Universidade de Aveiro
2021

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Técnicas de Equalização Híbridas para Sistemas Heterogéneos na Banda das Ondas Milimétricas

Hybrid Equalization Techniques for Heterogeneous Systems in the Millimeter Wave Band

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Adão Silva (orientador), Professor Auxiliar do Departamento de Eletrónica, Telecomunicações e Informática da Universidade de Aveiro e do Doutor Daniel Castanheira (co-orientador), investigador auxiliar no Instituto de Telecomunicações de Aveiro.

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agradecimentos

Primeiramente agradeço aos meus pais pelo apoio que me deram ao longo destes últimos anos, visto que pelo contrário não teria sido possível chegar aqui.

Em segundo, ao meu orientador Prof. Doutor Adão Silva e coorientador Doutor Daniel Castanheira que estiveram sempre disponíveis para qualquer eventualidade.

Por fim, agradeço a todos os professores que me acompanharam ao longo destes anos, à Universidade de Aveiro e ao Departamento de Eletrónica Telecomunicações e Informática pelo profissionalismo e empenho na formação de todos.

palavras-chave 5G, redes heterogéneas, comunicações na banda das ondas milimétricas, arquiteturas híbridas, MU-MIMO, massivo MIMO, alinhamento de interferência

resumo

Com a constante procura de melhores serviços e taxas de transmissão mais elevadas, as tecnologias atuais estão a atingir os limites de capacidade do canal. Contudo tecnologias como o MIMO e os sistemas heterogéneos permitem aumentar a capacidade do canal através da introdução de mais antenas nos transcetores e através da implementação de pequenos pontos de acesso espalhados pela célula primária, com o intuito de tornar as ligações entre os utilizadores e a estação base mais fiáveis. Tendo também em atenção que o espectro atual, sub-6GHz, está sobrecarregado e que devido às propriedades das frequências utilizadas a implementação de sistemas heterogéneos pode levar a níveis de interferência insustentáveis. Por modo a resolver esta sobrecarga futuros sistemas de comunicação devem aproveitar uma maior parte do espectro de frequências disponível. A banda das ondas milimétricas (mmWave) tem sido apontada como solução, o que permite aumentar a frequência utilizada para transportar o sinal e consequentemente aumentar as velocidades de transmissão. Uma outra vantagem da banda mmWave é que pode ser combinada com a tecnologia MIMO massivo, permitindo implementar mais elementos de antena nos terminais e consequentemente aumentar a capacidade do sistema. Umas das tecnologias desenvolvida para melhorar a eficiência energética em sistemas com centenas de antenas é a possibilidade de combinar técnicas de codificação analógica e digital, designadas como arquiteturas híbridas. A principal vantagem desta técnica é que, contrariamente ao processamento feito nos sistemas atuais, totalmente no domínio digital, esta nova arquitetura permite reduzir o número de cadeias RF por antena. Com o intuito de reduzir a interferência em sistemas heterogéneos, técnicas como o alinhamento de interferência são usadas para separar utilizadores das células secundárias dos utilizadores das células primárias de modo a reduzir a interferência multi-nível existente no sistema geral.

Nesta dissertação, é implementado e avaliado um sistema heterogéneo que combina MIMO massivo e ondas milimétricas. Este sistema é projetado com equalizadores analógico-digitais para remover com eficiência a interferência intra e inter-camadas. No domínio digital é utilizada a técnica de alinhamento de interferência para remover a interferência e aumentar a eficiência espectral. Os resultados mostram que as soluções propostas são eficientes para remover a interferência entre as células secundárias e a primária.

keywords

5G, Heterogeneous Networks, mmWave band communication, Hybrid architectures, MU-MIMO, Massive MIMO, Interference Alignment

abstract

With the constant demand for better service and higher transmission rates current technologies are reaching the limits of the channel capacity. Although, technologies such as MIMO and Heterogeneous systems appear to increase the channel capacity by introducing more antennas at the transceivers making the link between users and base station more reliable. Furthermore, the current spectrum, sub-6GHz, is becoming saturated and due to the properties of such frequencies the deployment of heterogeneous systems can introduce some levels of interference. Towards improving future communication systems a new part of the frequencies spectrum available should be used, researchers have their eyes on the mmWave band. This band allows to increase the carrier frequency and respective signal bandwidth and therefore increase the transmission speeds, moreover the properties of such frequencies unlock some advantages over the frequencies used in the sub-6G band. Additionally, mmWave band can be combined with massive MIMO technology to enhance the system capacity and to deploy more antenna elements in the transceivers. One more key technology that improves the energy efficiency in systems with hundreds of antenna elements is the possibility to combine analog and digital precoding techniques denoted as hybrid architectures. The main advantages of such techniques is that contrary to the full digital precoding processing used in current systems this new architecture allows to reduce the number of RF chains per antenna leading to improved energy efficiency.

Furthermore to handle heterogeneous systems that have small-cells within the macro-cell, techniques such as Interference Alignment (IA) can be used to efficiently remove the existing multi-tier interference.

In this dissertation a massive MIMO mmWave heterogeneous system is implemented and evaluated. It is designed analog-digital equalizers to efficiently remove both the intra an inter-tier interference. At digital level, an interference alignment technique is used to remove the interference and increase the spectral efficiency. The results showed that the proposed solutions are efficient to remove the macro and small cells interference.

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Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AA	Arrays of Antennas
ABS	Almost Blank Subframe
AP	Access Point
B5G	Beyond Fifth Generation
BS	Base Station
CoMP	Coordinated Multi-Point
CSI	Channel State Information
CU	Central Unit
DoF	Degrees of Freedom
EGC	Equal Gain Combining
eICIC	Enhanced Inter-Cell Interference Coordination
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GPRS	General Packet Radio Service
GSM	Global System for Mobile
HetNet	Heterogeneous Network
HSPA	High Speed Packet Access
IA	Interference Alignment
ICIC	Inter-Cell Interference Coordination
IP	Internet Protocol
ISI	Inter-Symbol Interference
IUI	Inter-User Interference
LOS	Line of Sight
LS-MIMO	Large-Scale Multiple-Input Multiple-Output
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution Advanced
MIMO	Multiple-Input Multiple-Output
mMIMO	Massive Multiple-Input Multiple-Output
MMS	Multimedia Messaging Service
MMSE	Minimum Mean Square Error
mmWave	Millimeter Wave
MRC	Maximal Ratio Combining
MUI	Multi-User Interference

MUT	Macro User Terminal
NMT	Nordic Mobile Telephone
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-to-Average-Power Ratio
QoS	Quality of Service
RF	Radio Frequency
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDMA	Spatial Division Multiple Access
SISO	Single-Input Single-Output
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SU-MIMO	Single User Multiple-Input Multiple-Output
SUT	Secondary User Terminal
SVD	Singular Value Decomposition
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunication System
WCDMA	Wideband Code Division Multiple Access
ZF	Zero-Forcing

1. Introduction

With the continuous evolution of technology, mobile users are growing and demanding better coverage and higher data rates. To accommodate all requirements from the users, mobile communication systems have developed throughout history. In this first chapter is portrayed the evolution of such systems since the beginning up to the current days.

1.1 Evolution from 1G to 4G

The first generation of mobile communications was introduced in the early 1980 by Nordic Mobile Telephone (NMT). This system only supported voice services in the analog domain based on circuit switching [1]. This type of systems used FDMA (Frequency Division Multiple Access) to secure multiple connections from different users through the same radio spectrum. Furthermore, FDMA and TDMA (Time Division Multiple Access) are two multiple access techniques, where the difference between these two techniques is that in the FDMA the users communicate with the receiver at the same time but in different frequencies, contrary to TDMA where each user uses a time slot to communicate with the receiver while sharing the same frequency resource.

With the exponential growth of technology and user subscription, 10 years later in 1990 was launched the 2nd Generation (2G) of mobile communication, also known as GSM (Global System for Mobile), based on TDMA and FDD (Frequency Division Duplex) to divide the bandwidth between uplink and downlink. The leap between 1G and 2G brought some new features to the mobile communication systems. Starting by the change from the analog domain to the digital domain, the 2nd Generation also provide a new service over the already existing voice service. The new service provided the possibility to exchange data services between users, such as SMS and MMS. The continuous research for better system, led to the development of GPRS (General Packet Radio Service). This new technology introduced the packet-switch transmission method to the GSM system. The GPRS has the advantage of dynamically adapt the available bandwidth among the users that have packets ready to transmit, resulting in an efficient management of resources [2]. To sum up, the new generation also showed improvements on data rate, capacity and in the quality of voice services.

The 3^{rd} Generation aimed to achieve even higher data rates, capacity, and better Quality of Services (QoS). Announced in the early 2000s the most well-known system of this generation is the Universal Mobile Telecommunication System (UMTS) [3]. The new generation uses Wideband Code Division Multiple Access (WCDMA) as air interface scheme and FDD and TDD (Time Division Duplex) to separate the downlink and the uplink direction. The use of WCDMA allow the use of a wider bandwidth improving the system data rate. With constant search for improvement, 3^{rd} Generation also developed the High Speed Packet Access (HSPA), which was able to reduce latency and provide even higher data rates in the downlink as in the uplink compared to its predecessor WCDMA.

The appearance of even more sophisticated terminals with greedy applications, demanding higher data rates, increase in system capacity, coverage and mobility, the 4^{th} Generation, also known as Long-Term Evolution (LTE) emerge in 2010. Using Orthogonal Frequency Division Multiple Access (OFDMA) for downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink. This multiple access scheme used reduced the interference between users providing even more robustness to the system. Furthermore, LTE introduced the IP-based networks for voice, video, broadcasting media and internet access [4].

With the oncoming LTE-Advanced systems a particular one seems ideal to further improve the system capacity, by using multiple antennas in the transmitter and in the receiver. The appearance of Multiple-Input Multiple-Output (MIMO) systems enable the usage of SDMA (Spatial Division Multiple Access) to handle multiple users in the same channel [5]. Moreover, in LTE-A rise the idea to densify the old-style macro cell by deploying small cells within the macro cell coverage. The advantage of small cells is the power consumption that decreases compared to the high power base station used in the homogenous grid [6].

In the Figure 1.1 is illustrated the evolution of mobile communication systems. It also presents the average transmission rate for the 2G, 3G and 4G.

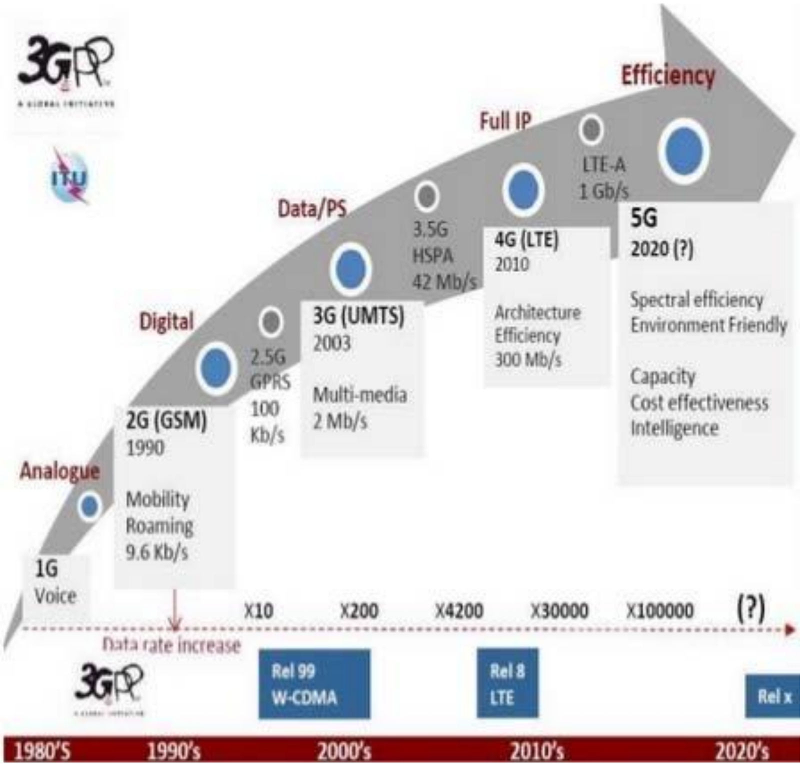

Figure 1.1 Evolution of mobile communication systems [7].

1.2 Future of mobile systems: 5G/B5G

With the number of mobile users increasing every day and the technological innovations in the user equipment, are forcing researchers to find better systems that can accommodate all the demands from each user. These demands as seen in the evolution of mobile communications are always the enhancements on capacity, data rates, coverage, mobility and the development of new systems capable of support even more multimedia services [8]. However, this constant increase is leading to the saturation of the frequency spectrum used, as solution to the crowed spectrum, researchers start exploring other bands available such as the millimeter band.

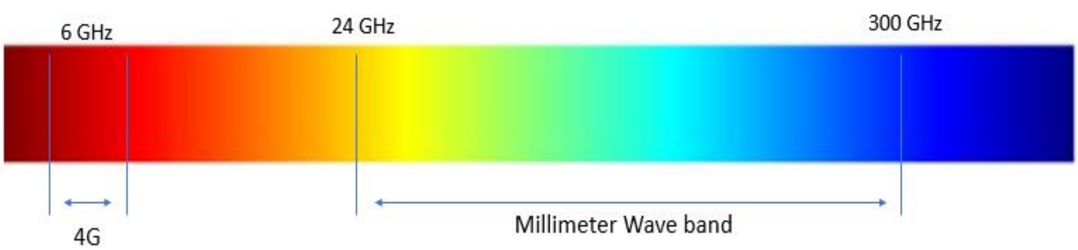

Figure 1.2 - Spectrum available for future communication systems.

