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**Optimization of Spectrum Management in Massive
Array Antenna Systems with MIMO**
(versão final após defesa)

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I would like to dedicate this thesis to all my family and especially my wife, Fernanda Cálida,
who was present throughout this journey

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Abstract

Fifth generation (5G), is being considered as a revolutionary technology in the telecommunication domain whose the challenges are mainly to achieve signal quality and great ability to work with free spectrum in the millimetre waves. Besides, other important innovations are the introduction of a more current architecture and the use of multiple antennas in transmission and reception. Digital communication using multiple input and multiple output (MIMO) wireless links has recently emerged as one of the most significant technical advances in modern communications. MIMO technology is able to offer a large increase in the capacity of these systems, without requiring a considerable increase in bandwidth or power required for transmission.

This dissertation presents an overview of theoretical concepts of MIMO systems. With such a system a spatial diversity gain can be obtained by using space-time codes, which simultaneously exploit the spatial domain and the time domain. SISO, SIMO and MISO systems are differentiated by their channel capacity and their configuration in relation to the number of antennas in the transmitter/receiver. To verify the effectiveness of the MIMO systems a comparison between the capacity of SISO and MIMO systems has been performed using the Shannon's principles. In the MIMO system some variations in the number of antennas arrays have been considered, and the superiority of transmission gains of the MIMO systems have been demonstrated. Combined with millimetre waves (mmWaves) technology, massive MIMO systems, where the number of antennas in the base station and the number of users are large, is a promising solution.

SDR implementations have been performed considering a platform with Matlab code applied to MIMO 2x2 Radio and Universal Software Peripheral Radio (USRP). A detailed study was initially conducted to analyze the architecture of the USRP. Complex structures of MIMO systems can be simplified by using mathematical methods implemented in Matlab for the synchronization of the USRP in the receiver side. SISO transmission and reception techniques have been considered to refine the synchronization (with 16-QAM), thus facilitating the future implementation of the MIMO system. OpenAirInterface has been considered for 4G and 5G implementations of actual mobile radio communication systems. Together with the practical MIMO, this type of solution is the starting point for future hardware building blocks involving massive MIMO systems.

Keywords

5G, Beamforming, MIMO, Millimeter waves, Massive MIMO, Synchronization, USRP.

Resumo

A quinta geração (5G) está sendo considerada uma tecnologia revolucionária no setor de telecomunicações, cujos desafios são principalmente a obtenção de qualidade de sinal e grande capacidade de trabalhar com espectro livre nas ondas milimétricas. Além disso, outras inovações importantes são a introdução de uma arquitetura mais atual e o uso de múltiplas antenas em transmissão e recepção. A comunicação digital usando ligação sem fio de múltiplas entradas e múltiplas saídas (MIMO) emergiu recentemente como um dos avanços técnicos mais significativos nas comunicações modernas. A tecnologia MIMO é capaz de oferecer um elevado aumento na capacidade, sem exigir um aumento considerável na largura de banda ou potência transmitida. Esta dissertação apresenta uma visão geral dos conceitos teóricos dos sistemas MIMO. Com esses sistemas, um ganho de diversidade espacial pode ser obtido utilizando códigos espaço-tempo reais. Os sistemas SISO, SIMO e MISO são diferenciados pela capacidade de seus canais e a sua configuração em relação ao número de antenas no emissor/receptor. Para verificar a eficiência dos sistemas MIMO, realizou-se uma comparação entre a capacidade dos sistemas SISO e MIMO utilizando os princípios de Shannon. Nos sistemas MIMO consideraram-se algumas variações no número de agregados de antenas, e a superioridade dos ganhos de transmissão dos sistemas MIMO foi demonstrada. Combinado com a tecnologia de ondas milimétricas (mmWaves), os sistemas massivos MIMO, onde o número de antenas na estação base e o número de usuários são grandes, são uma solução promissora.

As implementações do SDR foram realizadas considerando uma plataforma com código Matlab aplicado aos rádios MIMO 2x2 e Universal Software Peripheral Radio (USRP). Um estudo detalhado foi inicialmente conduzido para analisar a arquitetura da USRP. Estruturas complexas de sistemas MIMO podem ser simplificadas usando métodos matemáticos implementados no Matlab para a sincronização do USRP no lado do receptor. Consideraram-se técnicas de transmissão e recepção SISO para refinar a sincronização (com 16-QAM), facilitando assim a implementação futura do sistema MIMO. Considerou-se o OpenAirInterface para implementações 4G e 5G de sistemas reais de comunicações móveis. Juntamente com o MIMO na prática, este tipo de solução é o ponto de partida para futuros blocos de construção de hardware envolvendo sistemas MIMO massivos.

Palavras-chave

5G, Formação de feixe, Massivo MIMO, MIMO, Ondas milimétricas, Sincronização, USRP.

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List of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
AA	Array Antenna
ACI	Adjacent Carrier Interference
ADSL	Asymmetric Digital Subscriber Line
AMPS	Advanced Mobile Phone System
BER	Bit Error Rate
BF	Beamformer
BS	Base Station
BSC	Base Station Controller
CAP-MIMO	Continuous Aperture Phased Multiple Input Multiple Output
CDMA	Code Division Multiple Access
CSI	Channel State Information
DFE	Decision Feedback Equalizer
DFT	Discrete Fourier Transform
EGC	Equal Gain Combining
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
GPRS	General Packet Radio Service
GSA	Global Mobile Suppliers Association
GSM	Global System for Mobile Communications
HPB	Half Power Beam
HPBW	Half Power Beam Width
HSPA	High Speed Packet Access
IB-DFE	Iterative Block Decision feedback equalizer
IDFT	Inverse of Discrete Fourier Transform
IMT2000	International Mobile Telecommunications-2000
IRACON	Inclusive Radio Communications
ISI	Intersymbol Interference

LTE	Long Term Evolution
LTE-A	LTE- Advanced
MAAS	Massive Array Antenna Systems
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
mMIMO	Massive MIMO
mmRF-HARVESTING	Radio Frequency Energy Harvesting
MMSE	Minimum Mean Squared Error
mmWave	Millimeter Wave
MRC	Maximal Ratio Combining
MSE	Mean Squared Error
OFDM	Orthogonal Frequency-Division Multiplexing
PA	Power Amplifier
PLP	Physical Layer Pipes
QoS	Quality of Service
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Networks
RNC	Radio Network Controller
RF chain	Radio Frequency Chain
SC	Selection Combining
SFBC	Space Frequency Block Code
SIMO	Single Input Multiple Output
SINR	Signal to Interference plus-Noise Ratio
SISO	Single Input Single Output
SMS	Short Messaging Service
SNR	Signal to Noise Ratio
STBC	Space Time Block Code
TDD	Time Division Duplex
TDMA	Time-Division Multiple Access
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TFS	Time-Frequency Slicing
TI	Time Interleaving
UBI	Universidade da Beira Interior
UCA	Uniform Circular Array
ULA	Uniform Linear Array

ULA	Uniform Linear Array
UMTS	Universal Mobile Telecommunication System
UPA	Uniform Planar Array
URA	Uniform Rectangular Array
USRP	Universal Software Radio Peripherals
UT	User Terminal
UTRA	Universal Terrestrial Radio Access
V-BLAST	Vertical Bell Labs Layered Space-Time
WCDMA	Wide Band Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwave Access
Wireless-WWW	Wireless World Wide Web
WLAN	Wireless Local Area Networks
WRC	World Radio Communications Conferences

Chapter 1

Introduction

1.1 Motivation

The potential benefits of increasing by several orders of magnitude the number of antennas used in wireless communications have been theoretically established. However, existing systems fail to deliver on this promise. The research within this Master dissertation considers a combination of two technologies, in order to make the way for Tbit/s wireless communication. It considers antennas with spatial precessing using Multiple Input Multiple Output (MIMO) techniques. It is considered that millimetre wave (mmWave) bands have a wide range of spectra available that allows for fast transmission.

The evolution of wireless communications from analogue to digital led to the enhancement of early propagation models, which provided information about power, in order to also consider time delay information. Further consideration of the space domain either with space diversity or smart antennas or, nowadays, MIMO systems has also pushed the evolution of propagation modeling toward more complex spatial-temporal considerations [7].

Multiple Input Multiple Output (MIMO) is a key technology for a new step in Fifth Generation (5G) systems along with Massive MIMO, which would use large antenna arrays to transmit data to multiple devices within a small cell in the same frequency range. MIMO technology emerges as one of the most efficient in the portability environment, where the signal transmission and reception must be error free in order to avoid damages in communication and data sent. MIMO technology has emerged as one of the techniques that are capable of optimizing transmission channels, ensuring high signal reception quality.

In the low frequency bands it is difficult to reduce the size of the antennas, as well as the complexity of the architecture and AC/DC conversion. However, in upper bands as the millimetre wavebands, it is possible to insert large arrays even in small mobile transmitted in view of the relationship between the size and energy consumption in these physical systems, the study has, as a starting point, developed of mathematical methods to reduce the system complexity, the size and power consumption, further magnifying Massive Array Antenna Systems (MAAS) gain and spatial processing capabilities, matrix for the MAAS.

In MAAS at the mmWave frequency bands, the envisioned solution to overcome hardware and software complexity is to use hybrid analogue-digital transceiver architectures that, together

with the appropriate signal processing and modulation design whilst decreasing the power consumption.

The aim of this research is two-fold, to develop and and verify them through simulation and experimental validation, signal processing algorithms at the link-level to provide an increase of the data rates at feasible complexity (precoding and receiving schemes), adequate to the mixed analogue-digital architectures.

The Fifth Generation (5G) technology has had a very broad growth over the last few years, suffering more in some respects, such as bandwidth, energy consumption and the complexity of the architecture, which generates a great financial cost. Considering that 5G technology, compared to its predecessor at Fourth Generation (4G), has a much higher transfer rate coupled with a more efficient transmission, more affected by the limitation of the demand of spectra for transmission and high frequencies, contributing to the application of new applications related to the use of millimetre waves (mmWave), to which using little licensed spectra. Which means that the spectra millimetre waves are available to be used [13],[14].

