concept and likewise proceeds with a sound and optimum business model prior to its deployment in the real market. The process of hurdling the difficulties of traditional models is crucial; thus, innovation in terms of business models is substantially necessary. However, we note that the models currently used constantly have room for enhancement and progression. Figure 1 demonstrates the crucial aspects for business model innovation. This figure further indicates that new techniques to enhance the current bases of competitive advantage and develop a novel value proposition are importance for innovations in business [4]. Business model innovation should establish and provide novel potential and contributions that are sustainably effective, beneficial in terms of the financial aspects, and able to meet the needs of customers. With regard to future communication technology (i.e., 5G), innovation in offerings that concern technology and service should take into account business model innovation to offer and provide numerous rapid services. Ericsson, which is a leading global supplier of telecommunication equipment, has reiterated the significance of novel and creative business for 5G technology [5]. The report of Ericsson emphasized that those involved in the wireless industry should offer innovative business models to effectively use the developing 5G technology. At present, the field of telecommunication is facing revolutionary improvements in terms of various technologies being developed, requirements of users, procedures, and rules that must be followed. An important advantage for network operators is that of establishing the necessary network infrastructure that is crucial in establishing subscriber relationships and ensuring business profitability, particularly in terms of generating revenues. Accordingly, a new perspective in terms of novel business models is a substantially necessary task that network operators should consider. The reason is that 5G is developing as a next-generation communication technology that intends to provide large volume of data, low latency, and network services that are considerably reliable to the incessantly increasing number of wireless subscribers. Furthermore, the enormous increase in the number of subscribers is disproportional to the rate of increase of revenues earned by the providers of wireless services. Accordingly, the necessity of innovating business models will lead investors in the marker, leading telecommunication companies, and manufacturers of equipment to doubt their profit-making strategies in the delivery of mobile and communication services. In considering the needs of novel business approaches, models that are independent of time, place, and people should be important factors for mobile operators in terms of the market in the future [6][7]. In terms of achieving this condition, among the crucial factors should focus on platforms that should be positioned and implemented [8]. The outdated platforms of mobile networks no longer applicable for flexible spectrum usage or implementing mission critical or massive machine type of traffic [8]. The succeeding models of the universal implementation of ultra-broadband network platforms needs rethinking, restructuring, and redesigning of techniques to the development and expansion of mobile networks [9]. The aim of the implementation of a radio access network (RAN) infrastructure for the mobile communication of the future should consider four critical aspects, namely, massive capacity, massive coverage/connectivity, quality of services (anytime and anywhere), and user mobility. In [9], researchers explained a business model in the terms of the mobile communication sector. These researchers the V4 model, which is a general business model structure for mobile network operators and is exclusively based on value. This model comprises four dimensions: value proposition, network, architecture, and finance. The aforementioned researchers proposed that network operators should improve their propensity to determine the factors that comprise the most feasible business model, which is necessary in realizing their tactical objectives in immediately enhancing communication situations. The future communication networks will develop an ecosystem for innovation in the technical and business aspects with the majority of network services maximizing the use of software, thereby necessitating flexible and responsive platforms. Moreover, 5G will considerably provide new players in industries, such as vertical industries, new service providers, or owners and providers of infrastructure to develop over-the-top network architecture and infrastructure. Therefore, novel business models should assist the 5G infrastructure in a manner that will emphasize flexibility and programmability (i.e., advanced software embedded with artificial intelligence) in addition to assisting numerous services and user mobility conditions.

The study on the human bond communication (HBC) business models is still in the initial stages. Accordingly, we will explain a few of the models that have been proposed in previous studies (see, figure 2 for illustration of HBC). A few examples are provided in [10], which proposed three important business models on the basis of the service providers' roles: asset (AP), provider (CP), or partner service provider (PSP). The first business model explains asset as different components of a network infrastructure that are operated for or on behalf of third parties that results in a service proposition. Moreover, this model asserts that "anything as a service (XaaS)," in which X represents an infrastructure, network, or platform. One other aspect is sharing the network infrastructure between at least two service operators on the basis of policies that are static/dynamic (e.g., congestion/excess capacity policies). The second business model is the service operator providing the best effort IP connectivity for retail and wholesale customers. Such features as self-configuration options for the customer or third party are presented to enhance this business scheme. Two variants are recommended for PSP in the last model. First, the operator addresses end customers in a direct manner and offers integrated services on the bases of the capabilities of the operator. The second variant enables the partners (i.e., third parties, etc.) to offer directly to end customers that the operator network enhances.