As Figure 1.2 depicts the millimeter wave band is allocated between 24-300 GHz, which offer far superior data rates in the order of multi-Gb/s compared to the actual used spectrum that already implements frequencies in 28 GHz band. However, these frequencies have a superior wavelength making them vulnerable to objects in their path [9]. Towards solving the attenuation suffered by the millimeter waves, small cell deployment is a reliable, cost effective method to bring closer the user equipment and the access point increasing even more the coverage and capacity of the communications systems. Initially introduced by 3rd Generation Partnership Project (3GPP) and LTE the deployment of smaller access points in dense areas or at the macro cell edges can effectively enhance the connection reliability and provide a better experience for the user [10].

The development and improvement of sophisticated systems with multiple antennas such as MIMO, are also proving to be the answer for the future. This system has proven to be extremely efficient by delivering higher transmission rates, reliability and coverage [11]. The main goal is to increase the number of antennas in the receiver and in the transmitter. With the development of MIMO, systems such as multiuser MIMO and massive MIMO appear as great innovation to future systems. However due to the digital domain of communication systems each antenna requires a dedicated RF chain, leading to hardware limitations and power consumption.

Considering the deployment of small cell across the macro cell coverage results in the enhancement in spectral efficiency and lower power consumption since the user is communicating with a closer access point leading to lower transmitting power usage. Additionally, network densification can substantially improve the system capacity by spatial reuse [12]. However, the deployment of huge amounts of small cell can led to the increase in interference between multi-tier systems, to overcome this problem interference management techniques were developed [13].

The appearance of Massive MIMO concept allows the combination of the mmWaves, small cells deployments and MIMO systems with hundreds of antennas per base station. Being these some key technologies for the development of future networks B5G, additionally the combination of MIMO systems and frequencies in the millimeter, established a new design known as hybrid analog-digital transceivers that enables the possibility of having more than on antenna per RF chain, thus reducing some hardware constrains. The new method combines high dimensional analog phase shifters with low digital complexity [14] making it a great approach for 5G and beyond. Figure 1.3 shows 7 key aspects of 5G communication systems.

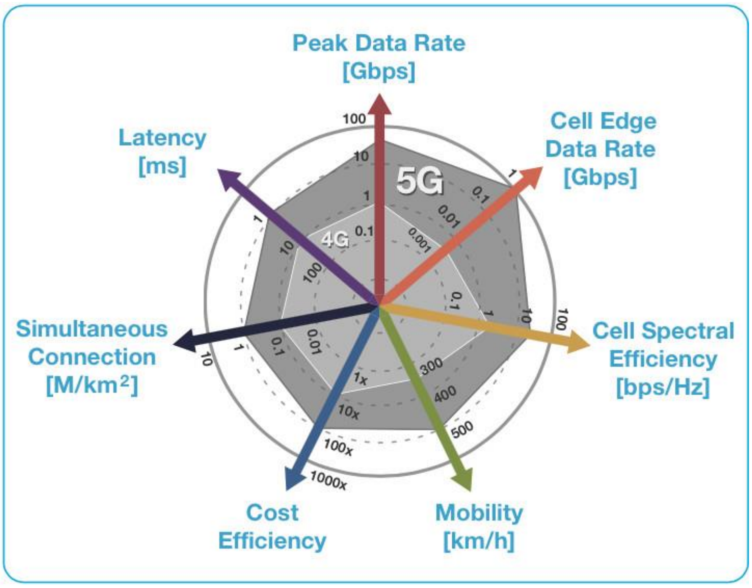

Figure 1.3 Key Aspects for 5G [15].

1.3 Motivations and Objectives

With the exponential increase of subscriber for each generation launched, since the release of the first generation the most important motivation for future systems was to provide enough coverage and higher data rate around the world. The expected massive proliferation of wireless systems points out that in the year 2024, 8.9-billion mobile subscriptions and 22-billion connected devices are anticipated [16]. Furthermore, the data-traffic is expected to continue its past trend of doubling every year (1000 times in 10 years) [17]. Besides, ten times more users will have to be managed and there will be a need to enable Gigabit per second peak speeds.

The traditional methods have a limited capability to cope with the requirements of system capacity, spectral and energy efficiency among others. The foreseen key enabling technology for the evolution of mobile technologies towards B5G are: cell densification, the use of higher frequencies, new air-interfaces, use of massive number of antennas, cognitive terminals and massive levels of coordination/cooperation among the network nodes.

The original grid design for mobile communications were based in strategical located base stations that served all users in a particular area. However, LTE-A and the concept of Heterogeneous networks (HetNets) shifted the networks by densification of the macro cell. Although problems of interference rise in HetNets, like the multi-tier interference, it can be resolved with Interference Alignment (IA), that take advantages of the remaining Degrees of Freedom (DoFs) available in the MIMO systems and use them to align all signals coming from the small cell in a sub dimension spanned by the existing channel between the macro cell and its users. In this manner the macro cell can still communicate with multiple users and not suffer interference from users that are currently transmitting to a small cell Access Point (AP).

On the other hand, the usage of frequencies in the mmWave band can diminish some of this interference due to higher path losses when compared to the sub-6G band. With higher path losses the mmWave signals only travel for short distances. Furthermore, the mmWave band unlocks the possibility to aggregate even more antennas in smaller spaces due to the signal wavelength. Although, hardware limitations start to appear with the increase in the number of antennas in the terminals. In the fully digital transceivers, each antenna needs a dedicated RF chain which is not a valid solution for the future. As solution hybrid techniques resulting from combining analog and digital precoding allows to use more than one antenna per RF chain, therefore the number of antennas can increase independently of the RF chains available.

The main objective of this dissertation is to implement and evaluate the performance, ultra-dense heterogeneous systems, where a set of small-cells coexist within the macro-cell. Macro-cell and small-cell users work under the same spectrum and communicate towards the BS and AP, uplink direction, such as in [18]. In a scenario where the carrier frequency is in the mmWave band and combined with MIMO technology either in the receivers and transmitters. Furthermore, hybrid architectures are considered to handle the massive number of antennas deployed, such architectures bring together analog and digital processing techniques to improve energy and spectral efficiency. The focus is to enable multiusers in the macro-cell, where the base station should be able to handle multiple connections from the different active users in the macro-cell. The small-cells are kept simple, where each small-cell only needs to listen one user. However, the existing small-cells must be coordinated between them to remove the interference from other small-cell users.

1.4 Outline

This dissertation is organized as follows:

In the first chapter is given an introduction of mobile communication system and their evolution throughout the years, from the very first till the fifth generation are detailed, then the motivations towards the future of wireless communication are mentioned. For last the notation used in this dissertation is defined.

In the second chapter are introduced the multiple antenna systems, the concept of diversity and spatial multiplexing. Furthermore, is performed an overview of the MIMO systems, scenarios with single-user and multi-user are reviewed, then the current state of massive MIMO systems is also assessed pointing out the advantages and limitation of the present technology.

In the third chapter the characteristics of the frequencies in the mmWave band are evaluated, then Massive MIMO technology and hybrid architectures are portrayed, potential benefits and limitations are presented regarding the combination of massive MIMO and mmWave band technologies. Moreover, heterogeneous networks are assessed as an important technology that can enable the enhancement of the system capacity for future wireless systems.

In the fourth chapter a heterogeneous network is evaluated, composed by a macro-cell and several small-cells. The overall system is assessed in the uplink direction, where multiple users distributed in the small-cells and in the macro-cell are trying to send data towards the receivers. Furthermore, a fully connected hybrid architecture is considered in the transmitter and receiver, where exists processing in the analog and digital domain. Additionally, to handle the existing multi-tier interference, the IA method is used to remove from the macro-cell signals upcoming from the small-cells. In the end, the performance results are present and reviewed.

Lastly, in the fifth chapter this dissertation is concluded, and some possible guidelines are given for future research.

1.5 Notation

The following notation is used in this dissertation: boldface uppercase letters, boldface lowercase letters and italic letters denote matrices, vectors and scalars, respectively. The operations $(\,.\,)^H$, $(\,.\,)^T$ and $(\,.\,)^*$ represents the Hermitian transpose, the transpose and the conjugate operators, respectively.

2. Multiple Antenna Systems

In this chapter is presented a brief on the evolution of MIMO systems which was a prominent technology used in the third Generation of mobile communication systems for the first time, although MIMO technology is dated prior to 1990. Furthermore, in this chapter the single and multiple user's scenarios are reviewed under MIMO characteristics. Additionally, an overview of massive MIMO systems in the current spectrum, sub-6GHz, is performed to weigh the opportunities offered by the deployment of huge amounts of antennas in the base station. All these groundbreaking technologic advances in wireless communication networks are providing better experience to all users around the world.

2.1 MIMO System

The major improvement when MIMO systems were introduced was the incorporation of multiple antennas in the receivers and transmitters, in Figure 2.1 is illustrated a Single User MIMO (SU-MIMO) scenario. When compared to the traditional Single-Input Single-Output, (SISO), where each terminal only has one antenna, the MIMO system with the extra antenna elements is able to achieve higher data rates and increase the channel capacity. Additionally, the usage of terminals with multiple antennas improves the overall performance without requiring additional bandwidth when compared to single antenna systems [19].

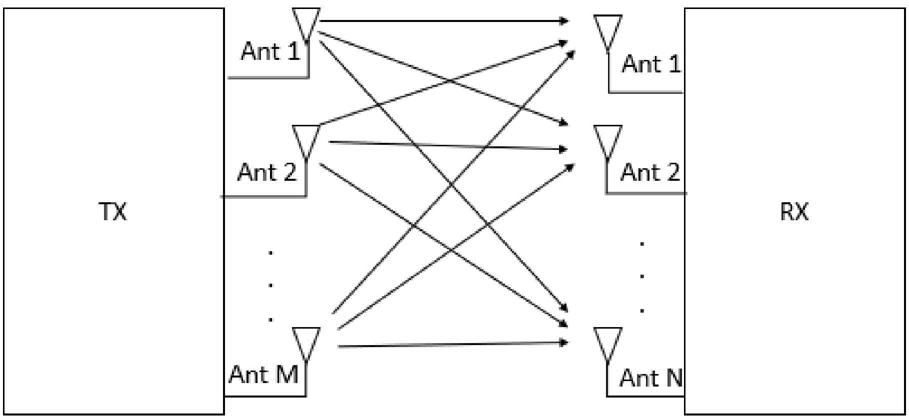

Figure 2.1 - MIMO configuration with M transmitting antennas and N receiving antennas.

With the introduction of multiple antennas transceivers there are two new techniques aimed to led communication system even further. Both techniques take advantage on the number of antennas deployed at the transceiver, to create individual channels between receiver and transmitter. Furthermore, the channels can be used to send copies of the same signal or to increase the data rate by use each channel to send different streams.

These techniques are based on the rich scattering environment provided by MIMO systems and are defined as Spatial Diversity and Spatial Multiplexing, that are studied in the following points of this chapter.

2.1.1 Spatial Diversity

The fact that MIMO is able to create independent paths between transmitter and receiver, exploiting the multipath signal propagation turns out to be the perfect direction for communication systems. With multiple antennas in the transmitter and in the receiver, the diversity gain is achieved by using each transmitting antenna available to send the same stream towards the receiver, this method allows to introduce redundancy on the system and therefore improve the reliability of the channel [20].

In the receiver side, each available antenna receives a different copy of the signal, the overall signal received by each antenna has different interferences and slightly different times, due to the different paths that the signal took. To deal with the different fades suffered by the signal, the receiver reconstructs it by sum up all the copies received in a constructive manner. To achieve the best signal reconstruction linear combiners such as Maximal Ratio Combining (MRC) and Equal Gain Combining (EGC) can be used for achieving receive diversity.

When the linear combining technique MRC is used, all received signals from each antenna are weighed considering the signal SNR. Furthermore, signals with higher SNR are amplified and the signals with lower SNR are further attenuated to not interfere destructively with the signal reconstruction, this method tend to maximize the SNR by increasing the detection algorithm. In the case where the EGC technique is used, each individual signal received is co-phased and then all signals are combined with equal weight. Moreover, the EGC have a low complexity when compared to the MRC, however, it can have worst performance due to the fact that all signals received independently of the SNR are combined.

The concept behind diversity is to ensure that at least one copy from the transmitter reaches the receiver and therefore improving the reliability of the connection, furthermore, the probability to occur errors are decreased. Diversity can be achieved in the time and frequency where in the first case consists in send the same data in different time slots and in the second case the same data is sent in different frequencies.

2.1.2 Spatial Multiplexing

An additional way to improve multiple antenna systems, such as MIMO, is by using spatial multiplexing. This method can be adopted to improve the data rate without increase bandwidth usage. Spatial multiplexing allows to create parallel channels between the transmitter and the receiver when Channel State Information (CSI) is available at both ends of the channel or only available at the transmitter or receiver sides. In this manner the transmitter can send multiple different streams of data through the channels.