With increasing frequencies, to use the mmWave parameter where more spectral features are available, the general amplification of Power Amplifiers (PAs) is a problem whose solution makes the architecture much more complex. In order to minimize the complexity of transmission systems on multiple antennas for mmWave systems, we can adopt the concept of phased array techniques that consists of using several antennas to compost by antennas constructed in microstrip pattern, taking this concept in mind and thus be possible considerably increase the effective aperture of the antennas as can be studied in more detail in [14]. The use of this technique is also being assumed in the context fort of this research.

1.2 Evolution of Telecommunications Technology

Mobile communication has become more popular in recent years due to the rapid overhaul of First Generation (1G) to Fifth Generation (5G) in mobile technology. This reform is due to the requirement of transmission technology compatible with the service and the very high increase of telecommunications customers. Generation refers to change in the nature of the transmission technology compatible with the service and new frequency bands. In the 1980s, the cell phone era began, and since then mobile communications have undergone considerable changes and experienced massive growth. In this , we discuss the evolution of wireless communication from the emergence of 1G to the current 5G, a major breakthrough in mobile communication, since the technologies most used today and the main contributions will be addressed.

1.2.1 First Generation

The input technology in mobile communication systems first appeared in the 1980s, where these types of systems were known as First Generation (1G) the first generation, and used an Advanced Mobile Phone System (AMPS) network technology that was only possible the transmission of voice data. It used an analog system and its speed of transfer was around 9 kbps [15]. Until then, all mobile communication was centralized, thus having low traffic capacity and high cost. Its success was due to the novelty that came up: making phone calls away from home, on a wireless device, and on the move. Being a new system, little was known about its potential and its acceptance in the market. It is worth remembering that, at the time of the development of this technology, everything that humanity did was done without the use of this system, which could lead many people to think that this might not be so important or that it was not worth the investment cost [16]. For this reason, in the first generation, little effort was made to standardize use in all countries. Indeed, a number of standards have been proposed and implemented, in isolation, in just one country. After the consolidation of this generation, it was found that Europe had been divided into standards:

- TACS standard: United Kingdom, Austria, Spain, Ireland, Italy;
- NMT450: Sweden, Norway, Finland, Denmark;
- Radiocom2000: France.

The AMPS system was frequency modulated and used frequency division multiple access (FDMA) with a channel capacity of 30 kHz and frequency band of 824-894 MHz. Its basic features are the following ones:

- Bit rate/Speed: 2.4 kbps;
- Allows voice calls in 1 country;
- Use analog signal;
- Poor voice quality;
- Poor battery life;
- Large phone size;
- Limited capacity;
- Poor hand-off reliability;
- Poor security;

- Offered very low level of spectrum efficiency.

In mobile technologies such as Mobile Telephony System (MTS), Advanced Mobile Phone System (AMTS), Improved Mobile Telephone Service (IMTS) and Push to Talk (PTT). System capacity is low and still was not reliable, voice links were bad and have no security for the user, because the voice calls were reproduced in radio towers, making these calls susceptible to third party unwanted interception [17].

1.2.2 Second Generation

The second generation (2G) appears a decade after first generation (1G) in the mid-1990, starting to get more popular due to improved transfer rate and voice signal. The 2G technology has a fully digital structure, having as its main characteristics the security, robustness, efficient use of the spectrum and support of low value data transmission services. Using a Global System for Mobile Communications (GSM) technology, which uses one enabled the use of transfer data beyond voice [15]. It is basic features are:

- Speed was up to 64 kbps;
- Use digital signals;
- Enables services such as text messages, picture messages and Multimedia Message Service (MMS);
- Provides better quality and capacity;
- Unable to handle complex data such as videos;
- Required strong digital signals to help mobile phones work. If there is no network coverage in any specific area, digital signals would weak.

1.2.3 Second and a half Generation

Serving as transient technology between the second generation (2G) and the third generation (3G). The Second and a half Generation (2.5G) technology has introduced some services, such as Short Messaging Service (SMS), General Packet Radio Service (GPRS) that provides a significant increase in data transfer speed, as well as allowing the user to connect to the internet, and Enhanced Data Rates For GSM Evolution (EDGE) that is nothing more than the evolution of GSM technology and the closest to 3G [15].

The GSM technology was continuously improved to provide better services which led to development of advanced Technology between 2G and 3G.

- Provides phone calls;
- Send/receive e-mail messages;
- Web browsing;
- Speed : 64-144 kbps;
- Camera phones;
- Take a time of 6-9 min to download a 3 min MP3 song.

1.2.4 Third Generation

The Third Generation (3G) is based on GSM and was launched in 2000. The aim of this technology was to offer high speed data. The original technology was improved to allow data up to 14 Mbps and more using packet switching. It uses Wide Band Wireless Network with which clarity is increased. It also offers data services, access to television/video, new services like Global Roaming. It operates at 2100 MHz and has a bandwidth of 15-20 MHz used for High-speed internet service, video chatting [18]. The third generation (3G), which can be currently the gold generation of the technology, mainly because it is the most used so far, has as main evolution in comparison to its predecessors, the improvement in the efficiency of Internet browsing, the possibility of social networking, and compatibility with new smartphone technologies, facilitating and integrating its users. Using technology of incorporates next to its systems, like for example Universal Mobile Telecommunication System (UMTS) that aims at a better quality in the fixed network and generating a connection speed of up to 2 Mbps, Wide-Band Code-Division Multiple Access (WCDMA) which roughly and technology used in the 3G-UMTS to which it allows the high speed compared to previous technologies, and the High Speed Packet Access (HSPA) technology that allows an even higher download and upload rate [15].

The main characteristics of 3G are as follows:

- Speed: 2 Mbps;
- Typically called smart phones;
- Increased bandwidth and data transfer rates to accommodate web-based applications and audio and video files;
- Provides faster communication;
- Send/receive large email messages;
- High speed web, more security and video conferencing;

- Large capacities and broadband capabilities;
- TV streaming/mobile TV/Phone calls;
- To download a most fast;
- Expensive fees for 3G licenses services;
- It was challenge to build the infrastructure for 3G;
- High bandwidth requirement;
- Large cell phones.

The Third Generation (3G) mobile system was called as Universal Mobile Telecommunication System (UMTS) in Europe, while Code Division Multiple Access (CDMA2000) is the name of American 3G variant. Also the International Mobile Telecommunications-2000 (IMT2000) has accepted a new 3G standard from China, i.e Time Division Synchronous Code Division Multiple Access (TD-SCDMA). WCDMA is the air-interface technology for UMTS [17].

1.2.5 Fourth Generation

The Fourth Generation (4G) is the new generation of mobile communications that are improving 3G systems and are associated with a set of advantages that will equip the experience of using mobile services to fixed-fiber communications, higher speed, greater bandwidth, better coverage and network quality. Through 4G, users will have the opportunity to enjoy greater data transfer rates, as well as greater efficiency and performance in accessing services available on the Internet. Compared to 3G, mobile users can also benefit from improved efficiency in the use of the radio spectrum and lower latency, using mobile services that until now have only been possible through Fiber Optic or Asymmetric Digital Subscriber Line (ADSL). Technologies such as Worldwide Interoperability for Microwave Access (WiMax) or Long Term Evolution (LTE) were introduced to the market in 2006, and due to their evolution, have been "tagged" with 4G technologies [19]. The Long Term Evolution (LTE) is considered as 4G technology. The 4G is being developed to accommodate the Quality of Service (QoS) and rate requirements set by forthcoming applications like wireless broadband access, Multimedia Messaging Service (MMS), video chat, mobile TV, HDTV content, Digital Video Broadcasting (DVB), minimal services like voice and data, and other services that utilize bandwidth [19]. The main characteristics of 4G are as follows:

- Capable of provide 10 Mbps, 1 Gbps speed;

- High quality streaming video;
- Combination of Wi-Fi and Wi-Max;
- High security;
- Provide any kind of service at any time as per user requirements anywhere;
- Expanded multimedia services;
- Low cost per-bit;
- Battery uses is more;
- Hard to implement;
- It needs complex hardware;
- Expensive equipment required to implement next generation network.

Figure 1.1 shows a comparison between the Network Architectures of 2G, 3G and 4G technologies, demonstrating how the architecture of each architecture is structured with its evolution and how the successors of each one take advantage of its predecessor technologies to adapter evolution.

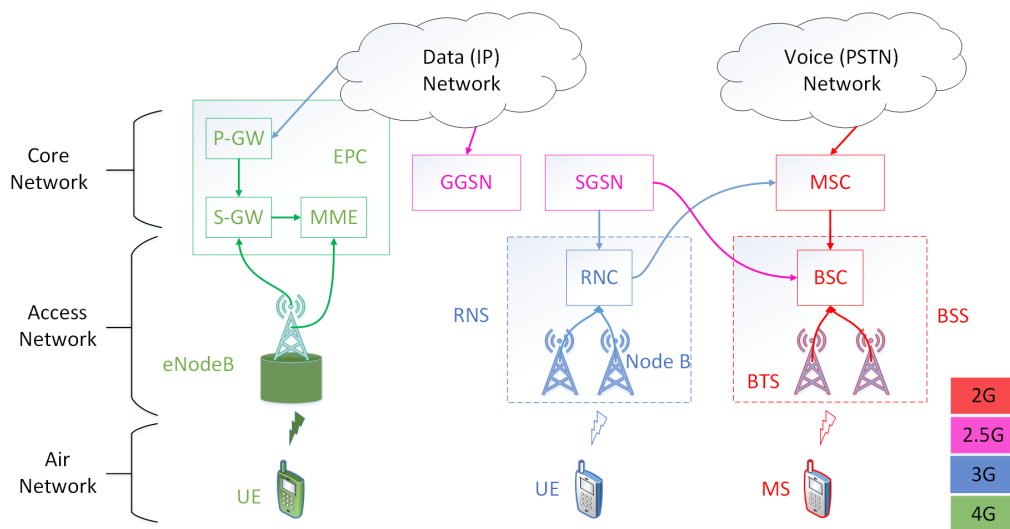


Figure 1.1: 2G, 3G and 4G network architecture, adapted from [1].

1.2.6 Fifth Generation

The Fifth Generation (5G) refers to Fifth Generation which was started from late 2010s. 5G Facilities that might be seen with 5G technology includes far better levels of connectivity and coverage. The main focus of 5G will be on world-Wireless World Wide Web (Wireless-WWW). It is a complete wireless communication with no limitations. The main features of 5G are:

- It is highly supportable to Wireless World Wide Web (Wireless-WWW);
- High speed, high capacity;
- Provides large broadcasting of data in Gbps;
- Multi-media newspapers;
- Faster data transmission that of the previous generation;
- Support interactive multimedia, voice, streaming video, Internet and other;
- More effective and attractive.