Overall, new business models should be embraced, thereby enabling operators, service providers, investors, and equipment manufacturers obtain cost benefits. The objective of this undertaking is to serve the end users of future communication networks, particularly in terms of a small-cell environment.

## II. Business Model Scenario for the HBC Architecture

This section will discuss the varying scenarios of business models for installing an HBC system (see, figure 3). We used our previous studies [11], [12] and [13] as bases to determine the appropriate network, security, and physical layers that are required for HBC. This undertaking represents a substantial evolution in the scientific, industrial, and marketing fields. The current study centers on such factors as HBC's network provider and physical layer users.

### *A. Core Network Extension*

The HBC system is connected to the central network. Hence, the HBC network endeavors to expand the central network and small business partners related to network developers. For the purpose of HBC, the present platform of the network architecture can be reused multiple times and in places. Moreover, we perceive that the footprint of the ground network increases without additional costs. From the perspective of a user, the connection footprint is attractive and the services are substantially available. Accordingly, this factor increases the average revenue per user (ARPU) and emphasizes the network health and revenue.

### *B. Mobile Virtual Network Operator (MVNO)*

Prior to making a decision on the network structure type, planning is crucial to the operator in defining the crucial objectives of the business. If Mobile Network operator ( MNO) requires an increase in the market share to address the intense competition in price and stabilize ARPU, then an expected option is merger or acquisition that involves a competitor.

If the impetus of an operator is to increase the efficiency of operations and reduce Total Cost of Ownership (TCO) to acquire a novel technology and expand the network, then network sharing, specifically RAN, is a viable option. Accordingly, the concept of network sharing indirectly addresses businesses' revenue component. However, the operators who are engaged in sharing the network will enhance their cost efficiency relative to that of the other operators who are excluded in the sharing joint venture.

For a considerably small MNO, a third possibility is entering into a mobile virtual network operator agreement with an established MNO, sell the network assets to this MNO, and buy back capacity thereafter. A provisional strategy is that the smaller MNO can alternatively sign a national roaming agreement with the larger MNO to obtain a substantial coverage footprint while expanding its own network infrastructure.

### *C. New Trust Models for Security Purposes*

Evidently, trust models undergo constant change and one such sample is the trend in enterprises called bring-your-own-device. User devices were previously presumed to be trustworthy due to the fact that they have the same type and provided and supervised by the information technology (IT) department of a corporation. Users currently opt to use their own devices, thereby proving to be threats due to the creation of possible Trojan horses behind the existing corporate firewalls.

Expectedly, models of devices are anticipated to cover extensive security requirements and simultaneously own a variety of security components, such as industry automation control devices, shipping containers, vehicles forming entire capillary networks, tiny climate monitoring sensors, and next-generation tablets and smartphones. However, the existing trust models lack such evolving scenarios in the business and technological fields. Hence, the trust model map should be revised, thereby ensuring that the wireless communication technology of the future can sustain the needs of new business models and ensure adequate security.

### *D. Security for New Service Delivery Models*

Among the factors that affect security and emphasize dependency on secure software are cloud usage and virtualization. The meaning of software and hardware decoupling is that the particular security properties of a specific platform of telecom hardware can no longer be relied upon by telecom software. The emergence of increasing demands on virtualization with considerable isolation properties occurs third-party applications are hosted in the telecom clouds of operators via implementation on the same hardware as native telecom.

### *E. Physical Layer Market Models*

Numerous novel business models can be applied in the physical layer, from the point of view of design to application and usage. Antenna, massive MIMO, cooperative algorithms, and software development (embedded and platform) are examples of system designs.

Massive modifications in terms of industrial products, such as those in featured in online marketing and electronic shopping, are forthcoming. For example, users can smell the perfumes that Amazon sells before ordering. Clothes sold online can be touched or felt. However, this massive amount of data need infrastructure that will handle various innovations.