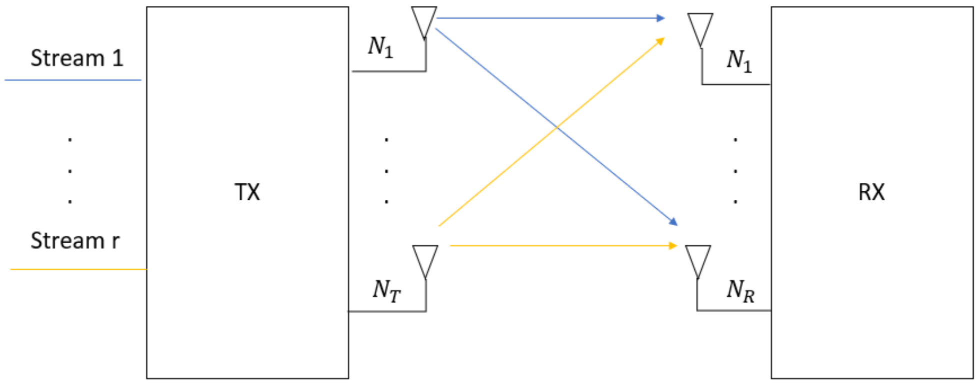

Figure 2.2 Spatial multiplexing in MIMO

While diversity aimed to send multiple copies of the same signal through the available channels between receiver and transmitter, spatial multiplexing uses the available channels to transmit different data. In Figure 2.2 is depicted one transmitter that want to send multiple streams to the base station, the limit of streams that the transmitter can send is min (N_T, N_R), assuming uncorrelated antenna channels, where N_T is the number of transmitting antennas and N_R is the number of receiving in antennas.

2.1.2.1 Channel Known at the Transmitter

For a SU-MIMO system that have CSI at the transmitter is possible use a singular value decomposition (SVD) to convert the channel matrix $\mathbf{H} \in \mathbb{C}^{N_R \times N_T}$ into a set of parallel channels [21]. In Figure 2.3 is depicted a transmitter and a receiver with N_T and N_R antennas, respectively. For the receiver the signal can be described as

$$\mathbf{y} = \mathbf{Hx} + \mathbf{n} \tag{1}$$

where $\mathbf{y} \in \mathbb{C}^{N_R \times 1}$ denotes the signal received, $\mathbf{x} \in \mathbb{C}^{N_T \times 1}$ the transmitted signal and $\mathbf{n} \in \mathbb{C}^{N_R \times 1}$ refer to the additive white Gaussian noise with variance σ^2.

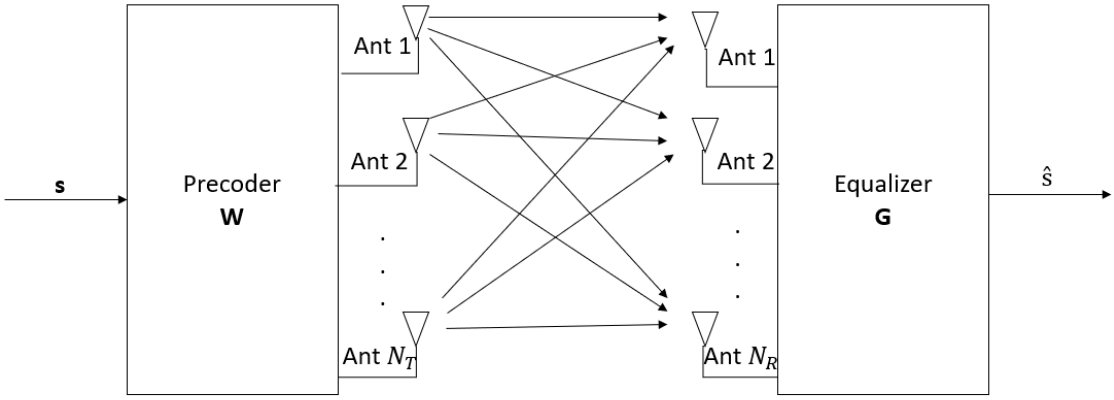

Figure 2.3 SU-MIMO System.

Decomposing the channel matrix **H** using SVD

$$\mathbf{H} = \mathbf{UDV}^H \tag{2}$$

where $\mathbf{U} \in \mathbb{C}^{N_R \times r}$ and $\mathbf{V} \in \mathbb{C}^{N_T \times r}$ are unitary matrices and $\mathbf{D} \in \mathbb{R}^{r \times r}$ is a diagonal matrix with non-negative real numbers that represent the singular values of the matrix **H** such that $r = rank(\mathbf{H}) \leq$ min (N_T, N_R).

The precoder matrix **W** is given by:

$$\mathbf{W} = \mathbf{VP}^{1/2} \tag{3}$$

where $\mathbf{W} \in \mathbb{C}^{N_R \times r}$ and $\mathbf{P} \in \mathbb{R}^{r \times r}$ is a diagonal matrix related to power allocation for the different data streams.

The equalizer, denoted by **G**, is given by:

$$\mathbf{G} = \mathbf{U}^H \tag{4}$$

where $\mathbf{G} \in \mathbb{C}^{r \times N_R}$.

The transmitting signal from the user is then:

$$\mathbf{x} = \mathbf{Ws} \tag{5}$$

where $\mathbf{s} \in \mathbb{R}^{r \times 1}$ is a vector with the r symbols the transmitter intends to send in parallel. Then the received signal at the base station is described mathematically as:

$$\mathbf{y} = \mathbf{UDV}^H\mathbf{VP}^{1/2}\mathbf{s} + \mathbf{n} \tag{6}$$

To estimate the transmitted r symbols the receiver only has to apply the equalizer **G**. the obtained estimate is:

$$\hat{\mathbf{s}} = \mathbf{Gy} = \mathbf{U}^H\ \mathbf{UDV}^H\ \mathbf{VP}^{1/2}\ \mathbf{s} + \mathbf{U}^H\ \mathbf{n}\ = \mathbf{DP}^{1/2}\ \mathbf{s} + \mathbf{U}^H\ \mathbf{n} \tag{7}$$

Therefore, together the precoder and equalizer diagonalize the channel, transforming it into a set of r parallel and independent SISO channels. This enables the scaling of the channel capacity proportionally to number of parallel channels created.

2.1.2.2 Channel Not Known at the Transmitter but known at the Receiver Side

For the case where the transmitter does not have CSI knowledge, multi-symbol equalizer is needed to recover the transmitted symbols transmitted over N_T antennas. The most used linear equalizers are Zero-Forcing (ZF) and Minimum Mean Square Error (MMSE) which achieve sub-optimal performance when $N_R \geq N_T$

Zero Forcing

The ZF is a linear equalizing method that achieves sub-optimal performance but decrease the receiver complexity [22]. This method is designed to eliminate the channel interference from the signal and thus removing the Inter-Symbol Interference ISI.

The ZF equalizer is given by the pseudo-inverse of the channel matrix $\mathbf{H}$ defined as:

$$\mathbf{G}_{\mathrm{ZF}} = (\mathbf{H}^H\mathbf{H})^{-1}\mathbf{H}^H \tag{8}$$

Then the symbols can be retrieved as:

$$\hat{\mathbf{s}} = \mathbf{G}_{\mathrm{ZF}}\,\mathbf{H}\mathbf{s} + \mathbf{G}_{\mathrm{ZF}}\,\mathbf{n} \tag{9}$$

However, the ZF method has the disadvantage of amplify the noise term in the presence of low Signal-to-Noise Ratio (SNR).

Minimum Mean Square Error

The MMSE equalizer aims to minimize the mean square error between the transmitted symbols and the estimated received symbols by using the knowledge of the noise statistics, thus providing a better estimate of the data symbols, making a compromise between noise enhancement and intersymbol interference reduction. The MMSE equalizer, considering independent white Gaussian noise with variance σ^2, is:

$$\mathbf{G}_{\mathrm{MMSE}} = \left(\mathbf{H}^H\mathbf{H} + \sigma^2\mathbf{I}_{\mathrm{N_T}}\right)^{-1}\mathbf{H}^H \tag{10}$$

With the implementation of MMSE the noise term is not amplified at lower SNR as happens in the ZF, thus the performance is improved. However, for higher values of SNR the performance is equal to the ZF [23].

2.2 MU-MIMO

Initial work done on MIMO systems were only focused on point-to-point communication, where only one user can communicate with the receiver, but the focus has changed and exploiting the spatial multiplexing technique allows various users to share the same frequency and time resources to communicate with the receiver [24].

The MU-MIMO systems are able to handle different users due to the spatial separation between them, in contrast with SU-MIMO where only one user benefits from the spatial multiplexing techniques here several users are served within the same time/frequency resources. Some advantages over the SU-MIMO system are listed below [25].

- MU-MIMO allows spatial multiplexing gain at the base station for users that only have one antenna, single antenna users, enabling the development of cheaper terminals.
- MU-MIMO is more immune to path loss and the LOS that causes degradation in the SU-MIMO, which is not a problem for multiuser scenarios.

However, the MU-MIMO system needs CSI to correctly recover the symbols from each user, opposing to the SU-MIMO, moreover the signal processing can be done only on the base station due to the capability of acquiring the CSI at the BS.

Furthermore, the multiuser interference (MUI) is managed by the multiple antennas available in the base station and/or the DoF provided. Additionally, in a MIMO system the DoF also provides the number of users that can communicate simultaneous with the base station without interfering with other users.

MU-MIMO technology applies different multiple access techniques for the uplink and downlink, with interest in keep the terminals as simple as possible MU-MIMO uses SC-FDMA for the uplink direction due to the improvement in the peak-to-average-power ratio (PAPR) and the decrease in the power needed to transmit [26] when compared to the technique used in the downlink that is based in OFDMA methods. Furthermore, in the next two following section the uplink and downlink are presented.

2.2.1 Uplink

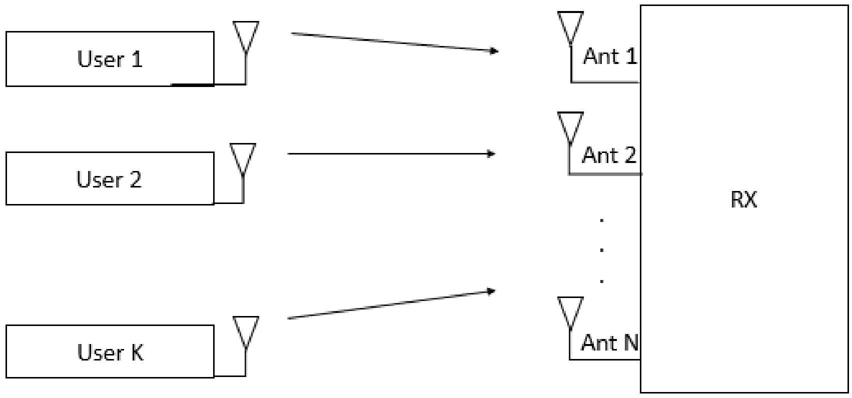

Figure 2.4 Uplink Communication MU-MIMO system

In the uplink direction the *K* users spatially separated can transmit data to the BS, the signal received at the BS is recovered based in linear methods such as ZF and MMSE, already discussed. With the channel knowledge at the BS its only necessary the equalization of the received signal with the inversion of the channel matrix. Thus, retrieving each user data, the uplink direction is mostly similar to the single user case where the transmitter does not have CSI. Moreover, a limitation of these systems is that the number of transmitting antennas must be less than the number of receiving antennas in the receiver, in this case the BS.

To recover the transmitted symbols, the baste station applies a linear equalizer to the signal received. Furthermore, one example of such a linear equalizer is the ZF. The recovered symbols at the base station is:

$$\mathbf{y} = \mathbf{G}_{\mathrm{ZF}}\,\mathbf{Hx} + \mathbf{G}_{\mathrm{ZF}}\mathbf{n} \tag{11}$$

where $\mathbf{y}$ is receiving symbols vector in the BS, $\mathbf{G}_{\mathrm{ZF}}$ is a linear ZF equalizer, $\mathbf{x}$ is the transmitted vector that contains the symbols of all users. Furthermore $\mathbf{H}$ is the channel matrix between all users and the BS, de dimensions of the channel matrix depends on the *K* active users and the number of antennas at the BS.

2.2.2 Downlink

For the downlink MU-MIMO the base station communicates with all users using the same time-frequency spectrum. Since the BS have CSI, the signal transmitter to each user pass through a precoder, that can be either a ZF or MMSE, thus the signal that arrives at each user is already the correct symbol up to a constant factor. This happens due to the application of the linear precoding techniques that remove the channel component before the signal being sent through the channel.

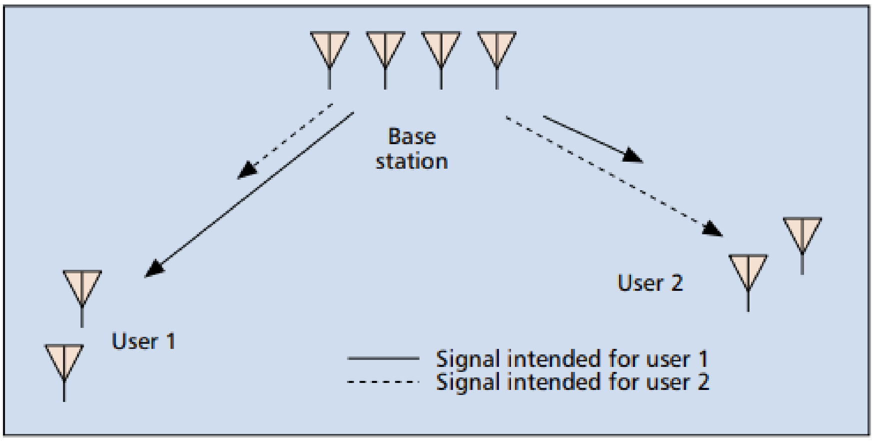

Figure 2.5 Downlink interference in MU-MIMO system [27].