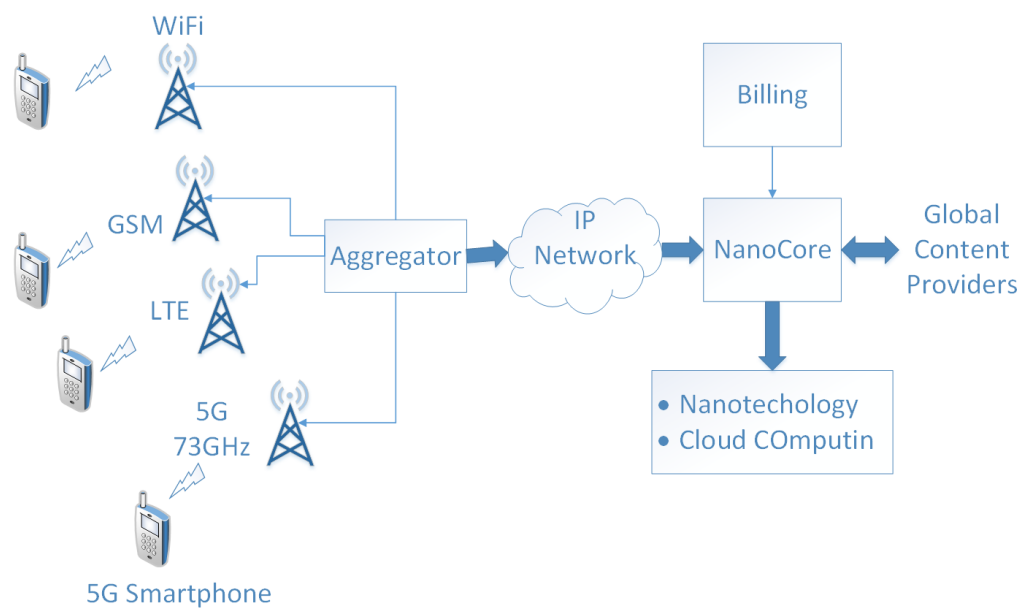


Figure 1.2: 5G network architecture, adapted from [2].

Figure 1.2 shows the 5G network architecture. As 5G network uses flat IP concept so that different Radio Access Networks (RANs) can use the same single Nanocore for communication. The RANs supported by 5G architecture are GSM, GPRS/EDGE, UMTS, LTE, LTE-Advanced, WiMAX, WiFi, EV-DO and CDMA One.

Flat IP architecture identifies devices using symbolic names unlike hierarchical architecture where in normal IP addresses are used. This architecture reduces number of network elements in data path and hence reduces cost to greater extent. It also minimizes latency [2]. 5G aggregator aggregates all the RAN traffics and route it to gateway. 5G aggregator is located at Base Station Controller (BSC) Radio Network Controller (RNC) place. 5G mobile terminal houses different radio interfaces for each RAT in order to provide support for all the spectrum access and wireless technologies. Another component in the 5G network architecture is 5G nanocore. It consists of nanotechnology, cloud computing. Cloud computing utilizes internet as well as central remote

servers to maintain data and applications of the users. It allows consumers to use applications without any installation and access their files from any computer across the globe with the use of Internet.

Figure 1.3 shown below the evolutionary line of mobile communication networks, which shows the time of implementation and use and the technology that has evolved through the process from to the 5G.

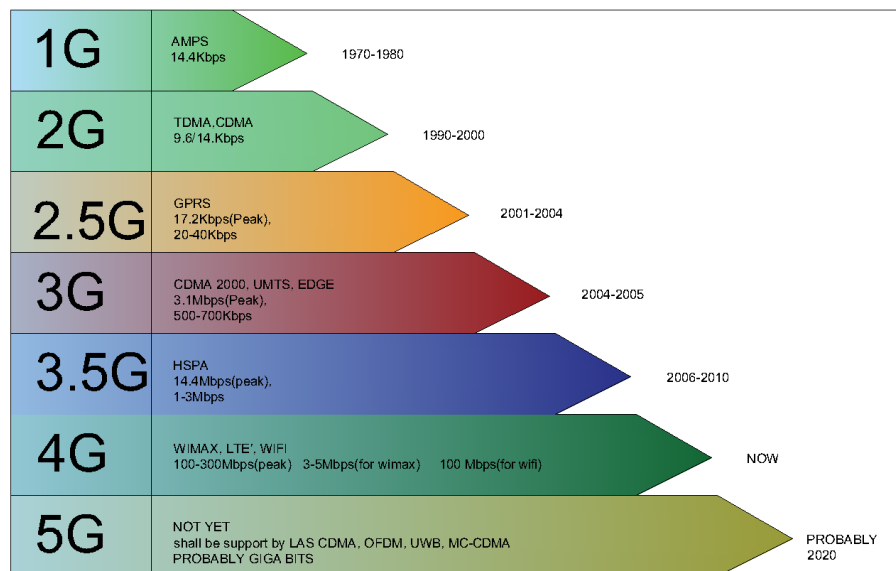


Figure 1.3: Evolution of mobile communication networks, adapted from [3]

1.3 Objectives and Approach

With the uncontrolled increase of the wireless communication devices, it has been an increasing challenge to meet the demand, aiming at this need for greater bandwidth and greater energy efficiency of the transmission and reception systems, being studied the use of technology that join elements of MIMO, such as continuous-aperture antennas and phased arrays, in order to reach Line of Sight (LoS). Includes at the most effective mathematical modulation for the Continuous Aperture Phased Multiple Input Multiple Output (CAP-MIMO) proposal using a Discrete High-resolution Matrix Array (DLA) that communicates with analogue beamforming [20], [21], [22]. Multiple Input and Multiple Output (MIMO) technology is the use of multiple antennas at both transmitter and receiver to improve communication performance. The MIMO technology has attracted attention in wireless communications, because it offers significant increases in data throughput and link range without additional bandwidth or transmit power. It achieves this by higher spectral efficiency (more bits per second per hertz of bandwidth) and link reliability or diversity (reduced fading).

The approach comprises to compare different synchronization algorithms at the receiver and experimentally verify them with Universal Software Radio Peripheral (USRPs) and Adalm Pluto, implement a simple version of a receiver with 2x2 MIMO and synchronization, and make efforts to implement the receiver with a more complex structure towards massive MIMO.

1.4 Contributions

The main contribution of this dissertation was the elaboration of the Matlab project that originated the following article and paper and some work was done in cooperation with the Universidad Carlos III de Madrid, and some papers in conferences.

The work associated with this dissertation is based on research on the practical implementation of MIMO and Massive MIMO that is being carried out in Instituto de Telecomunicações, in a collaboration with Universidad Carlos III de Madrid, and considers the research infrastructure of strategic relevance ORCIP (<http://www.orcip.pt>). With the inspiration of achieving future Beyond 5G networks operating in the millimetre wavebands enabled by joint Analogue-digital signal processing, we consider hardware architectures with USRPs and Adalm Pluto SDRs to verify the feasibility of synchronization algorithms and simple MIMO configurations that will scale up while enabling to achieve more complex MIMO configurations, e.g., towards CAP-MIMO. Another contribution is the Prototyping of an architecture of LTE-Advanced with different eNBs and Evolved Packet Core, with Open Air Interface.

This applied research in the work developed has already been reflected in the framework of the ORCIP project, and in a temporary document presented in COST CA 15104 the Inclusive Radio Communications (IRACON) and two posters, as follows:

- Development of the Temporary Document (TD(18)07019) to present the results of the test of Implementation of Low-complexity Hybrid Analogue-digital Solutions in CAP-MIMO, focusing on SISO systems, presented at the Cartagena Meeting of COST CA15104 IRACON, of 30/5-1/6/2018 [23].
- Poster presentation on the "Implementation of Low-complexity Hybrid Analogue-digital Solutions in CAP-MIMO", focusing on SISO systems presented at the 25th Thematic Seminar on Mobile Communications (RTCM) held at the Faculty of Computer Science at the University of Porto, 06/22/2018.
- Poster on the "Implementation of Low-complexity Hybrid Analogue-digital Solutions in CAP-MIMO", focusing on SISO systems, presented at Instituto de Telecomunicações, Instituto de Superior Técnico the University of Lisbon, 22/07/2018.

1.5 Outline of the Dissertation

Apart from this Chapter, this dissertation is divided into four chapters, which are briefly described below.

Chapter 2 discusses the new technology to meet the growing demand for demand related to the transmission frequencies, and the study of these technologies related to wireless systems with Multiple Antennas, concepts of Single Input Single Output (SISO), Single Input Multiple Output (SIMO), Multiple Input Single Output (MISO) and Multiple Input Multiple Output (MIMO) transmission capabilities.

The use of a more focused scheme in the investigation of Massive MIMO systems and the approach and conceptualization of the importance of the use of millimetre waves (mmWave) to supply the demand and lack of licensed bands and their generalization for transmitters and receivers is presented in chapter 3.

In chapter 4 present the implementation of the mathematical modulation implemented in Matlab while applying to the universal software radio peripherals (USRP) Hardware interconnected so that it forms a network in SISO standard, with capacity of application in 2x2 MIMO systems where the results obtained on the adopted implementation are analyzed.

Finally, chapter 5 summarizes the main ideas and conclusions of the developed work, as well as the contributions made and possible future work.

Chapter 2

Wireless Systems with Multiple Antennas

2.1 Introduction

The use of today's wireless communication systems has been a bit undermined by the wide range of information being exchanged and are increasingly calling for high transfer rates, thus requiring more and more system improvements, and one of the most auspicious technology and the use of multiple antennas, which we will see in more detail below.

It is fundamental to understand the nature of the MIMO channel in order to operate the MIMO systems, as well as all its aspects. Wireless communication systems have been developed to transmit information through a radio channel between the transmitter and the receiver. In SISO systems the radio channel is formed by a single path between transmitter and receiver, ignoring the effects of multi-path fading. However in MIMO systems composed of several antennas for transmission and reception, the number of paths between transmitter and receiver is equal to the product between the number of transmitting antennas by the number of receiving antennas, as shown in Figure 2.1.