New aspects will also emerge, such as effective factors for organizations or companies that endeavored to apply business models for HBC and marketing analysis for the implementations. The succeeding sections will discuss these two aspects.

#### *1) Internal and External Factors*

The analysis of the HBC business model at the physical layer intends to determine the critical internal and external factors that are crucial to achieve the enterprises' goals. This analysis classifies the critical pieces of information into two major categories:

- Internal factors – strengths and weaknesses that are internal to an organization
- External factors – opportunities and threats presented by the environment that are external to an organization

Analysis may consider the internal factors as either strengths or weaknesses. This consideration depends on their consequence on the objectives of an organization. The factors that may denote strengths with respect to one objective may be considered weaknesses (i.e., distractions, competition) for another objective. These factors may also contain personnel, finance, and manufacturing capabilities, among others.

External factors may include changes in terms of macroeconomic matters, technological change, legislation, and sociocultural changes. In addition, changes in the marketplace or in competitive positions are included. A matrix may often be used to present the results.

An analysis is merely among the numerous methods of categorization and exhibits disadvantages. To illustrate, this undertaking possibly tends to influence users to gather lists instead of thinking of the actual critical factors to achieve the objectives. It likewise uncritically provides the resulting lists and lacks precise prioritization (e.g., weak opportunities possibly balance strong threats).

#### *2) Marketing*

Numerous competitor analyses indicate that marketers develop comprehensive profiles of each market competitor. The particular focus is on the analysis of the relative competitive strengths and weaknesses. Moreover, marketing managers analyzes each competitor's cost structure, sources of profits, resources and competencies, competitive positioning and product differentiation, degree of vertical integration, historical responses to industry developments, and other similar factors.

In addition, marketing management sees the necessity of investing in research to gather the required data to perform accurate marketing analysis. Consequently, management frequently performs market research (alternately marketing research) to acquire information. Moreover, marketers utilize various techniques to engage in market research, including the following common methods:

- qualitative marketing research (e.g., focus groups),
- quantitative marketing research (e.g., statistical surveys),
- experimental techniques (e.g., test markets), and
- observational techniques (e.g., ethnographic (on-site) observation).

Furthermore, marketing managers may design and manage a variety of processes involved in environmental scanning and competitive intelligence to facilitate the identification of trends and provide information regarding the marketing analysis of a company.

## III. Conclusions

The current study centered on the novel business model for HBCs that recently captured the attention of researchers because of its ability to possibly evolve into an advanced communication level. This research discussed the market development and business modeling for HBC in a variety of layers. Evidently, a novel business model should be presented in the face of the expected massive changes after the initial implementation of HBC in the actual market. The results indicated that the network and physical layers have immense potential to develop novel business models in the coming years. Further analysis and explanation will definitely result in a considerably accurate design of the future market for network providers, RF engineers, and application developers (in the final stage). These innovations will definitely enhance the business model of HBC.

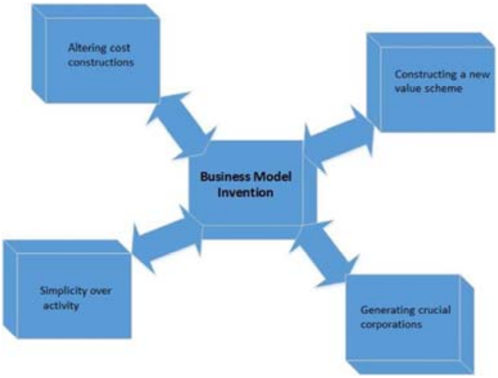


Fig. 1. Business Model Innovation [4]