In the Figure 2.5 is depicted a MU-MIMO downlink scenario where the base station wants to send data to two terminals, each one equipped with at least two antennas. The output signals at the BS and using the ZF method can be given by:

$$\mathbf{y} = \mathbf{W}_{\mathrm{ZF}}\,\mathbf{x} \tag{12}$$

where $\mathbf{y}$ is the transmitting vector from the BS to the multiple users, and $\mathbf{W}_{\mathrm{ZF}}$ is a linear ZF precoder given by:

$$\mathbf{W}_{\mathrm{ZF}} = \mathbf{H}^{H}(\mathbf{H}\mathbf{H}^{H})^{-1} \tag{13}$$

Furthermore, this precoder must be computed respecting the power constrain at the BS, due to the possibility of the channel be in bad condition and require more than available power to be inverted.

Once the signal is sent through the air, is affected by the channel characteristics that should be instantaneously removed by the precoder. In this way the BS eliminates the channel component before the symbols arrive at the user, the received signal, $\mathbf{r}$, is given by:

$$\mathbf{r} = \mathbf{H}\mathbf{W}_{\mathrm{ZF}}\mathbf{x} + \mathbf{n} \tag{14}$$

2.3 Massive MIMO

The constant searching for providing even more capacity, transmission rate and coverage in the mobile communication led to the development of a system such as Massive MIMO (mMIMO), also called Large-Scale MIMO (LS-MIMO). The usage of hundreds of antennas in the base station allows the possibility to use beamforming techniques that increase the spatial dimensions and consequently increase the degrees of freedom of the system. Due to the higher number of antennas deployed, the mMIMO system is capable to increase the bandwidth efficiency and simultaneously reducing the transmitted power [28]. Moreover, with massive number of antennas is possible to increase energy efficiency due to the narrower beam used to communicate with the user.

Additionally, the usage of narrow beams allows the antenna array to cover a specific area and thus reducing Inter-User Interference (IUI). The Figure 2.6 illustrates the spatial multiplexing technique using narrow beams, where the antennas are at the same physical location.

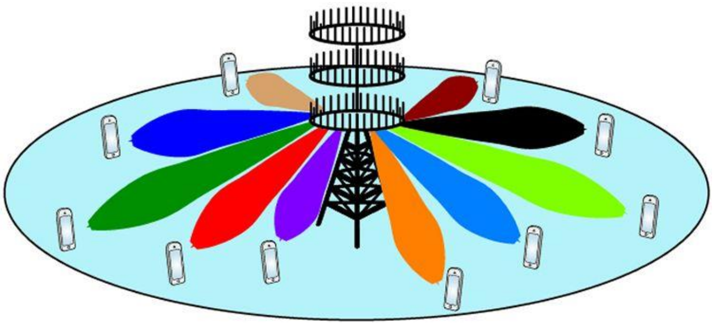

Figure 2.6 MIMO spatial multiplexing [29].

However, the deployment of massive number of antennas at the BS is impractical in the sub-6G wave band, due to the big size of the antennas and also the antenna elements need to be physical separated to reduce the levels of correlation between channels. To overcome this constrain, one possibility is to give the BS various Arrays of Antennas (AA) that are covering different areas. This scheme allows a distributed BS able to support more antennas and providing better services.

In Figure 2.7 is illustrated the typical configurations of AA for a distributed base station, configurations such as linear, spherical, cylindrical, rectangular and distributed can be used as antenna arrays. Traditional MIMO systems were known by using the linear AA that only adjust the beam in the horizontal direction, to control the vertical dimension the other configurations can be considered. The distributed AA is used mostly inside buildings or for outdoor cooperation [28].

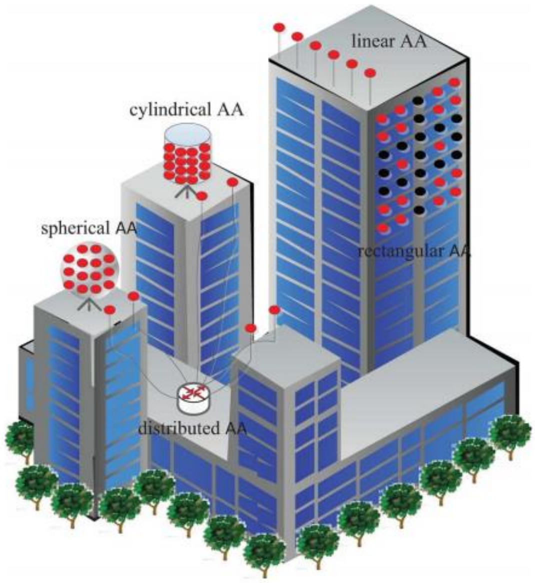

Figure 2.7 mMIMO deployment. [28].

By using the different AA configuration even more spatial gain can be extracted from the system, also the energy waste can be reduced due to the higher directivity provided by the higher number of antennas [30]. Furthermore, is expected that each AA and the RF circuit are integrated into a single circuit board, cutting down the cost to deploy large number of antennas [28].

In the two following sections are summarized the benefits and limitations of mMIMO, [31] [32] [33].

2.3.1 Advantages of Massive MIMO

With the implementation of massive MIMO technology in wireless communication systems the overall throughput and energy efficiency are enhanced. Moreover, due to the huge amount of antennas deployed at the base station the link reliability between user and the BS is further improved, additionally the communication between two ends is faster, thus the latency provided is lower. Furthermore, the DoF of such system increase with the number of antennas deployed and can be used to allow more connections without interference between users, also relatable with interference management mMIMO can separate users using beamforming techniques that allows the beam to be steered in the desired direction [34].

Massive MIMO systems use TDD techniques to estimate the CSI, due to the reciprocity between the uplink and downlink direction. Since the channel characteristics are considered the same, massive MIMO can use pilot sequences that are transmitted by each user for CSI estimation in the downlink.

2.3.2 Limitations of Massive MIMO

For the current mMIMO system, whose implementation is in the sub-6G band, the dimensions of the AA described earlier can be huge, therefore typical AA only can be deployed if there exists sufficient space to deploy the hardware needed. For these reasons the implementation, the development and the maintenance of such AA is expensive.

As mentioned in the previous section mMIMO systems use TDD techniques to compute the CSI, this because FDD techniques are unrealistic, due to the different bands used in the uplink and downlink direction, thus the channel characteristics for both directions are different. Furthermore, the time necessary to exchange feedback increase proportionally to the number of antennas deployed.

Although, TDD techniques are more suitable to compute the CSI using pilot sequence this can led to pilot contamination. Due to the limit of pilot sequences available the number of users served is also limited, although nonorthogonal pilot sequences can be used, but at the cost of increase the level of interference between cells that are sharing the same sequence.

3. Millimeter-Wave Communication Systems

In this chapter is presented one of the key technologies that will enable the future of mobile communication. The combination of millimeter waves properties and the already existing multiple antenna transceivers will allow to pack even more antennas in the base station and in the user equipment. Further this chapter provides an overview about heterogeneous systems and how these can be used to improve system performance.

3.1 Millimeter Waves

With a larger spectrum than the sub-6Ghz counterpart the millimeter band spans from 30 to 300 GHz, being the usage of this band intended for the future of mobile communication. The particular interest in this band is the wavelength of such frequencies that require less space between antennas, allowing to pack a superior number of antennas per area.

However, the use of mmWave is not as simple as it sounds, the main problem at higher frequencies, where the communication between base station and the user terminal must be in line of sight (LOS) or near LOS, this happens because higher frequencies experience more path losses and attenuation than the current used frequency spectrum. Additionally, the mmWave spectrum experiences attenuation in some specific bands, these attenuations may be due the oxygen absorption between 57 GHz and 66 GHz and from water vapor absorption between 164 GHz and 200 GHz.

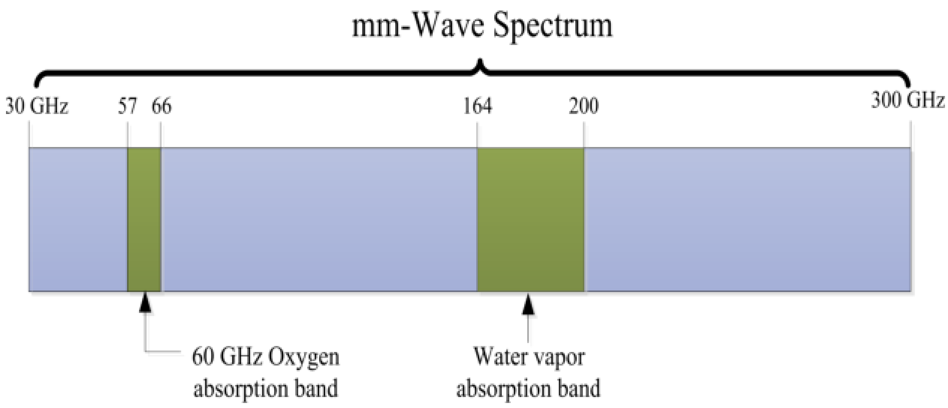

Figure 3.1 Millimeter attenuation band [35].

Although the mmWaves suffer from attenuation, the total spectrum affected is substantially smaller than the available spectrum provided by the mmWave band. The path loss suffered by mmWaves increase when compared with the current spectrum used. For mmWaves is hard to cross walls, glass as other objects described in the following table 1.

Table 1 mmWave attenuation values for different materials [9].

		Attenuation (dB)		
Material	**Thickness (cm)**	**< 3 GHz [6, 8]**	**40 GHz [7]**	**60 GHz [6]**
Drywall	2.5	5.4	–	6.0
Office whiteboard	1.9	0.5	–	9.6
Clear glass	0.3/0.4	6.4	2.5	3.6
Mesh glass	0.3	7.7	–	10.2
Chipwood	1.6	–	.6	–
Wood	0.7	5.4	3.5	–
Plasterboard	1.5	–	2.9	–
Mortar	10	–	160	–
Brick wall	10	–	t178	–
Concrete	10	17.7	175	–

As mmWaves are considered short-range waves, due to higher path losses, as previously described, the combination of mmWaves and the densification of small cell in the macro cells is a promising solution to improve the available data rate and system capacity for the future generations of mobile communication.

Although, the increase in wavelength enables the possibility to deploy massive MIMO systems due to the decrease in the space between antennas the future communication system needs overcome the RF constrain. To this end, hybrid analog-digital techniques appear as solution to operate more than one antenna per RF chain.

3.2 Millimeter Wave Massive MIMO

When combining the MIMO systems and frequencies at the mmWave band is possible to increase throughput, improve spectral and energy efficiencies, improve the channel capacity and reach higher gains in spatial multiplexing. Moreover, to provide better services mobile technology has three directions to follow, it is possible to improve the system capacity and coverage by deploying more base stations, use the mmWave band to achieve higher data rates, in the order of gigabits per second due to the large bandwidth available at higher carrier frequencies and the Massive MIMO technology.

By using mmWave the separation between antenna elements is smaller, thus is possible to create AA with smaller sizes, furthermore the short range of the mmWave are desire to reduce the levels of interference between cells [36]. The combination of mmWave Massive MIMO and the densification of the macro cell is the step to accomplish the main goals for the future of mobile communication systems. Additionally, the combination of large-scale antenna arrays with the higher frequency results in a promising solution to overcome the path losses suffered by the mmWave, thus the densification of the macro-cell is useful to reduce the short-range characteristic of the frequencies in the mmWave band.

In the sub-6GHz most processing methods are done in the digital domain, which require a dedicated RF chain per antenna [37]. For future system systems is important to reduce the power consumed by the RF circuits. To reduce the number of RF chains in the terminals and in the base station hybrid architectures urge to solve the hardware limitations.

3.3 Hybrid analog-digital architectures

The hybrid analog-digital massive MIMO systems appear as an answer to the hardware limitation in the conventional MIMO systems. The new technique enables the possibility of one RF chain to control many antennas, decreasing the power consumption of the base station while increasing the throughput by combining analog and digital precoding in the upcoming transceivers.

Moreover the full digital processing techniques are not suitable to handle systems in the mmWave band, due to the number of RF chains be equal to the number of antennas. Hybrid techniques can reduce the RF circuits due to the introduction of analog precoders/equalizers. Most of the analog techniques are based in a network of analog phase shifters that change the phases of the signal transmitted or received in each available antenna [38].

With the urge of hybrid techniques two main schemes are study, such as a fully connected and sub connected architectures.

3.3.1 Fully connected

In Figure 3.2 is illustrated the scheme of a fully connected transceiver, this specific structure connects each available RF chain with all antennas. If the systems have N_{RF} RF chains and N_T transmitting antennas, the final signal processing path is given by $N_T \times N_{RF}^2$ RF paths. This results in the increase of complexity, however the fully connected structure achieves full beamforming gain in each transceiver [39].