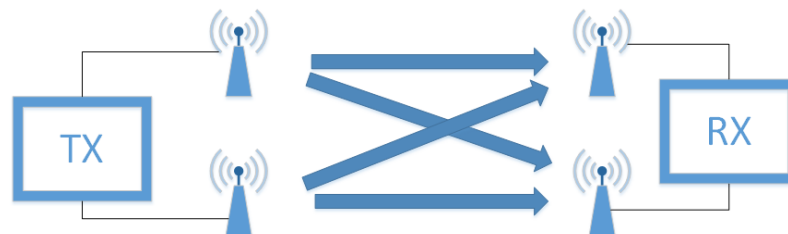


Figure 2.1: Multiple Input Multiple Output

2.2 Introduction Multiple Input Multiple Output

Multiple Input Multiple Output (MIMO) technology has been a major advance for 4G telecommunication systems and a key driver for technology in 5G systems and other innovative next technologies.

MIMO technology has emerged as one of the most efficient in the middle of portability, where the transmission and reception of the signals must be carried out with considerable precision in order to avoid losses in signal quality. Bandwidth has become an extremely scarce resource,

and its use is becoming more and more expensive due to the large number of requests and the low demand.

The multi-system are used to allow many mobile users to simultaneously share a common bandwidth. Since traditional wireless communication is based on the use of antennas in the configuration of a transmitter and receiver, or simply Single Input Single Output(SISO), as shown in Figure 2.2. The Base Stations (BS) are equipped with a different system, Single Input Multiple Output (SIMO) as shown in Figure 2.3 and Multiple Input Single Output (MISO) as shown in Figure 2.4, which can already have a significant gain. Different types of multiple access formats are being used, being one of the most used and most feasible and the effective gain in relation to the transfer and reception of data is the Multiple Input Multiple Output (MIMO) as shown in Figure 2.5.



Figure 2.2: Single Input Single Output.

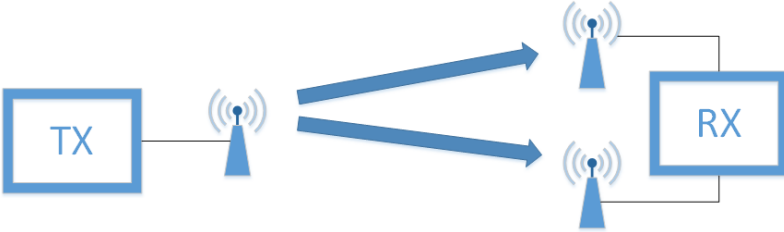


Figure 2.3: Single Input Multiple Output.

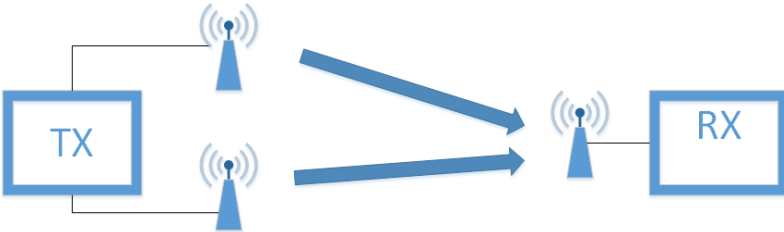


Figure 2.4: Multiple Input Single Output.

2.3 Single Input Single Output

The simplest form of radio link can be defined as SISO, that is, single input and single output. This is effectively a standard radio channel, to which both a transmitter or a receiver operates with a single antenna. There is no diversity and no further processing is required. The SISO system has the advantage of being a simplified system requiring no processing in terms

of the various forms of diversity to which they are subjected. However, the SISO channel is limited in performance because the transmitted and received signal uses only a single path. Taking as interfering and fading the impact on the system more than a MIMO system using some form of diversity where the channel bandwidth is limited by Shannon's law and the transfer rate be dependent on the channel bandwidth and signal relation/noise ratio [24].

2.4 Single Input Multiple Output

SIMO signal processing or single Input Multiple Output occurs where the transmitter has a single antenna and the receiver has multiple antennas. It is also known as a diversity receptor. They are often used to allow a system to receive signals from several independent sources in order to minimize the effects of fading. SIMO has been used in shortwave systems as listening / receiving stations to combat the effects of ionospheric fading and interference on incoming signals. SIMO has the advantage that the system is not as complex to be implemented, although it has some drawbacks in that processing is required at the receiver.

The use of SIMO may be quite acceptable in various applications, but to which the receiver is located in a mobile device, such as cellular telephone apparatus, where processing levels are limited by size, cost and battery consumption [24].

The SIMO can be used in two ways:

- Switching diversity SIMO: This form of SIMO searches for the strongest signal and switches to the antenna.
- Maximum ratio combining SIMO: This form of SIMO takes both signals and adds them to a combination. In this way, the signals from both antennas contribute to the overall signal

2.5 Multiple Input Single Output

The MISO system is an antenna technology for wireless communications, where multiple antennas are used to transmit signal, where antennas are combined to minimize errors and optimize the data transfer rate. The receiver has only one antenna that it uses to choose which signal to receive. In conventional wireless communications, a single antenna is used in the transfer, and another single antenna is used in the receiver. In some cases, this gives rise to problems with multiple path effects. When a signal is obstructed by an obstacle such as mountains, gorges, buildings. The late arrival of scattered parts of the signal causes problems such as fading, cropping and intermittent reception. In digital communication systems, such as wireless Internet,

can cause a reduction in data speed and an increase in the number of errors. The use of two or more antennas, together with the transmission of multiple signals in the transmission, can reduce the problem caused by the propagation of waves of several paths [24].

2.6 Multiple Input Multiple Output

Multiple Input and Multiple Output or simply MIMO, and the denotation of the use of several antennas in the transmission and reception of signals from a Base Station to another Base Station, using a set of antennas enables the transmission from several signals to a base station, which upon receipt of these signals, even if the signals arrive distorted, as the receiving antennas received several signals, these signals are combining generating a stable signal. In principle, MIMO offers three different benefits, namely spatial diversity, beamforming gain, and spatial multiplexing [25]. A MIMO system consists of several antenna elements at both transmitter and receiver, plus adaptive signal processing, this combination exploits the spatial dimension of the radio propagation channel [25]. MIMO technology opens enormous possibilities in the race for 5G improvement. Multiple Input Multiple Output is a method used to multiply the transmission capacity of multiple transmissions to antennas to exploit multiple propagation paths. The MIMO has become an essential element of wireless communication standards. MIMO applied in millimetre waves, with array of several antennas, and very interesting, since it provides a greater bandwidth and a wide range of free spectra, more due to the high number of antennas and the numbers of Radiofrequency (RF) chains that are required for the use of mmWave and MIMO, are quite high, considerably increasing the cost and affecting the energy efficiency, considering the use of beamspace in an attempt to reduce the complexity of the hardware [26].

MIMO emerges as a technology that uses the multiple antenna variant in both the transmitter and the receiver in order to obtain a diversity of paths by which the data signals are to be transported, due to the diversity of paths that the data can travel separately for each antenna both in the transmission and in the reception of the signal, denominated as multiple inputs and multiple outputs, thus improving the data to be communicated. In order to solve future problems with the large amount of data required by the large number of data-dependent equipment to be sent or received, MIMO technology provides a higher transfer rate, together with greater coverage distances, providing greater capacity of users and more reliability in the signal, that when using the variant of multiple antennas provides an effective gain in Transmission and Reception without it is necessary to increase the bandwidth nor the power of transmission.

Shown in Figure 2.5, the MIMO system intends the total study of the spatial domain. Thus, MIMO generates an expressive gain in diversity, beam acquisition, and the ability to transmit and

receive shared data. In the context of the diversity of the characterization of the environment that can be applied MIMO, and the possibility of using multiple antennas in the information sharing by the use of multipath that become independent, since each antenna that is used in the MIMO set sends or receives a part of the information or receive various different information. One of the main challenges related to the use of the MIMO system and the significant gain in the transfer rate that is provided by the multiplexing of the antennas leading to a high reliability of the information transferred and received.

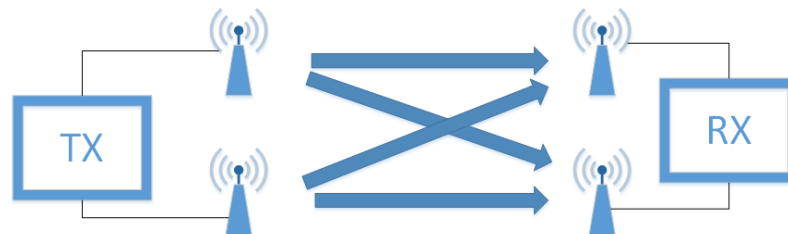


Figure 2.5: Multiple Input Multiple Output.

2.7 MIMO Transmission Techniques

MIMO consists of a communication system that uses two or more antennas at the transmission end and two or more antennas at the receiving end. This fact implies that, using spatial diversity techniques, spatial multiplexing, beamforming techniques that, through the use of several antennas in transmission and reception, allow an expressive gain in transmission capacity. However, current systems do not use all the benefits that these techniques can provide, simply by using systems with few antennas, will be discussed in more detail these technologies in the course of this chapter.

2.7.1 Diversity

Diversity can be defined as the technique that is used to overcome wear on the quality of the signal transmitted and received due to external media interference that are subject to exposure in various environments. The attenuation effect can be reduced by transmitting the same signal in different channels, i.e. by creating replicas of the original signal transmitted to the receiver, and thereby receiving the receiver several data simultaneously, thereby reducing the possibility of the received signal being damaged, thus increasing signal quality and transmission reliability [27]. The main system that suffers from the signal transmission and reception process are the mobile devices, and this has been the constant use of diversity techniques, in order to reduce the effects of the attenuation of multiple paths. Diversity systems can be represented by the

number of channels used. They can be divided into three systems, time diversity, frequency diversity and space diversity.

2.7.1.1 Time Diversity

Time diversity can be achieved by interleaving and encoding symbols at different coherent time periods. In this type of technique, we calculate the mean of channel fading over time using channel coding and interleaving to allow each replicate of transmitted signal is affected by different fading over time in order to minimize any deep fading, and thereby avoiding a more significant loss during data transmission. The diversity of time has a consequence that can not be exposed, which is the additional delay in the transfer of data, thus generating a loss in efficiency [27]. Figure 2.6 shows the interleaving principle in time. The replicates of the transmitted data are interlaced, so that multiple transmission is possible for a longer period of time.