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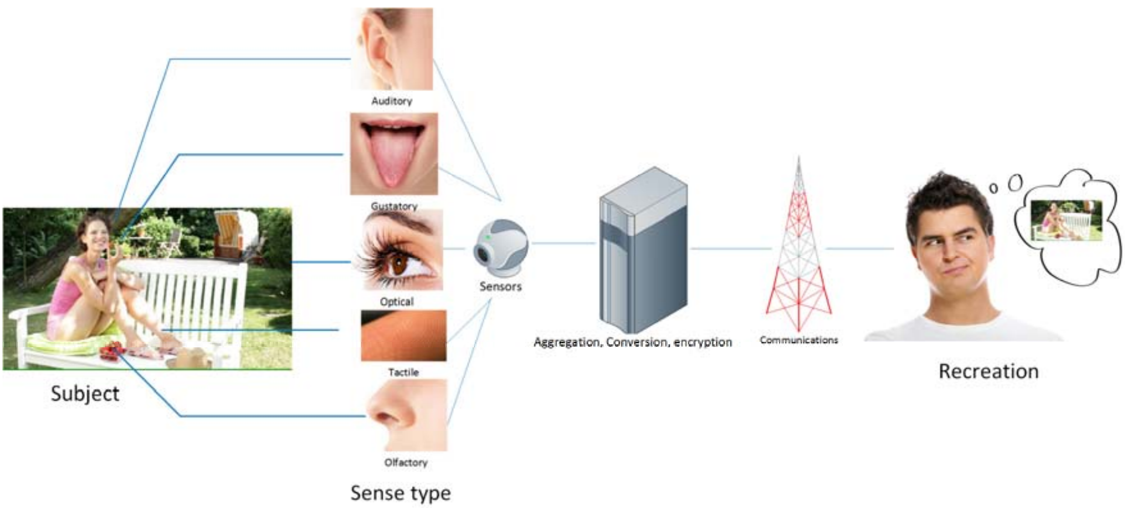


Fig. 2. Human Bond Communications

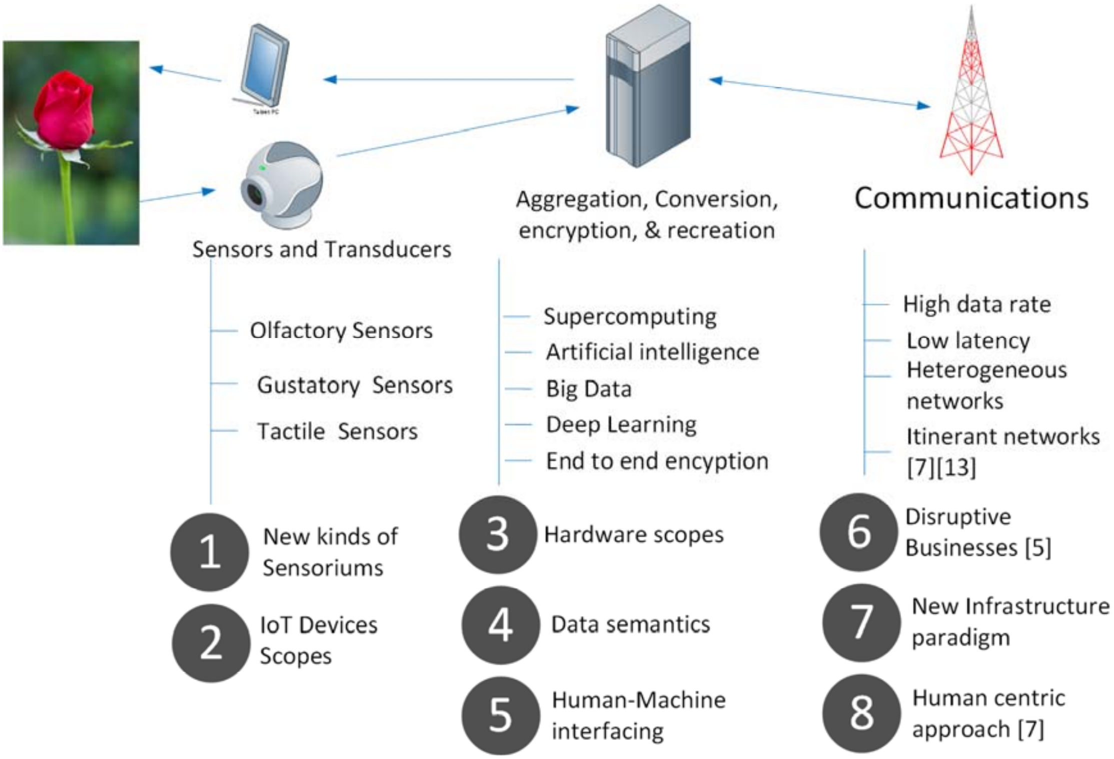


Fig. 3. Value proposition and new business model innovations in relation to HBC