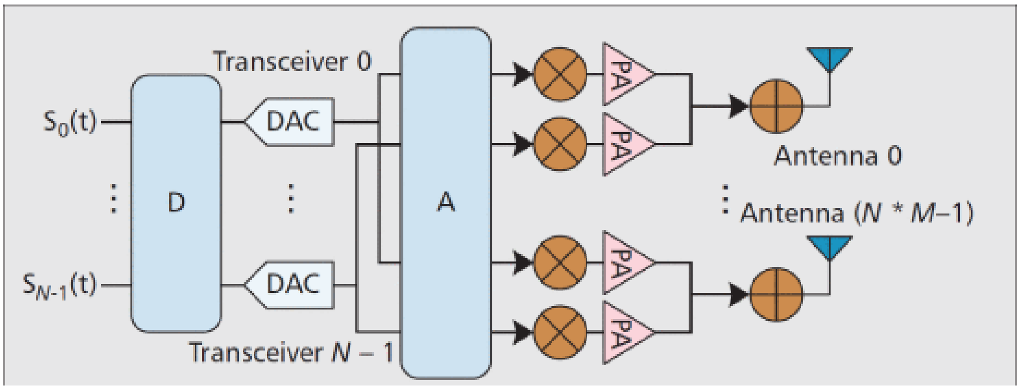

Figure 3.2 Fully connected hybrid structure [39].

3.3.2 Sub-connected

This next structure depicted in Figure 3.3 has the same function as the last one, but on the other hand is more practical to implement when compared with the last structure presented. Each N_{RF} chain is only connected to a subset of antenna elements and results in signal processing over $N_T \times N_{RF}$ RF paths [39]. The resulting beamforming gain is limited when compared to the fully connect counterpart.

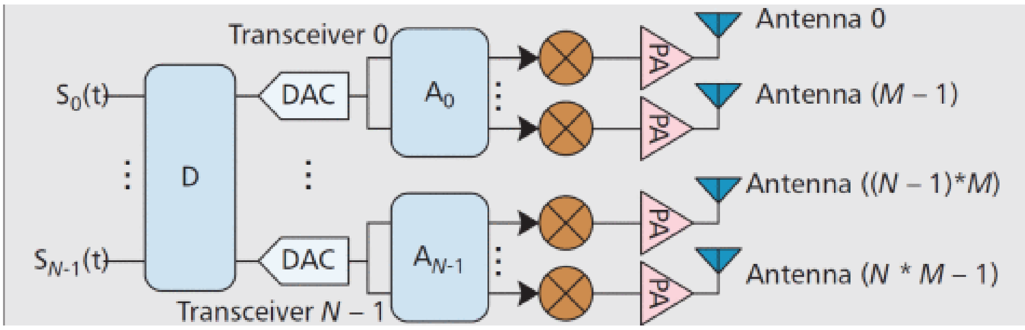

Figure 3.3 Sub-connected Hybrid structure [39].

3.4 Heterogeneous networks

Introduced by LTE-Advanced the concept of HetNets relies on the deployment of small cell within the traditional macro cell. The deployment these lower power, smaller dimensions and cheaper access points such as picocells, femtocells and relays, in the macro cell allow the increase in data rates, the improvement in the channel capacity and enhancements in the spectrum reuse. This new design aims to bring closer the user and the access point reducing waiting times [40].

In ultra-dense areas where the number of users that tries to communicate with the single base station is higher, like for example in urban areas, then the base station can have difficulty to serve all the requests. With the new layout, depicted in Figure 3.4, heterogeneous networks can use the macro base station to cover a vast area and providing mobility, while the smaller access point provides higher data rates with better energy efficiency.

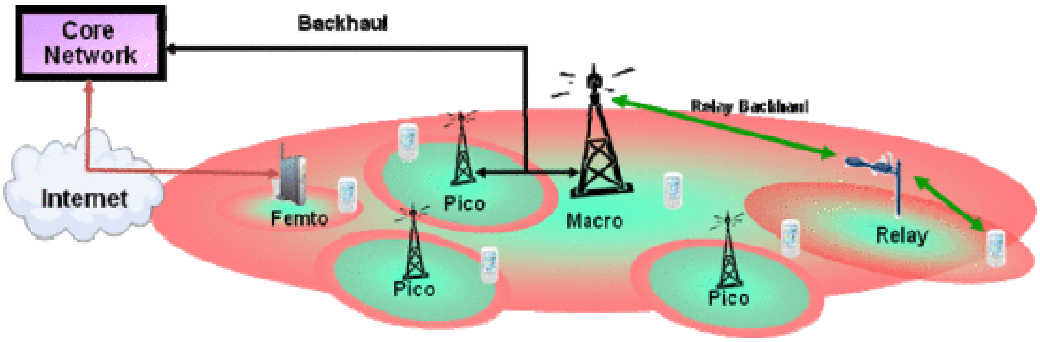

Figure 3.4 Heterogeneous Network deployment [41].

However, interference mitigation techniques must be used to reduce the interference between each small cell and between small cells and the macro cell, thus it still exist some difficulties to deploy small-cells in massive number.

As mentioned before the deployment of a large number of small cells within the macro cell can led to the increase of interference. To decrease the level of interference methods such as Range Expansion, Enhanced Inter-cell Interference Coordination (eICIC), Coordinated Multi-Point (CoMP) and Interference Alignment were developed to diminish the interference between small cell and macro cell.

Range Expansion

In homogenous networks the users normally connect itself to the strongest signal, normally sent by the macro BS, however in the HetNets this could not be the best option. One possible scenario is when the small cell is deployed nearby the macro BS, in this case the user should not connect to the stronger signal, because of design constrains small cells use much less power when compared to the macro BS. Therefore, instead of considering the signal strength to create an association, users should search for the base station that offer less path loss. In Figure 3.5 is illustrated this technique that results in the expansion of the small cell coverage.

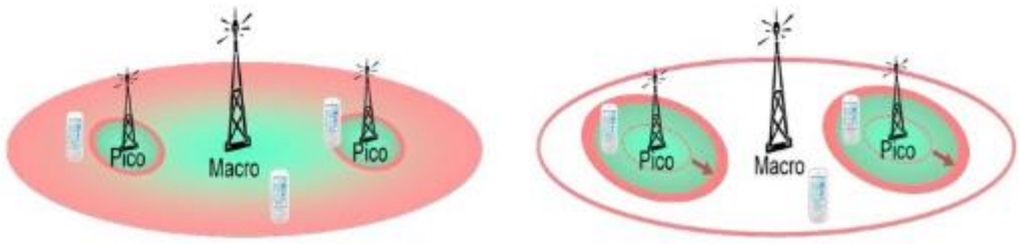

Figure 3.5 Range extension [41]

Enhanced Inter-cell Interference Coordination

Introduced by 3GPP eICIC is an evolution of ICIC to support HetNet conditions, ICIC aimed to deal with the interference of users that are in the cell edges. The eICIC allow the small cell and the macro cell to share de same co-channel but at different times, this led to the concept of Almost Blank Subframe (ABS). The ABS avoid interference between the macro cell and the small cell by marking some frames to the small cell, meaning that in certain time slots are not used by the macro-cell and are predefined to respond to the small cell, an example of such technique is depicted below.

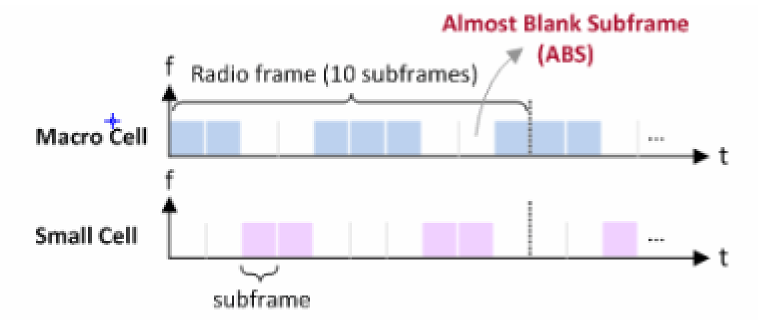

Figure 3.6 ABS Frames [42].

Coordinated Multi-Point

With CoMP a particular user at the cell edge can receive data from multiple cells, for this to be possible its necessary that the cells sharing data to the same user are coordinated between them to maintain a certain level of performance. In Figure 3.7 is depicted a downlink direction where the unique user is receiving data from the neighbors cells.

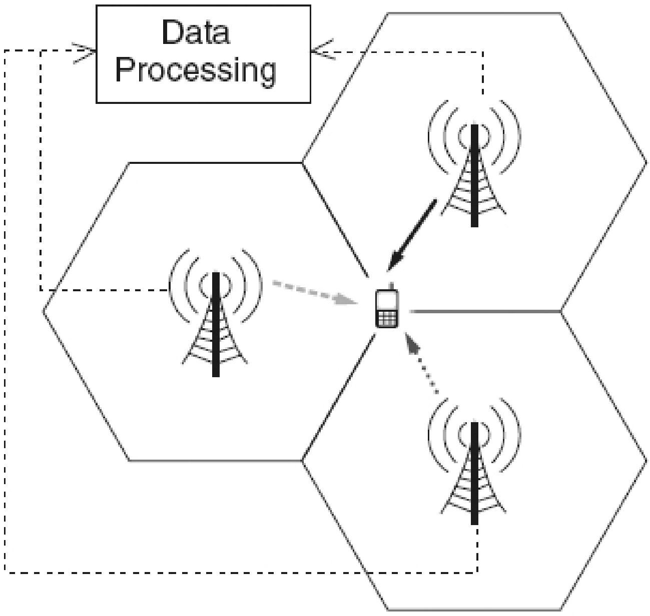

Figure 3.7 Downlink CoMP [43].

Interference Alignment

Another technique to reduce the levels of interference in HetNets is the Interference Alignment method that additionally maximize the degrees of freedom of the network. IA can be done in time, frequency and space dimension, being the last one the most prominent option due to the capability to work together with multiple antennas transceivers.

The concept of IA is to use precoders that line up the data into specific subspace of the channel, then at the receiver side the signal is retrieved by applying a decode matrix that is orthogonal to the subspace containing the interference from other users, in another words the intended signal is only decoded at the intended receiver since unwanted signal are inside the interference subspace [44].

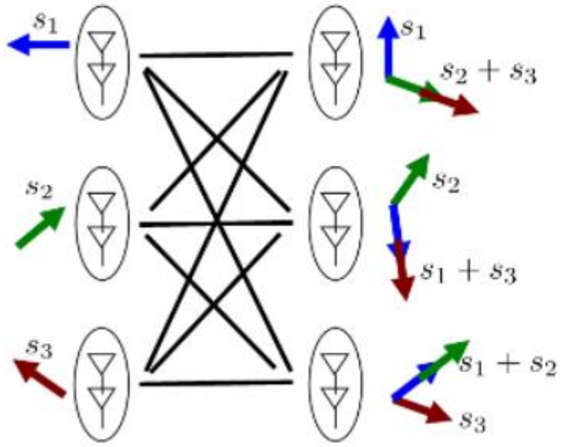

Figure 3.8 Three user scenario [45].

Figure 3.8 depicts a scenario where three different users are trying to communicate with its respective access point, to further understand the concept of IA. Scenarios like this can happen when three small cells are adjacent to each other and each user is trying to transmit.

For systems to implement IA method is necessary for the transmitter to have knowledge of the channel state, so for that the AP sends feedback to its users, normally the feedback is the direction vector that the users should use to transmit the data. In this way each cell have its users transmitting in a common direction that will be considered as interference for other APs. The desired receiver through linear methods can retrieve the correct data.

4. Hybrid analog-digital schemes for mmWave massive MIMO Heterogeneous systems

Technologies like densification of macro-cells, massive MIMO and millimeter waves are three fundamental key technologies for the evolution of the current systems, with the goal to increase capacity, provide better coverage, reduced latency and improve user experience.

The combination of MIMO system and mmWaves opens the door for the deployment of systems with a large number of antennas, due to the possibility to pack more antennas in smaller integrated circuit area. Although hardware complexity was increased due to the number of RF chains, that increase proportionally with the number of antennas deployed for fully digital architectures, architectures such as hybrid analog-digital transceivers allows to have less RF chains than antennas, improving power consumption.

The low range of mmWaves are attractive to the deployment of even more small cells, due to higher path losses, millimeter waves can only travel a short distance, reducing to some extent interference levels. However, interference management techniques are still required to remove existent multi-tier interference that can have a severe impact in the system performance. As already described, Interference Alignment technique allows the macro base station to eliminate the interference induced by users that are being served by the low power access point.

In this chapter a massive MIMO mmWave heterogeneous network is evaluated, starting by introducing the system model, then the analog and digital equalizers/precoders are explained in the system signals section and at the end the performance results are presented and analyzed, for different system configurations. The work proposed in [18], assuming a single user per macro-cell, is extended here for a set of users per macro-cell.

4.1 System Model

Considering the uplink direction in a heterogeneous network composed by N small cells within the coverage of a macro cell, sharing the same frequency resource that is in the mmWave band.

In respect to the macro cell components there are K users with N_{mut} transmitting antennas and a BS with N_{BS} receiving antennas. At the small cells we have a system composed by an AP with N_{AP} receiving antennas and each AP only serves one user with multiple antennas, N_{sut}. The secondary system includes all APs scattered within the macro cell coverage and a Central Unit (CU) responsible for coordinating all APs deployed.