- Repeatedly transmits information at the time spacing that exceeds the coherence time of the channel;
- The interval between transmission of same symbol should be at least the coherence time $(\Delta t)c$;
- Different copies undergo independent fading;
- Reduction in efficiency (*effective data rate* < *real data rate*).

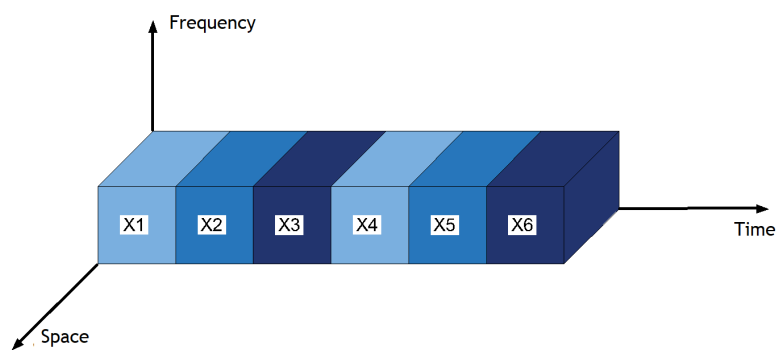


Figure 2.6: Time diversity, adapted from [4].

2.7.1.2 Frequency Diversity

Frequency diversity is implemented by transmitting the same data at different frequencies of the emitter. Thus making the emitter frequencies uncorrelated with the other frequencies,

so that they are not affected by the same fades. In order to make them less correlated, the sending frequencies are sent by more than the bandwidth which have the same coherence of the channel.

- Is implemented by transmitting same information on more than one carrier frequency;
- The separation between the carriers should be at least the coherent bandwidth $(\Delta f)c$;
- Different copies undergo independent fading;
- Only one antenna is needed.

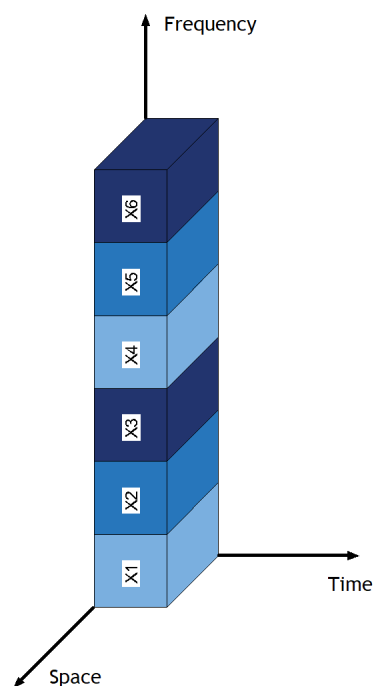


Figure 2.7: Frequency diversity, adapted from [4].

2.7.1.3 Spatial Diversity

Spatial diversity refers to a method for improving the reliability of a data signal by using various communication channels of transmitting and receiving characteristics, spatial diversity techniques predominantly aim at improved error performance and can be applied based on a diversity gain and coding gain. They can also be used to improve bit rates when used in conjunction with an adaptive modulation/channel coding scheme [12].

Diversity plays an important role in combating fading and between-channel Interference and avoiding error bursts [28]. The spatial diversity in the transmission and reception uses two separate antennas and are placed in disposition to act with the function of transmitting and receiving

data. This configuration mode eliminates the need for a duplexes that is used to be able to transmit and receive signal from a single antenna, with the configuration of spatial diversity we can use the variation of multiple antennas. Different types of combination techniques are used in spatial diversity as can be seen in Figure 2.8. Spatial diversity can be achieved with the aid of multiple transmitting antennas in transmission diversity or multiple receive antennas reception diversity with sufficient spacing between the antennas [29].

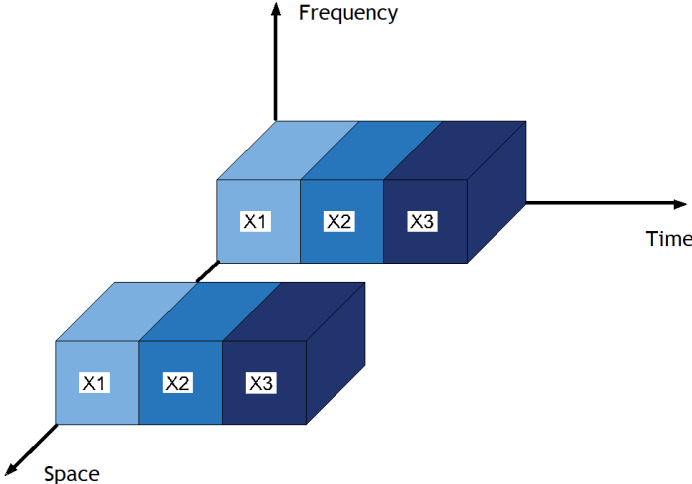


Figure 2.8: Space time diversity, adapted from [4].

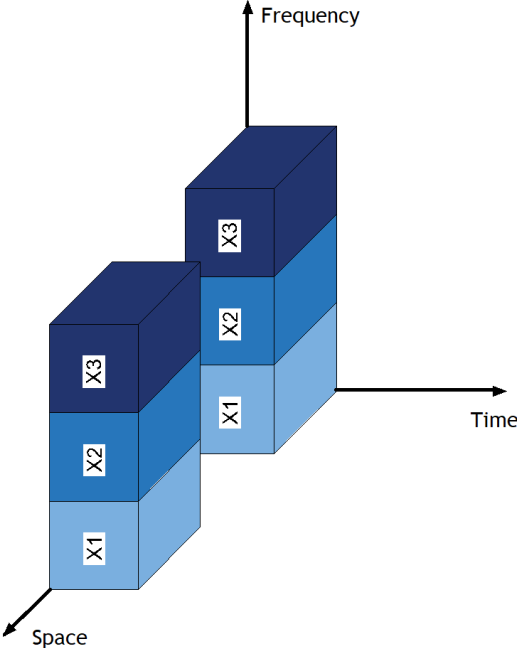


Figure 2.9: Space frequency diversity, adapted from [4].

The main idea of diversity is to transmit the signal multiple times such that the correlation is

low such that the gain in amplitude and phase change in the propagated signal is imperceptible, thereby increasing the difficulty of the signal undergoing a strong attenuation. In SISO diversity can be obtained in the time or frequency domain, that is, the diversity of the signal can be applied at different times or at different frequencies, thus consuming a lot of bandwidth making the system technically limited. Spatial diversity can be divided into two segments, diversity of reception and diversity of transmission. In diversity of reception a multiple antenna architecture is used in the receiver, where each antenna is responsible for receiving a copy of the transmitted signal, where the multiple copies are then combined in order to maximize the received signal and minimize the amount of SINR - there by improving the quality of the received signal.

2.7.1.4 Space Time Transmission Diversity

In the Space Time Transmission Diversity (STTD) schemes, the signals are sent by different antennas in order to pass through different channels, in this way, the possibility of receiving a signal that has undergone a less degradation appears. This allows the transmitted data to contain the same information. The main use of the space-time diversity, and the increase of the reliability of the data, thus allowing to obtain greater robustness of data using this type of technique. The shown in Figure 2.10 exemplifies the basic spatial of the processing in the transmission by diversity of space-time.

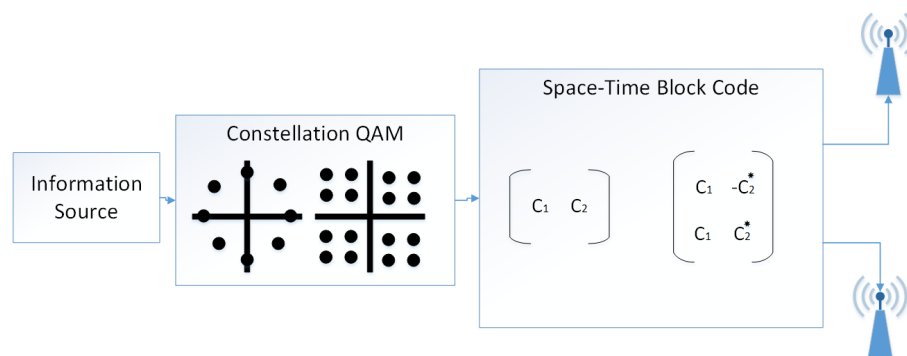


Figure 2.10: Space time block code with diversity space, adapted from [5]

Space Time block coding is a technique used in wireless communications to transmit multiple copies of a data stream across a number of antennas to improve the reliability of data received and transmitted. As the transmitted signal must travel in a potentially difficult environment with scattering, reflection, refraction, so the signal can be corrupted by the noise at the receiver, ie the coding space time combines all copies of the received signal in such a way as to be extracted the maximum information of each signal.

2.7.1.5 Spatial multiplexing

Spatial multiplexing techniques aim to provide higher bit rates taking into account a single antenna system, but spatial diversity techniques aim to achieve improved error performance. It is performed based on a diversity gain and a coding gain in the systems to be considered. Indirectly, spatial diversity techniques can also be used to improve bit rates when applied in conjunction with a modulation coding scheme in relation to the adaptive channel [7].

The signal transmitted and divided into several separate smaller and independent beam sequences on different channels, thus occupying a much smaller bandwidth than would be required if it were sent by a single channel [30]. The data are transmitted by the beams to the receivers through the antennas, and there may be several antennas coupled together. The data is sent on the same frequency of the carrier, to which it will be received by the receivers, the receiver will be responsible for regrouping the signals in a single signal [31].

The spatial multiplexing is one of the MIMO systems to which the ability of this type of systems to explore the capacity of each channel is related, thus managing to increase the data transmission rate of the system without the necessity of increasing any bandwidth or power of streaming. By means of the spatial multiplexing technique it is possible to obtain a linear increase in the capacity of a MIMO system by the number of antenna pair existing between the transmission/reception ratio or $\min(M_T \times N_R)$ [32], which are used virtual channels parallel, orthogonal to each other, by which the information to be transmitted is multiplexed. Considering that a MIMO system consists of several SISO channels, so the MIMO system will present a capacity gain many times higher than the SISO system. Having the disadvantage of using spatial multiplexing is the increase in complexity in the transmitter, and consequently in the receiver. Due to the increase in complexity, it appears in most decoding algorithms that the number of antennas in the receiving zone must be at least equal to the number of transmit antennas [32]. Another disadvantage presented by the technique of spatial multiplexing is the possibility that only a diversity of N_R is obtained, and not a total diversity of $(N_T \times N_R)$, thus generating an increase in the probability of error.