Moreover, for the secondary system the processing is divided in two parts: the APs include the analog domain processing and the CU the digital domain processing and perform joint processing of the signals received from all APs. Unlike the secondary system where the processing is done in a distributed manner in the primary system the analog-digital processing is centralized and is done at the BS.

The heterogeneous system described so far is represented in Figure 4.1.

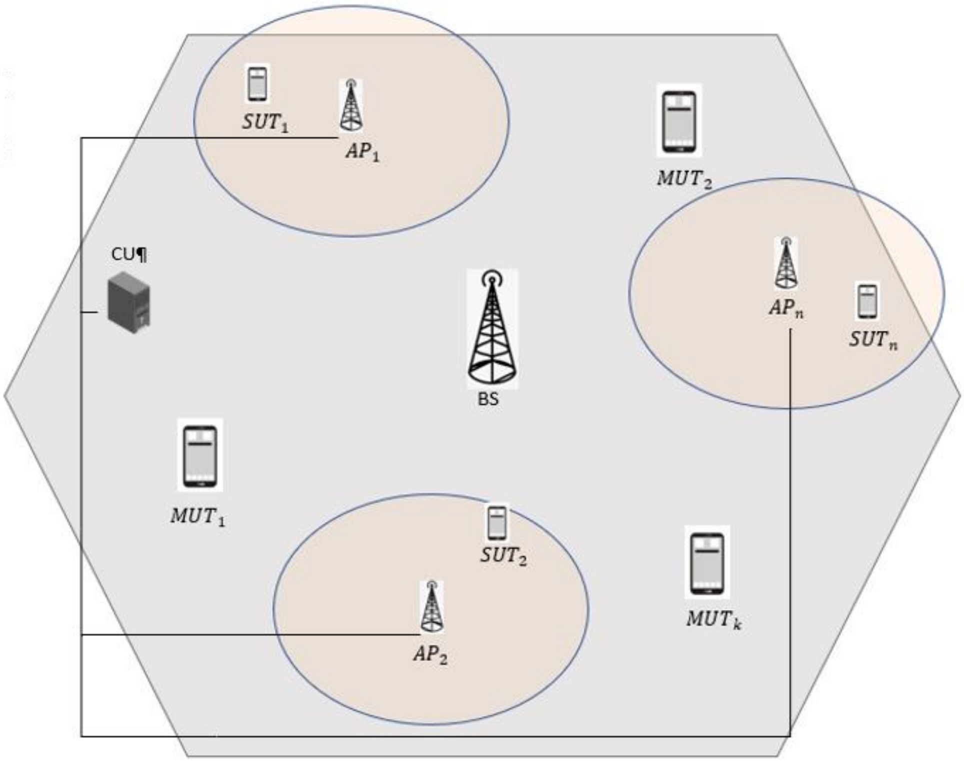

Figure 4.1 System model scheme.

Even though the BS is seen as a single entity, for simple understand let us consider that the BS is divided into two logical entities such as occur in the secondary system.

To normalize the notation between the primary and secondary system, the K macro user is denoted by MUT_k and the user of the small cell N is denoted by SUT_n. At the receiver side the entity that performs the analog processing is denoted by RX_p, with $p \in \{0, \dots, N\}$, where RX_0 is the analog processor for the primary system. The digital domain is denoted as BS for the primary systems and CU for the secondary system.

The channel model used is based in a narrowband clustered channel where the channel matrix is considered the sum of the contribution of N_{cl} scattering clusters, where each of the clusters contributes with N_{ray} propagation paths [18], furthermore, $\mathbf{H}_{\mathrm{p,u}}, p, u \in \{0, \dots, N\}$ is

$$\mathbf{H}_{\mathrm{p,u}} = \gamma \sum_{i,l} \alpha_{il}^{p.u} \mathbf{a}_{\mathrm{p,u}}(\phi_{il}^{p,u}, \theta_{il}^{p,u}) \mathbf{b}_{\mathrm{p,u}}(\varphi_{il}^{p,u}, \vartheta_{il}^{p,u}) \tag{15}$$

where $\gamma = \sqrt{N_T N_R / N_{cl} N_{ray}}$ denotes the normalization factor, $\alpha_{il}^{p.u}$ the complex gain of the *i-th* scattering cluster and the l^{th}ray for the channel between transmitter and receiver. Furthermore, the pairs $\phi_{il}^{p,u}, \theta_{il}^{p,u}$ and $\varphi_{il}^{p,u}, \vartheta_{il}^{p,u}$ represents the azimuth angles of arrival and departure for the channel between receiver and transmitter, respectively. The terms $\mathbf{a}_{\mathrm{p,u}}$ and $\mathbf{b}_{\mathrm{p,u}}$ denote the normalized received/transmitted array response for the channel between receiver and user.

4.1.1 User Terminal Block Diagram

For the heterogeneous system, the secondary user terminal (SUT) and the *K* macro user terminal (MUT) have different characteristics. For each SUT it is used multiple antennas and more than one RF chain but considering that the number of RF chains is always less than the number of antennas deployed, while the MUT only have one RF chain and can be seen as a single antenna terminal or a multiple antenna terminal.

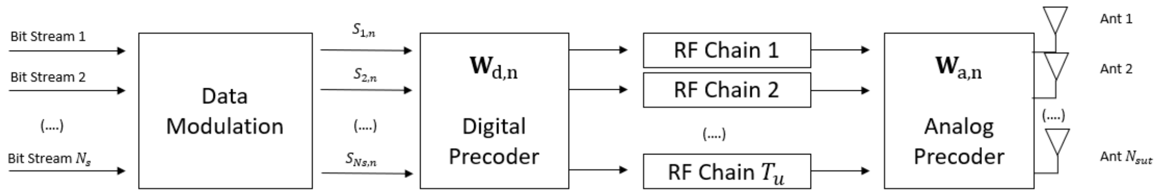

Figure 4.2 Small cell user design.

As depicted in Figure 4.2 the SUT has N_{sut} transmitting antennas that are connected to T_u RF chains. Furthermore, the transmitted signal from SUT_n is given by:

$$\mathbf{x}_{\mathrm{n}} = \mathbf{W}_{\mathrm{a,n}} \mathbf{W}_{\mathrm{d,n}} \mathbf{s}_{n} \tag{16}$$

where $\mathbf{W}_{\mathrm{a,n}} \in \mathbb{C}^{N_{sut} \times T_u}$ is the analog precoder that use a number of phase-shifters to connect each RF chain to the available antennas in a fully connected architecture, $\mathbf{W}_{\mathrm{d,n}} \in \mathbb{C}^{T_u \times N_s}$ is the digital precoder and $\mathbf{s}_{\mathrm{n}} \in \mathbb{C}^{N_s}$ denotes the SUT_n data symbols modulated with an M-QAM constellation.

For the primary system, each MUT only use one RF chain independently of the number of antennas deployed. As such the MUT precoder includes only the analog component as the digital component would correspond only to a scaling operation.

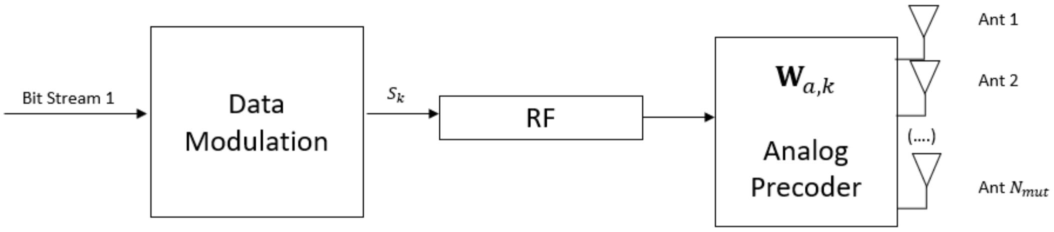

Figure 4.3 Macro cell user design.

The signal for each MUT_k is given by

$$\mathbf{x}_{\mathrm{k}} = \mathbf{w}_{\mathrm{a,k}} s_{\mathrm{k}} \tag{17}$$

where $\mathbf{w}_{\mathrm{a,k}} \in \mathbb{C}^{N_{mut} \times 1}$ denotes the analog precoder vector and s_{k} denotes the symbol to transmit.

4.1.2 Receiver Block Diagram

Starting by the macro cell, where the analog and digital processing techniques are done in the same physical location, Figure 4.4 depicts the block diagram for the macro cell receiver. As already stated, the RX_0 block is responsible to treat the analog domain of the signal received and send to the BS to be digitized by the R_0 RF chains. Then a ZF equalizer is applied to the signal, resulting in the elimination of the interference coming from the secondary system and the estimative of the expected symbol of each of the K users.

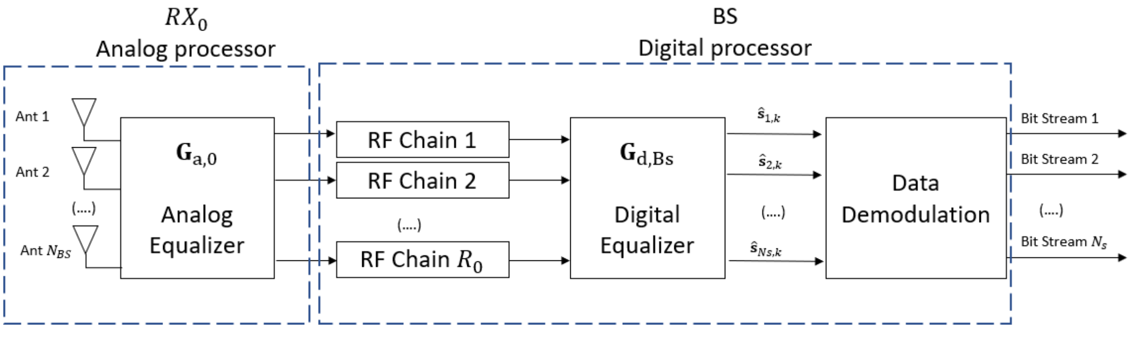

Figure 4.4 Macro Cell Receiver.

In the secondary systems the digital and analog domain are separated physically, where the analog processing is done by each AP and then the processed signal is sent through the backhaul to the CU where the digital processing is performed jointly.

The block diagram represented in Figure 4.5 illustrate the design of the secondary system, composed by the different RX_n and the CU. The major achievement of the distributed analog-digital scheme for the secondary system is that the quantity of information sent from the AP towards the CU is much smaller. The fact is that when the AP receives the signal from the respective SUT it is received at N_{sut} antennas, then AP after applying the analog equalizer send it though the RF chains that are less than the number of antennas.

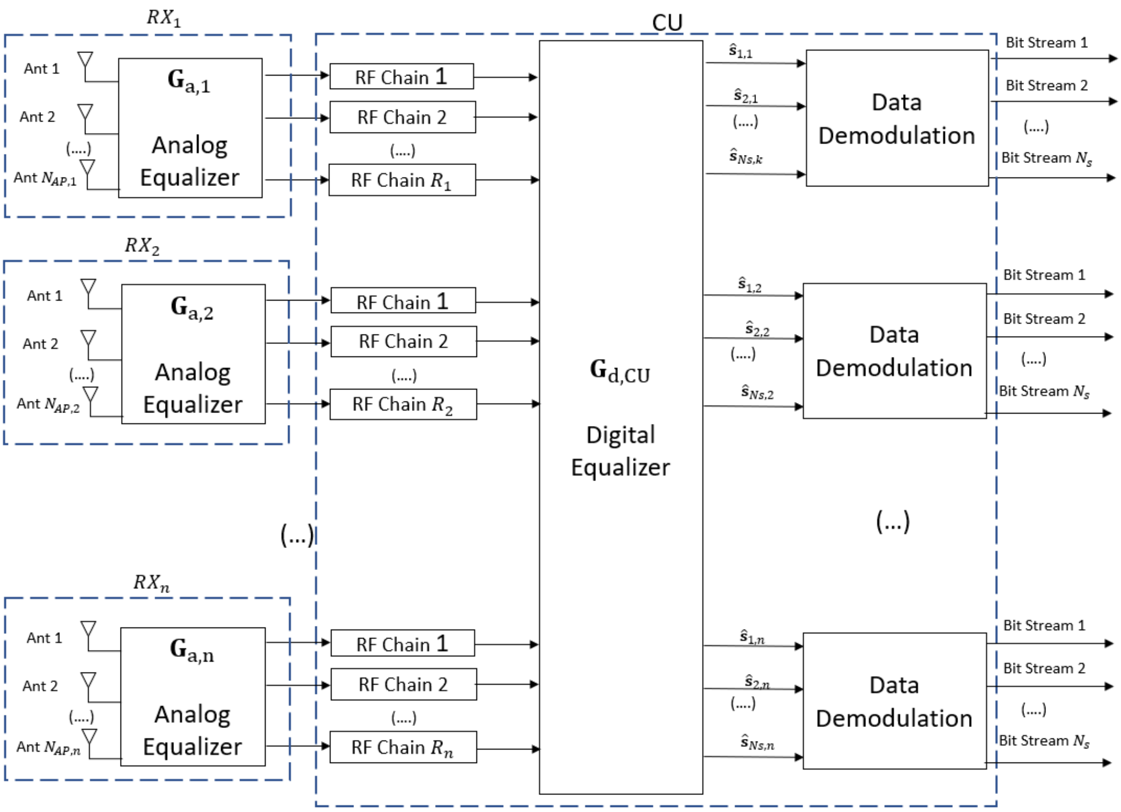

Figure 4.5 Secondary systems receiver.

4.2 System Signals

Starting by presenting the different channels in the heterogeneous network this section will result in the signal received at the BS and at the CU, moreover the equalizers and precoders used are explained and designed to reduce the multi-tier interference.

For the primary system, the channel between the K MUTs and the BS is denoted as $\mathbf{H}_{\mathrm{pp}} \in \mathbb{C}^{N_{BS}\times(KN_{mut})}$ and the channel between the K MUTs and the different N APs is denoted as $\mathbf{H}_{\mathrm{sp}} \in \mathbb{C}^{(NN_{AP})\times(NN_{sut})}$, being the later the interfering channel that are created towards the secondary system.

In secondary system the channel between each SUT_n and each AP_n is given by a matrix with size $N_{AP} \times N_{sut}$. The overall channel matrix for the secondary system is denoted by $\mathbf{H}_{\mathrm{ss}} \in$

$\mathbb{C}^{(NN_{AP})\times(NN_{sut})}$, where the diagonal is the channel of the pair SUT_n, AP_n and the remaining values are the channels between the pair $SUT_n, AP_j, n \neq j$, in other words, the interfering channel between small cells. As users of the primary system interfere with the users of the secondary systems the reverse also happens and $\mathbf{H}_{\mathrm{ps}} \in \mathbb{C}^{N_{BS}\times(NN_{sut})}$ denotes these interfering channels between the SUTs and the BS.

For the BS point of view the signal received at the antennas is defined as:

$$\mathbf{y}_{\mathrm{p}} = \mathbf{H}_{\mathrm{pp}}\mathbf{W}_{\mathrm{pa}}\mathbf{x}_{\mathrm{p}} + \mathbf{H}_{\mathrm{ps}}\mathbf{W}_{\mathrm{sa}}\mathbf{W}_{\mathrm{sd}}\mathbf{x}_{\mathrm{s}} + \mathbf{n} \tag{18}$$

where $\mathbf{x}_{\mathrm{p}} = [\mathbf{x}_1, \dots, \mathbf{x}_{\mathrm{k}}]^{\mathrm{T}}$ is the transmitted symbols from the MUTs, $\mathbf{x}_{\mathrm{s}} = [\mathbf{x}_1, \dots, \mathbf{x}_{\mathrm{n}}]^{\mathrm{T}}$ is the signal transmitted by the SUTs and $\mathbf{n} \in \mathbb{C}^{N_{BS}\times 1}$ refer to the additive white Gaussian noise with variance σ^2.

Considering each MUT analog precoder, the primary system analog precoder matrix is denoted by $\mathbf{W}_{\mathrm{pa}} \in \mathbb{C}^{(KN_{mut})\times K} = diag(\mathbf{W}_{\mathrm{a,1}} \dots \mathbf{W}_{\mathrm{a,k}})$ and includes all MUT's precoders.

For the secondary system $\mathbf{W}_{\mathrm{sa}}$ and $\mathbf{W}_{\mathrm{sd}}$**,** denote the overall analog precoder matrix and the digital precoder matrix for each SUT_n, respectively. Both matrices are diagonal and each entry correspond to the analog and digital precoder for the *N* SUTs.

For the secondary system, the signal available at the CU is the concatenation of the signals received at every AP is denoted as:

$$\mathbf{y}_{\mathrm{s}} = \mathbf{H}_{\mathrm{ss}}\mathbf{W}_{\mathrm{sa}}\mathbf{W}_{\mathrm{sd}}\mathbf{x}_{\mathrm{s}} + \mathbf{H}_{\mathrm{sp}}\mathbf{W}_{\mathrm{pa}}\mathbf{x}_{\mathrm{p}} + \mathbf{n} \tag{19}$$

4.2.1 Analog Equalizer

To overcome the hardware constraints, hybrid analog-digital equalizers allow to control more than one antenna per RF chain. For this work the analog equalizer design used was proposed in [18], initially design for the secondary system it also can be applied to the primary system, due to the fact that the BS can be seen as one pair of AP and CU.

For the primary system, the analog equalizer is denoted as $\mathbf{G}_{\mathrm{a,0}} \in \mathbb{C}^{R_0\times N_{BS}}$, and for the secondary system the analog equalizer is given by $\mathbf{G}_{\mathrm{a,n}} \in \mathbb{C}^{R_n\times N_{AP,n}}$.

The equivalent channel between the BS and all MUTs including the analog precoder and analog equalizer, can be seen as a smaller channel of size $R_0 \times K$, where before the analog component, the channel dimensionality was given by the number of antennas available in the primary system after the analog domain the channel size depends on the number of RF chains available. The equivalent channel is

$$\mathbf{H}_{\mathrm{eq}} = \mathbf{G}_{\mathrm{a,0}}\mathbf{H}_{\mathrm{pp}}\mathbf{W}_{\mathrm{pa}} \tag{20}$$

Moreover, the channel between each SUT and the BS is used to compute the equivalent channel from the secondary system towards the BS.

$$\mathbf{H}_{\mathrm{eqps,n}} = \mathbf{G}_{\mathrm{a,0}}\mathbf{H}_{\mathrm{ps,n}}\mathbf{W}_{\mathrm{sa,n}} \tag{21}$$

From now on, the equivalent channels are seen as if it were taken from a full digital system, therefore linear techniques can be applied to the system to remove the interference. Furthermore, $\mathbf{H}_{\mathrm{eqps}}$ matrix is computed for each channel between SUT and BS. Starting from the multi-tier interference, the next section is described the IA technique to remove the interference coming from the secondary systems to the primary system.

4.2.2 Interference Alignment

In a heterogeneous network, users that are being processed at a small cell, SUTs, can interfere with the users from the macro cell, MUTs in the uplink. To reduce the levels of interference between the multi-tier networks, the secondary system composed by the different APs and respective SUTs should be projected to not disturb the primary system.

It is important to remind that the number of users present in the primary system, denoted by K, should be less than the total number of RF chain at the BS ($K < R_0$), so that the number of DoF available are enough to align the secondary system transmission. By aligning the signals transmitted by the SUT of the secondary system in a common direction $\mathbf{v}$ the BS can remove the multi-tier interference from the system using a filter matrix $\mathbf{Q}$ that is in the null-space of $\mathbf{v}$, i.e. $\mathbf{Q} = null(\mathbf{v})$.

To accomplish the alignment of the secondary system the BS computes the singular value decomposition of $\mathbf{H}_{eq} = \mathbf{UDV}^{\mathrm{H}}$, where $\mathbf{U} \in \mathbb{C}^{R_0 \times R_0}$. By selecting a combination of linear vectors that offer a singular value equal to zero and denoting the resulting vector as $\mathbf{v} \in \mathbb{C}^{R_0 \times 1}$, the BS can feedback the vector $\mathbf{v}$ to the secondary users, where it will be used for precoding in each SUT.

To feed back the vector to the secondary system the BS transmits only a quantized version of $\mathbf{v}$, resulting in the transmission of the real and imaginary sign part of $\mathbf{v}$ to the secondary system. By only transmitting the quantized version of $\mathbf{v}$ the feedback requirements are reduced for each Transmission Time Interval (TTI). In the following it is assumed that the used SUT's alignment direction is this quantized version.

4.2.3 Digital Precoder

For the secondary users to transmit a signal without interfering with the primary system, these users, at different small cells, must align the signal in the direction $\mathbf{v}$. The digital precoder is computed by inverting the equivalent channel between each SUT_n and the BS, using the respective $\mathbf{H}_{\text{eqps,n}}$ and then multiply it by the alignment vector.

$$\mathbf{W}_{\text{sd}}^{n} = \left(\mathbf{H}_{\text{eqps,n}}\right)^{-1}\mathbf{v} \tag{22}$$

where $\mathbf{W}_{\text{sd}}^{n} \in \mathbb{C}^{(T_u \times N_s)}$ is digital precoder matrix for SUT_n, then the matrix $\mathbf{W}_{\text{sd}} = diag(\mathbf{W}_{\text{sd}}^{1}, \dots, \mathbf{W}_{\text{sd}}^{N})$ is the overall digital precoder matrix for the secondary users.

4.2.4 Digital Equalizers

As mentioned before linear techniques can be used to retrieve the symbols in the BS and in the CU. To remove the interference from the SUTs the equivalent channel seen by the BS after the analog equalizer, is multiplied by the filter matrix $\mathbf{Q}$, resulting in the $\mathbf{H}_{\text{eqBS}} = \mathbf{Q}\,\mathbf{H}_{\text{eq}}$. From this point, the BS is able to remove the unwanted signal from the secondary system due to the existing orthogonality between the filtering matrix $\mathbf{Q}$ and the vector $\mathbf{v}$. Furthermore, to separate the different symbol from each MUT the digital equalizer is given by:

$$\mathbf{G}_{\text{d,BS}} = \left(\mathbf{H}_{\text{eqBS}}^{T}\,\mathbf{H}_{\text{eqBS}}\right)^{-1}\mathbf{H}_{\text{eqBS}}^{T} \tag{23}$$

where $\mathbf{G}_{\text{d,BS}} \in \mathbb{C}^{(KN_{mut}) \times R_0}$.

To enforce the zero-interference condition the following constrain must be respected.

$$\mathbf{G}_{\text{d,BS}}\mathbf{H}_{\text{eqps}}\mathbf{W}_{\text{sd}} = 0 \tag{24}$$

By respecting the constrain is possible to see if the alignment was done correctly, it also visible that the signal of the secondary system is in the null-space of the primary system.

In the secondary system the digital equalizer is obtained in a similar way. With channel knowledge the CU is capable to separate each small cell due to the overall channel matrix $\mathbf{H}_{\text{ss}}$ where each diagonal entry is the channel between the pair (SUT_n, AP_n). Since the secondary system also suffers from interference from the MUTs present in the system, the overall channel can be seen as the concatenation of $\mathbf{H}_{\text{ss}}$ and $\mathbf{H}_{\text{sp}}$, where the later is the interfering channels between the K MUTs and the N APs. By applying the ZF method in the CU the interference from the primary system is eliminated and the symbols of each SUT are decoded.

4.3 Simulation and Results

To evaluate the heterogeneous system performance, various scenarios are considered, where the number of antennas and the number of the RF chains at either the transmitter or in the receiver are varied, with the exception of the macro cell user that can only adjust the number of antennas, to explore its impact in the system performance. Furthermore, the number of MUTs present in the primary system is also investigated to evaluate the performance of the macro cell BS.

Aiming to study different situations in the heterogeneous system five scenarios are analyzed as described in Table 2. Furthermore, the scenarios are summarized as follows.

For the first three scenarios, is considered that the macro BS only serves $K = 2$ MUTs, additionally, each MUT only has one antenna and one RF chain. For the secondary system, different combinations of antennas and RF chains are used either in the receiver or in the transmitter.

In Scenario 4 the secondary system is simulated as in Scenario 3, on the other hand, both users of the primary system see the number of antennas increased, while keeping the usage of one RF chain. The goal of this configuration is seeing the behavior of the primary system when the number of antennas in the transmitter is increased.

The previous scenarios only considered two MUTs in the macro cell, either as single antenna or as multiple antenna terminal. In Scenario 5 the number of K users is extended to four. Moreover for this scenario each user is again seen as a single antenna terminal.

Table 2 Parameters for the different Scenarios

Parameters	N	N_{BS}	N_{AP}	N_{mut}	N_{sut}	R_0	R_n	T_u
Scenario 1	2	32	16	1	16	4	4	4
Scenario 2	2	64	32	1	32	4	4	4
Scenario 3	2	64	32	1	32	8	8	8
Scenario 4	2	64	32	16	32	8	8	8
Scenario 5	2	64	32	1	32	8	8	8

The metric considered to evaluate the system performance is the BER, that is in function of E_b/N_0, where $E_b$denotes the average bit energy and N_0 the one-side noise power spectral density, i.e SNR.

In Figure 4.6 and Figure 4.7 are represented the performance results of the first three scenarios for the primary and secondary system, respectively. The results are based in the average BER achieved by each system.

The difference between Scenario 1 and Scenario 2 is noticeable in the number of antennas that the BS, AP and SUT have deployed, from one scenario to another the number of antennas is doubled. Towards Scenario 3 the number of RF chains and the number of RF chains of Scenario 1 is doubled up.

Starting by analyzing the primary system, represented in Figure 4.6, it is possible to observe that from the Scenario 1 to Scenario 2 at a $BER = 10^{-3}$ the system improves about 2 dB. From this is possible to see that the number of antennas deployed improve the system performance, as already stated, this is the major advantage of using MIMO technology, where is possible to extract higher spatial gains.

Furthermore, Scenario 3 achieves the better performance of the three scenarios considered, obtaining an improvement of 3 dB relatively to Scenario 1. When compared to Scenario 2 the achieved improvement in performance was around 1 dB. Although the number of RF chains as doubled from Scenario 2 to Scenario 3 the overall improvement does not make up for the extra RF chains.