The increase in the capacity of a MIMO system is then the result of applying the spatial multiplexing technique, which divides the information to be transmitted by parallel virtual channels.

$$\mathbf{A} = \begin{bmatrix} S_1 & S_2 & S_3 & S_4 & S_5 & S_6 \end{bmatrix} \quad (2.1)$$

$$\mathbf{A} = \begin{bmatrix} S_1 & S_4 \\ S_2 & S_5 \\ S_3 & S_6 \end{bmatrix} \quad (2.2)$$

The basis of multiplexing is to divide, as such, into spatial multiplexing, the data streams are divided into layers or branches and transmitted separately through each space or each independent antenna, being transmitted at the same frequency, in matrix 1 we can identify a system SISO where we have the data being transmitted by a single channel, already in the matrix 2 applying the multiplexing, it can be seen that the data are divided and transmitted by two channels or branches, the amount division will be limited the amount of transmitting antennas. As shown in Figure 2.11.

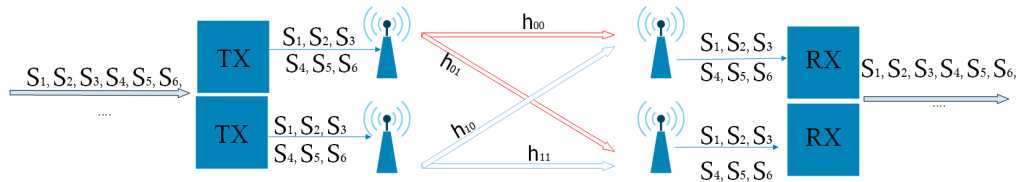


Figure 2.11: Spatial multiplexing channel matrix adapted from [6]

2.8 Channel Capacity in MIMO

Wireless communication systems are limited by the capacity of channels available and the burden on licensed spectrum, coupled with the exorbitant cost of such spectrum. According to theorem Shannon's [7] the Additive White Gaussian Noise (AWGN) channel is limited by the data transfer rate, which can approach theoretically the maximum transmission rate on a channel bandwidth by equation (2.3). Based on the assumption that the channel is a white Gaussian noise and the interference effects are not considered explicitly.

Increasing the bandwidth capacity of the channel used for transmission is not always a viable solution, given the amount paid by the spectra. In addition, the power used for data transmission as well and limited, especially where the battery and the power supply, leading to a context that for greater amount of power and need to increase the amount of energy in the power supply, or increase the size of the batteries. As an example of multiple antenna systems at the receiver and transmitter ends as shown in Figure 2.12, each antenna exhibits multiple input and multiple output channels where the capacity of each channel can be estimated by the capacity formula based on the theorem Shannon's, as can be seen from the equation (2.3).

In practice, a SISO system is considered where equation (2.3) provides a maximum limit for the transmission rate in the SISO system in order to obtain an error-free system:

$$C_{SISO} = B \cdot \log_2 \left(1 + \frac{P}{N_o B} \right) \quad (2.3)$$

where:

- C - is the transmission capacity of the channel;
- B - is the bandwidth on a channel;
- P - is the transmitted signal power;
- N_o - it is the single-sided noise spectrum.

If the baud rate is less than C bps, you must follow an appropriate encoding scheme that can lead to reliable and error-free transmission. If the baud rate is greater than C bps, then the received signal, regardless of the data size, will involve bit errors.

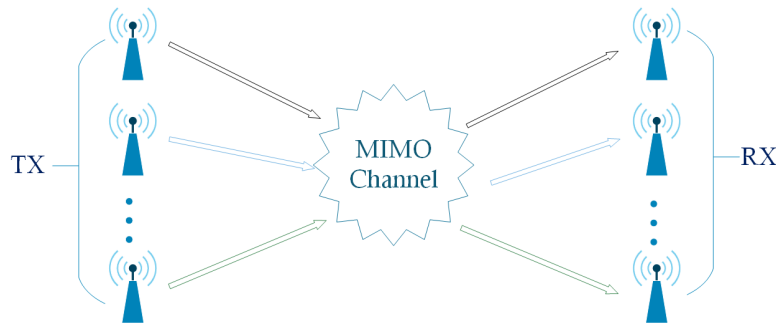


Figure 2.12: MIMO Channel, adapted from [7].

We consider an antenna array with n_t elements at the transmitter and an antenna array with n_r elements at the receiver. The impulse response of the channel between the j^{th} transmitter element and the i^{th} receiver element is denoted as $h_{i,j}(\gamma, t)$. The MIMO channel can then be described by the $n_r \times n_t$, $H(\tau, t)$ in matrix notation as shown below:

$$\mathbf{H}(\tau, \mathbf{t}) = \begin{bmatrix} h_{1,1}(\tau, t) & h_{1,2}(\tau, t) & \cdots & h_{1,n_t}(\tau, t) \\ h_{2,1}(\tau, t) & h_{2,2}(\tau, t) & \cdots & h_{2,n_t}(\tau, t) \\ \vdots & \vdots & \cdots & \vdots \\ h_{n_r,1}(\tau, t) & h_{n_r,2}(\tau, t) & \cdots & h_{n_r,n_t}(\tau, t) \end{bmatrix} \quad (2.4)$$

The matrix elements are complex numbers that correspond to the attenuation and phase shift that the wireless channel which was introduced to the signal reaching the receiver with delay τ . As can be seen in Figure (2.5). Where it can be expressed by the following equation for MIMO system::

$$y(t) = H(\tau, t) \otimes s(t) + u(t) \quad (2.5)$$

Where \otimes denotes convolution, $s(t)$ is a $n_{Tx} \times 1$ vector corresponding to the n_{Tx} transmitted signals, $y(t)$ is a $n_{Rx} \times 1$ vector corresponding to then n_{Rx} received signals and $u(t)$ is the additive white noise.

If we assume that the bandwidth of the transmitted signal is close enough that the channel response can be treated as a flat signal through the frequency, then the discrete time description may correspond to (2.6) is as follows:

$$r_\tau = H s_\tau + u_\tau \quad (2.6)$$

Considering a MIMO channel with n_{Rx} receiving antennas and n_{Tx} antennas transmitters, the H -channel transfer matrix has dimension $n_{Rx} \times n_{Tx}$. O element ij of matrix H corresponds to the result of propagation of the signal from the j_n transmitting antenna to the i_n receiving antenna. Thus, which can be calculated by (2.7):

$$\vec{r} = H \vec{s} + \vec{n} \quad (2.7)$$

where \vec{r} is the vector column of dimension $n_{Rx} \times 1$ which corresponds to the signal received on each of the receiving antennas n_{Rx} , \vec{s} is the vector column of dimension $n_{Tx} \times 1$ which corresponds to the signal transmitted by each of the transmitting antennas n_{Tx} and n corresponds to the noise column vector of dimension $n_{Tx} \times 1$. One can determine each of the elements of the matrix H through the parameters of the multipath components, can be obtained from equation (2.8):

$$H_{ik} = \sum_{p=1}^{n_s} \left[\gamma_p e^{j \left(\frac{2\pi}{\lambda} i d \sin(\varphi_{Rx,p}) \right)} e^{j \left(\frac{2\pi}{\lambda} k d \sin(\varphi_{Tx,p}) \right)} \right] \quad (2.8)$$

Where n_s is the number of scatterers, γ_p is the complex scattering coefficient, λ is the wave-

length, d is the spacing between the antennas of the transmitter and receiver sets; the angle of arrival at the receiver being relative to the normal to the receiver set and $\varphi_{T,p}$ being the starting angle of the transmitter relative to the transmitter assembly. The capacity of a communications channel can be deduced by Shannon's theorem as described [33], corresponding to the maximum error-free transmission rate supported by the channel to be used. Taking this consideration, the standard formula deduced by Shannon's for the capacity, expressed in bit/s/Hz, as it can be observed from equation (2.9):

$$C_{MIMO} = \log_2 \left(1 + \frac{S}{N|H|^2} \right) \quad (2.9)$$

The challenge of increasing transmission rates and the reliability of information involves a number of difficulties. According to Shannon's theorem to increase the capacity of a channel in (bps) it is necessary to increase the transmission bandwidth or increase the signal-noise Ratio (SNR). The limitation to the use of higher bandwidth is in the fact that the frequency spectrum is a rare and expensive resource. On the other hand, in order to increase the SNR it is necessary to increase the transmit power, which is not desirable, since in a mobile device that must coexist with the need for frequency reuse and also with the longevity of the battery life, as well limiting the amount of power that can be implemented. A MIMO system with N_T transmitting antennas and N_R receiving antennas has a capacity given by [5], as can be expressed in equation (2.10):

$$C_{MIMO} = \log_2 \det \left(I_{N_r} + \frac{P_t}{N \cdot N_t} H \cdot Q \cdot H^+ \right) \quad (2.10)$$

Where:

- C_{MIMO} - is the transmission capacity of the channel;
- I_{N_r} - is the dimension identity matrix $N_R \times N_T$;
- H - is the dimension Channel matrix $N_R \times N_T$;
- N_o - it is the single-sided noise spectrum;
- H^+ - is the trasn-conjugate matrix of the channel $N_R \times N_T$;
- Q - is the covariance matrix of the signal vector to transmit.

For systems with Transmitter without MIMO Channel Information. In the case where the transmitter has no information about the transmission channel, each transmitting antenna is considered

to radiate the same power and the transmitted signals are independent. This consideration leads to $Q = I_{N_t}$. Substituting the matrix Q into equation (2.10) and effecting the self-decomposition of HH^+ , denoted by λ_k , according to [5], one obt the capacity of the MIMO channel under these conditions we can verify how it can be expressed in the equation (2.11):

$$C_{MIMO} = \log_2 \det(I_{N_r} + \frac{P_t}{N_t N_r} \lambda_k) \quad (2.11)$$

We notice that the achieved capacity depends on the algorithm used for allocating power to each sub-channel. The theoretical analysis assumes the channel state known at the receiver. This assumption stands correct since the receiver usually performs tracking methods in order to obtain CSI, however the same consideration does not apply to the transmitter [7]. When the channel is not known at the transmitter, the transmitting signal s is chosen to be statistically non-preferential, which implies that the n_{Tx} components of the transmitted signal are independent and equi-powered at the transmit antennas.