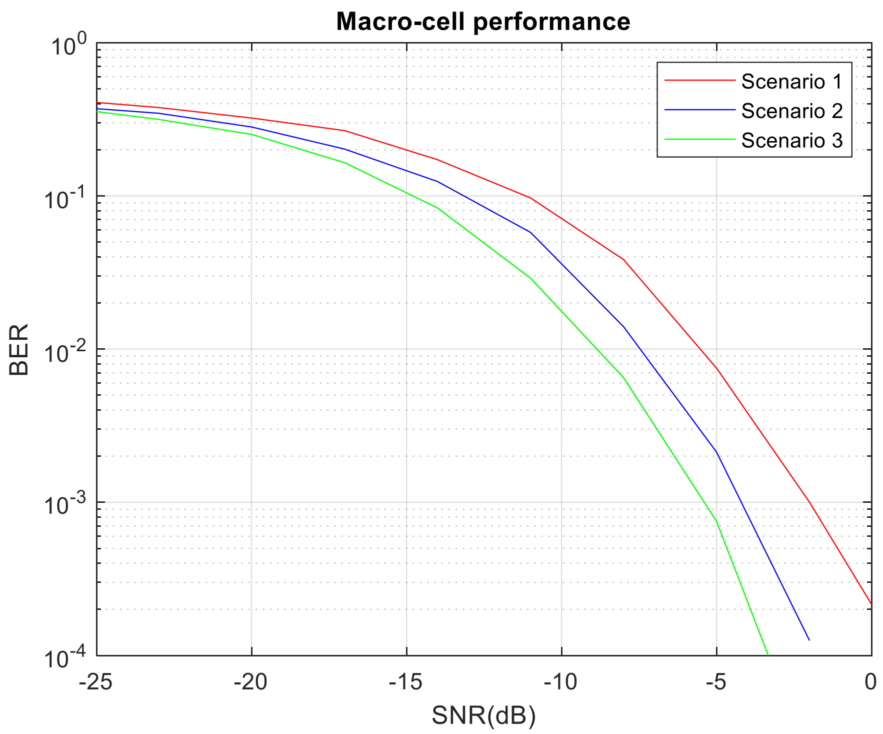

Figure 4.6 Macro-cell average BER.

Looking at the performance of the secondary system, represented Figure 4.7, it is possible to see that the worst performance is obtained in the Scenario 1, where the number of antennas and RF chains considered are the lowest. Comparing the Scenario 1 and Scenario 2 its visible an improvement of approximately 4 dB when $BER = 10^{-3}$, this happens due to the number of antennas deployed in Scenario 2.

Moreover, the large number of RF chains used in Scenario 3 achieves the same performance as Scenario 2, thus the usage of high number of RF chains is not always necessary to obtain the best performance. Besides, in this Scenario the increase in the RF chains only will consume more power.

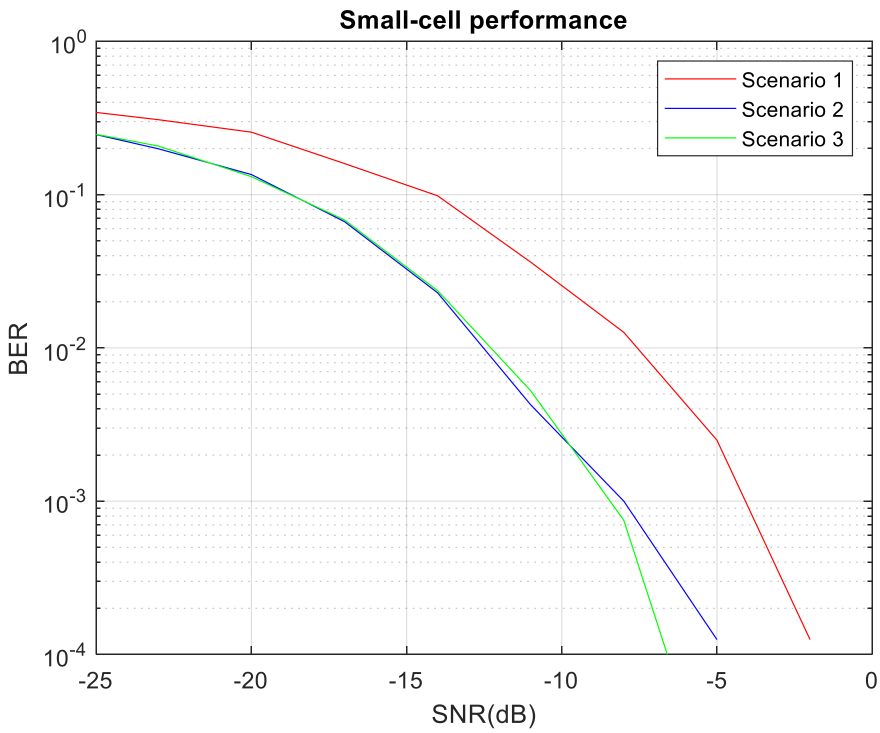

Figure 4.7 Small-cell average BER

When assessing the performance of the primary and secondary system in each Scenario, is possible to see that the secondary system always outperforms the primary system. For comparison let us consider Scenario 2 in both systems, where the secondary system has 8 dB gain over the primary system, due to the amount of DoF available at the secondary system.

In order to exploit the usage of multiple antenna terminal in the primary system, Scenario 4 evaluates the system performance when each MUT is equipped with multiple antennas and the remaining parameters are configured as in Scenario 3. From Figure 4.8, that represents the system performance, shows that with the increase of antennas deployed in the MUT, the primary system tends to perform better than the secondary system. For instance, the primary system achieves a $BER = 10^{-3}$ at around -14dB, while the secondary achieves it at approximately -8 dB, which results in a gain of 6 dB.

The advantages of multiple antennas in the transmitter and the diversity gains are reflected in the gains in performance for the primary system.

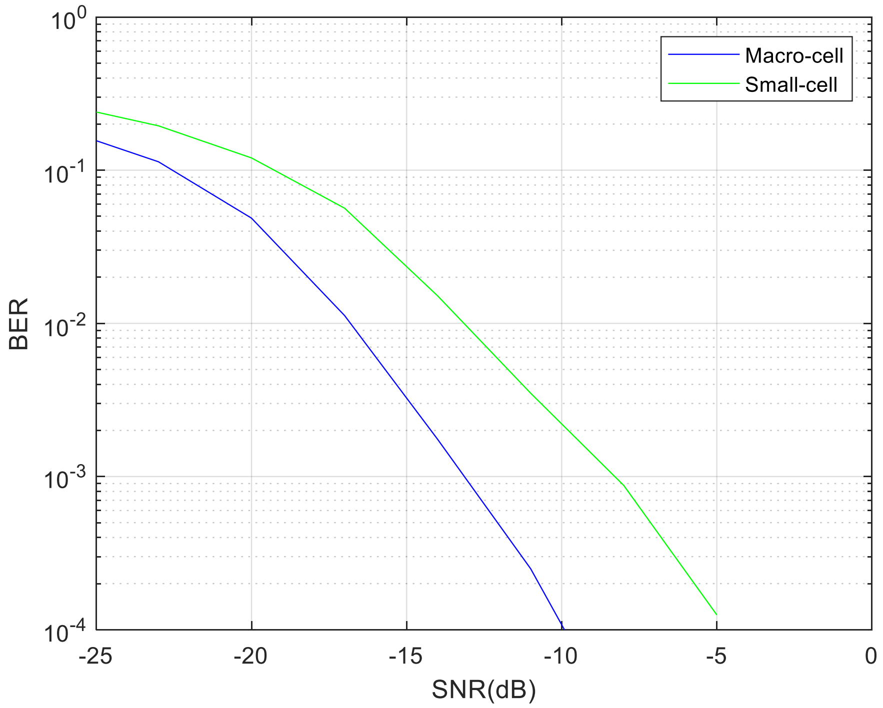

Figure 4.8 Results for Scenario 4.

For the last, Scenario 5, assess the performance of both systems when the number of macro cell users is extended to $K = 4$, furthermore, the K users are again considered as single antenna terminal. Scenario 5 is based in the parameters used in Scenario 3 for the BS, AP and SUT. The performance results are depicted in Figure 4.9.

For the primary systems the performance result is similar to the achieved in Scenario 3, Figure 4.6, where only two users were served. This shows that although the number of users increase the system is able to handle the multiple connections and decode each symbol sended by the different MUTs.

For the secondary system the performance results demonstrate that Scenario 5 has a slightly worst performance, due to the increase in macro cell users the secondary system suffers more interference coming from the MUTs and more DoF are used to cancel this interference.

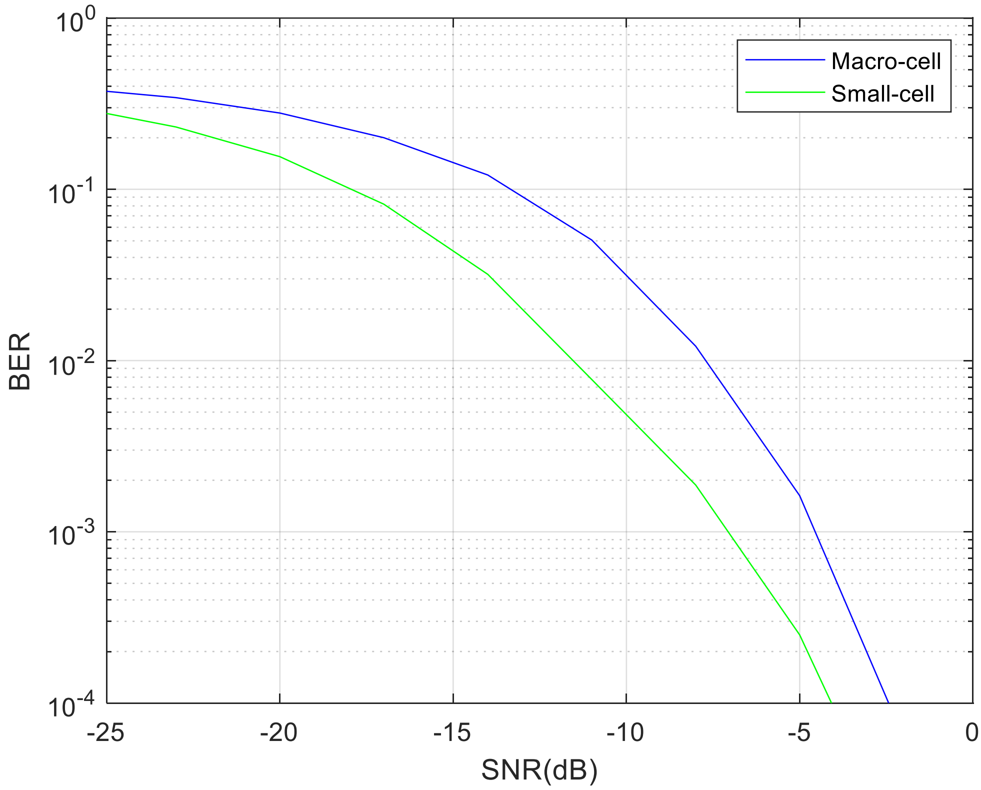

Figure 4.9 Results for Scenario 5.

5. Conclusions and Future Work

The technologic advances in MIMO systems, heterogenous networks and the usage of the mmWave spectrum enable the possibility to exploit higher data rates and better services that are expected in future wireless communication systems. Furthermore, it is seen that MIMO technology can be combined with the higher frequencies to get huge improvements over the current sub-6G band. Moreover, the development of hybrid architectures allows the base station and the terminals to have more antennas while keeping the power consumption low. Heterogeneous networks also benefits from the previous combination, where the short range of mmWave allows to densify even more the macro-cell. Although, increasing the number of small-cells can produce higher levels of interference in the system, which needs to be solved.

In this Chapter is presented the main conclusions of this dissertation and a future perspective of what can be done to improve the current heterogeneous system.

5.1 Conclusion

In this dissertation a multi-user HetNet was considered, where each small cell has one active user and the macro cell is composed by multiple users. The communication in the uplink direction between the transmitters and the receivers is done in the mmWave band, 28GHz, where both use a hybrid analog-digital architecture to handle the massive number of antennas with only few RF chains. Moreover, the small cell processing is done in a distributed manner, where the analog is done by the different APs, while the CU performs joint processing in the digital domain of all users in the secondary system in order to eliminate the intra/inter tier interference.

To summarize the results obtained with this work is possible to conclude that hybrid architectures achieve almost same results as full digital architecture due to the fact that the base station after applying the analog equalizer to the channel obtains a smaller equivalent channel that can be compared to the full digital channel. Additionally, the amount of DoFs available at the base station needs to be higher than the number of users, due to the fact that the primary system require at least one DoF to align the signals from the secondary users. Thus, the DoFs of the primary systems allows to eliminate the inference coming from the secondary system. Therefore, the number of users served by the BS must be lower than the number of RF chains, to recover all symbols from the K MUTs. Also the increase in the number of antennas for the primary users results in the improvement of the macro cell performance due to the fact that MUT can exploit the diversity offered by the multiple antennas deployed, with this the probability of occur an error decrease in the primary system.

5.2 Future Work

This work focused in the macro cell performance when multiple users are trying to communicating at the same time with BS. Furthermore the BS is responsible to align the interference from the secondary system, with the available CSI. For future work, scenarios where a more realist CSI is used need to be studied, due to the fact that in real situation is almost impossible to have the perfect CSI. The small cells should be more realistic and consider scenarios where more than one user can be connected to each AP. Regarding the primary systems, the users can also be improved by exploit opportunities offered by deploying more RF chains. Furthermore, a sub-connected architecture can also be used to lower the system complexity.

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