From equation (2.11), it is seen that the capacity of the MIMO channel is the sum of the independent SISO channels capacities N_R , where the SISO channel gains are the eigenvalues of the matrix HH^+ and whose total power is evenly distributed for each transmitter antenna. In this case the MIMO system allows an increase of the capacity that grows linearly with $\min(N_T, N_R)$. Since the gain of capacity depends on the eigenvalues of the matrix HH^+ , if the gains have low or zero values it may be impossible to perform the transmission in a virtual channel, so that power of the channel signal may not be sufficient to reach the receiver.

Where S/N corresponds to the signal-to-noise ratio and H , the transfer matrix of the channel. Observing the equation (2.11), it is verified that a growth of 3 dB in the relation Signal-to-noise ratio, causes a 1 bps/Hz increase in capacity. In the case of MIMO systems, the calculation of capacity is related to the diversity of space in which the receiver makes the most of the data received by vector \vec{r} . Assuming that the vector \vec{s} of the transmitted signal is composed of equal and statistically independent n_{Tx} components, each with a Gaussian distribution, we can deduce the capacity for a MIMO system from equation (2.11).

2.8.1 Capacity of Orthogonal Channels

Capacity of the Orthogonal Channel, has as finality to study the capacity of the channel MIMO where the system has its capacity maximized. As an example we consider a simple case where we will have a composite MIMO system can $n_t = n_r = n$, along with a fixed total power through the SISO sub-channels, i.e $\sum_{k=1} \varepsilon_k^2 = a$ where a is a constant. The capacity in equation (2.12)

is concave in the variables ε_k^2 ($k= 1,2, \dots, n$), and as a result, maximizing your system when $\varepsilon_k^2 = \varepsilon_i^2 = a/n$ ($k= 1,2, \dots, n$). Thus, the equation can show that $HH^+ = H^+ = (a/n)I_n$. Substituting $HH^+ = (a/n)I_n$ into the equation (2.12).

$$C_{MIMO} = \log_2[\det(I + \frac{pa}{n^2}I_n)] \Rightarrow C = n.\log_2(1 + \frac{pa}{n^2}) \quad (2.12)$$

If $|H_{i,j}|^2 = 1$, the matrix H satisfies $HH^+ = nI_n$, hence, equation (2.13) became,

$$C_{MIMO} = \log_2[\det(I + \frac{p}{n}nI_n)] \Rightarrow C = n.\log_2(1 + pa) \quad (2.13)$$

The last equation indicates that the capacity of an orthogonal MIMO channel is n times the capacity of the SISO Channel.

2.8.2 Simulation Capability MIMO Channel

The MIMO channel simulation capability, using the Matlab simulation platform, makes it possible to compare the Shannon capacity and the MIMO channel capacity for different MIMO systems. In Figure 2.13 we have shown the simulation results of mean MIMO channel capacity for different distributions. Shannon capacity for Gaussian channel, is compared with other distributions. Channel is assumed with perfect estimation at both transmitter and receiver. The capacity of a MIMO channel with n_t transmit antenna and n_r receive antenna is analyzed. MIMO capacity dependencies (bit/s/Hz), and SNR (dB), in this simulation we used the initial simulation results SNR = 2, for MIMO 2x2, MIMO 3x3, MIMO 4x4 systems capacity. In Figure 2.13 it can be observed that with the increase of the number of antennas we have a greater variation of the SNR in relation to the number of antennas, where the transmission capacity in (bit/s/Hz) of each system is increased when a larger number of antennas are introduced, so it is possible to use multiple antenna systems for more reliable transmission. We can also verify that, from the results shown in Figure 2.13, it is possible to visualize that the capacity of the MIMO channel increases as we increase the number of antennas.

2.9 Capacity of SIMO and MISO Channel

Single Input Multiple Output (SIMO) and Multiple Input Single Output (MISO) channels are special cases of MIMO channels. In this paragraph discuss the capacity formulas for the case of SIMO

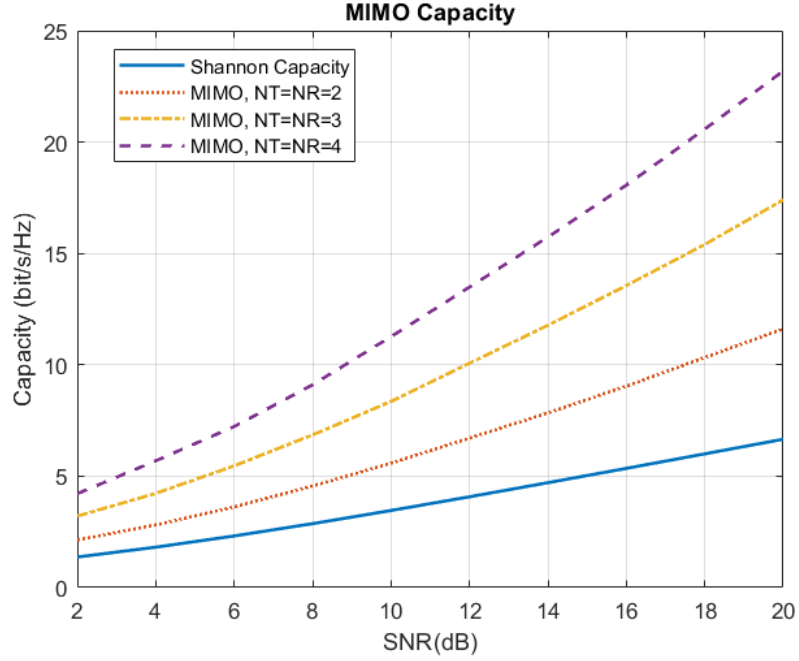


Figure 2.13: MIMO Capacity, according to equations (2.3) and (2.13)

and MISO channels. For a SIMO channel $n_{tx}=1$, so $n = \min(n_{rx}, n_{tx})=1$, hence, this channel state information (CSI) at the transmitter does not affect the SIMO channel capacity [7]:

$$C_{SIMO} = \log_2(1 + p \times \varepsilon_1^2) \quad (2.14)$$

If we considered $|h_i|^2 = 1$ then $\varepsilon_1^2 = n_{rx}$. Hence equation (2.15) stands:

$$C_{SIMO} = \log_2(1 + p \times n_r) \quad (2.15)$$

MISO systems are systems that have multiple antennas in the transmitter and only one antenna in the receiver. Using the channel capacity for CSI in the receiver with fast fading, we can find channel capacity for MISO systems by analyzing the behavior of the equation (2.16) [7]. For a Multiple Input Single Output (MISO) channel $n_r = 1$ and $n = \min(n_r, n_t) = 1$. With no channel state information (CSI) at the transmitter, the capacity formula can be expressed as follows:

$$C_{MISO} = \log_2\left(1 + \left(\frac{p}{n_t}\right) \times \varepsilon_1^2\right) \quad (2.16)$$

For systems that have a very large n_t , that is, $n_t \rightarrow \text{infinity}$, we can simulate the equation

(2.16) and use the equation (2.17). If we make the same assumption as earlier and consider that $|H_k|^2 = 1$, Then $\varepsilon_1^2 = n_t$. Hence equation (2.17):

$$C_{SIMO} = \log_2(1 + p) \quad (2.17)$$

Comparing equation (2.17) and (2.15) we can see that $C_{SIMO} > C_{MISO}$. This is because the transmitter, as opposed to the receiver, can not exploit the antenna array since it has no CSI and, as a result, cannot retrieve the receiver's signal direction.

The larger the number of antennas in the transmitter, the greater the possibility of reaching infinity, getting closer and closer to the capacity with the addition of white Gaussian Noise (WGN).

When $n_t = 1$, that is, the system has only one transmitting antenna and one antenna receiving signal, we have a considerably reduced capacity, taking into account the capacity of a channel system with white Gaussian noise, due to the loss of Jensen. The increase in the number of antennas in the transmission generates an effect of reducing the fluctuation of the instant SNR, thus reducing the loss of Jensen. For a SIMO system, where the transmission is made by only one antenna and on the receiver side has n_r antennas, we obtain, as in the MISO system, for a CSI channel in the receiver, we can obtain the channel capacity from the equation (2.15). For a large n_r , tending to infinity, equation (2.18) can be considered to calculate the capacity of SIMO systems:

$$C_{SIMO} \approx \log(n_r \cdot SNR) = \log(n_r) + \log(SNR) \quad (2.18)$$

2.10 Beamforming

Beamforming is a word that can be used in different perspectives. *Beamforming* can be defined as the ability to adapt to the radiation pattern of determined sets of antennas in a given scenario. In the wireless communication space, many conceptualize beamforming as being a guide of the signal in a direction having as its principal toward that of a user, as it is shown in Figure 2.14. The amplitude and phase changes can be applied to each element of the antennas, thus allowing the transmission signals from the antenna arrays to be received homogeneously in order to obtain a specific transmission/reception angle. *Beamforming* can still be considered as a signal processing technique using array signal for directional signal transmission/reception by combining antenna array elements such that the antenna angles combine as can be seen in

the Figure 2.15.

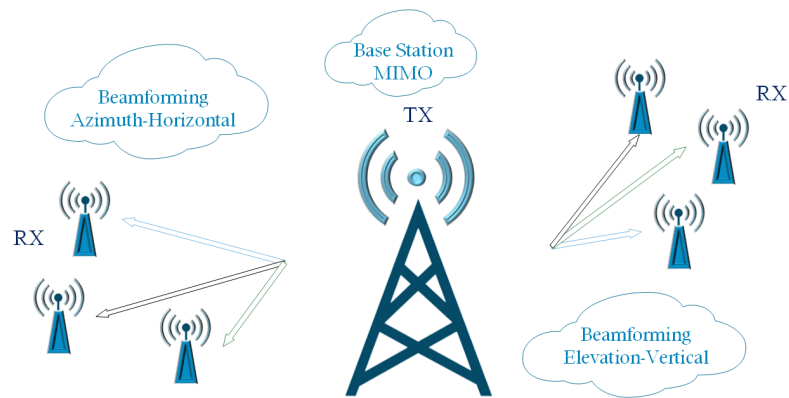


Figure 2.14: Beamforming

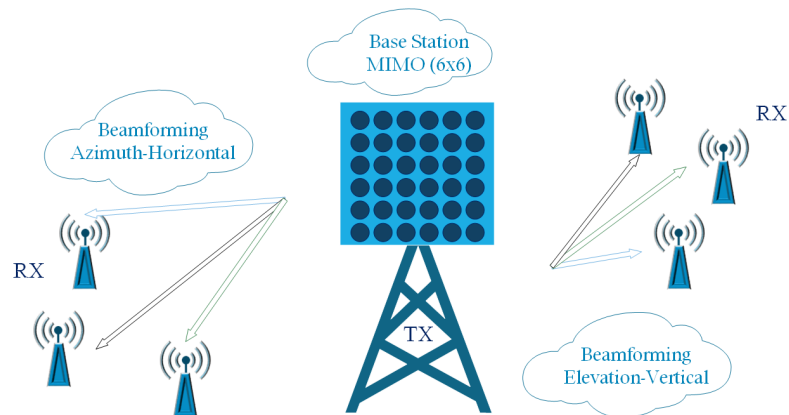


Figure 2.15: Beamforming with MIMO 6x6

The term beamforming derives from the fact that early spatial filters were designed to form pencil beams, in order to receive a signal radiating from a specific location and attenuate signals from other locations. *Forming beams* seems to indicate radiation of energy, however, beamforming is applicable to either transmission or reception of signal. Systems designed to receive spatially propagating signals often encounter the presence of interference signals. If the desired signal and interferer occupy the same temporal frequency band, the temporal filtering cannot be used to separate signal from interference. However, the desired and interfering signals from interference using a spatial filter at the receiver. Implementing a temporal filter requires processing of data collected over a temporal aperture. Similarly, implementing a spatial filter requires processing of data collected over a spatial aperture [34].

The beamforming is based on a spatial filtering, thus allowing the signal to be concentrated and directed directly to the desired location, increasing the SNR, blocking most of the noise located in the directions that were destined. The acquisition of CSI consists of integrating a key ingredient in wireless communication systems, especially after the emergence of multiple antenna systems, such as MIMO and consequently Massive MIMO. Being a technique that focuses

on concentrating more energy in a specific direction requires CSI to be available. In addition, the quality and quantity of CSI available are extremely important, especially in transmission systems. However, it can be assumed that the perfect channel state information is not properly fitting when applied in several different practical scenarios. The beamforming technique can be applied at the transmission and reception ends, generating in the transmission systems an increase in the directivity of a specific direction and minimizing the power to the desired direction by configuring the transmitted signal radiation pattern, beamforming is used to increase and decrease receiver sensitivity for specific directions of interest [34].

Therefore, each base station can increase the coverage range focusing its energy toward the intended users instead of wasting it with unnecessary directions. With this technique, fewer base stations are required which means a potentially cheaper implementation offering. Beamforming allows us to extend the concept of MIMO to multiple simultaneous transmissions on the same channel, due to its increased directivity. Without beamforming, two simultaneous transmissions on the same channel would cause a collision [?]. The multipath propagation present in mobile environments can be mitigated using beamforming by constructively adding multipath to increase the strength of desired signal [35]. In addition to directivity, the radiation patterns of antennas are also characterized by their beam widths and side-lobe levels. Some important pattern lobes and beam widths are presented in Figure 2.16. The half power beam width is the angular separation in which the magnitude of the radiation pattern decreases by 50% ($-3dB$) from the peak of the main lobe, which is often the parameter most commonly referred to as just beamwidth.

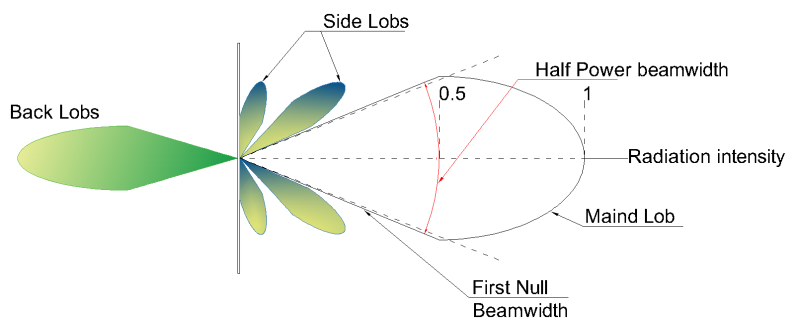


Figure 2.16: First Null Beamwidth, adapted from [8]

There are beamforming techniques that can generate multiple beams simultaneously, where these beams can be calculated to have a high gain and low side lobes, or even controlled beam. Adaptive beamforming automatically adjusts the pattern of the matrices for the adjustment of some characteristic of the received signal. The desired and interfering signals generally originate from their different spatial species. The antenna arrangements may exploit a spatial characteristic to reject interfering signals with a different Direction of Arrival (DOA) from a de-

sired signal source [35]. A multi-polar array can reject the signals with different interferences with the different polarization states, even if the signals have the same sense of arrival DOA. The process of maximizing the Signal to Interference plus noise ratio SINR based on its spatial characteristic is not called the airbase. Thus, based on the information estimated from the up-link, beamforming is used in the downlink of the base station for the user, in order to maximize the transmission power of the base station to a desired user while other less important signals. The antenna elements in an adaptive array may be spatial from propagation fields, which are processed by the light beam [34].

The array factor is the most fundamental of the antenna parameters and depends on the number of elements, the element spacing, amplitude and the phase of the applied signal to each element. In [36] is shown the impact of spacing and number of elements in terms of gain and HPBW. By increasing the separation between the elements and the number of elements, the matrix factor improves, that is, a higher gain of the antenna can be obtained and a value of beam width smaller than half the power. The separation between elements will depend on the wavelength (λ), which can be calculated by equation (2.19).

$$\lambda = \frac{c}{f} \quad (2.19)$$

where f is the frequency and $c = 3 \times 10^8$ m/s. Thus, in order to avoid an increase in interference, the separation between each antenna element should be at least half of the wavelength, which can be calculated by equation(2.20).

$$d = k\lambda, \quad (2.20)$$

Where $k \geq 1/2$. Another important antenna parameter is the effective antenna aperture A_e , generally calculated by (2.21):

$$A_e = \left(\frac{\lambda^2}{4\pi}\right)G, \quad (2.21)$$

$$A_e = \left(\frac{c^2}{4\pi f^2}\right)G \quad (2.22)$$

where G is the gain of the antenna. As can be seen in equation (2.19) and equation (2.20), both the distance between the antenna d and the effective aperture of the antenna A_e are dependent on the frequency, that is, it is only possible to vary the distance or the effective opening of the

antenna when we vary at system frequencies. In [37] the compromise between directivity and beam width is presented. Through equation (2.23):

$$D = \frac{T_{LA}dN_{beam}}{\lambda} \quad (2.23)$$

$$D = \frac{T_{LA}dN_{beam}f}{\lambda} \quad (2.24)$$

where T_{LA} depends on the linear matrix type, for example, for a broadside arrangement $T_{LA} = 2$ and $T_{LA} = 4$ for ordinary end-fire array, which is a stacked collinear antenna consisting of half-wave dipoles spaced from each other by half-wavelength ($\lambda/2$). The total number of generated beams N_{beam} must be less than or equal to the number of transmitting antennas ($N_{beam} \leq N_{tx}$). Thus, the relations between beam directivity and beamwidth can be expressed in the for a given linear antenna array, with its designed beam directivity and bandwidth can be adjusted, then the relationship between them a which can be calculated from the (2.23) [37]. For a uniform linear array, the expression associated to the beam width is based on the half power beam (HPB) where it is expressed by equation (2.25):

$$HPB = \frac{C\lambda}{\pi dN_{beam}} \quad (2.25)$$

$$HPB = \frac{Cc}{\pi dN_{beam}f} \quad (2.26)$$

where $C = 2.782$ is a constant parameter in antenna design. Theoretically, adding more antennas (elements) can improve the beamforming performance due to the increased directive and also narrows down the beam width. Thus, despite the distance between antennas should be enough to obtain low correlation among channels, close distance is also required to produce a narrow beam for not generating lobes introducing interference [27].

2.11 Conclusions

MIMO systems are configurations that relate multiple inputs to multiple outputs. In modern control it is defined as a multi-variable system that has a much more complex response than systems with a single input and single output (Single Input Single Output). In the case of wireless communications, they are point-to-point communication techniques that use multiple antennas for both transmission and reception. This transcript gives a clear advantage of diversity performance over SISO and its SIMO and MISO derivations. Providing greater quality and stability of

services. MIMO techniques exploit the spatial dimension to improve capacity and increase data throughput without increasing the power and bandwidth used. Multiple-Input Multiple-Output (MIMO) systems can increase the spectral efficiency of wireless communications. However, such interference becomes the main disadvantage by increasing the computational complexity in the transmitter and the receiver. As an efficient mathematical tool, low-complexity approaches can be devised to slow down interference in MIMO systems.

Chapter 3

Millimetre Wave Communications

3.1 Introduction

Millimetre wave (mmWave) communications are a promising enabler of extremely high data rate in future wireless networks and offers a significant improvement in per-user throughput, network throughput, and power and spectral efficiencies compared to traditional wireless networks. The main features of a mmWave system are very high attenuation, sparse dispersion environment, huge bandwidth, vulnerability to obstacles and antenna misalignment, massive beam formation and limited interference, which differentiate mmWave systems from legacy systems that operate in microwave bands .

This huge bandwidth, even if used with very low spectral efficiency, can easily provide a data rate per gigabit per second. With the rapid increase in the demand for mobile data and the use of smartphones has been an unprecedented challenge that has hit wireless service providers and can thus generate a global shortage of bandwidth related to licensed spectrum [38]. As mobile operators have been increasingly required to improve the delivery of interconnection to their users, it has offered a wide range of high-quality, low-latency multimedia and video applications for wireless devices, where they will circumvent the limitation of the carrier frequency spectra ranging from 700 MHz to 2.6 GHz which are the frequencies currently available. As it can be seen in Table 3.1, the global spectrum bandwidth allocation for all cellular technologies does not exceed 780 MHz, where each primary wireless provider has approximately 200 MHz in all different spectrum bands available to them. Currently, the spectrum allocated to operators is divided into disjoint frequency bands, each of which has different radio networks with different propagation characteristics and losses of penetration of buildings. This means that base station projects must serve many different bands with different cell sites, where each site has multiple base stations, one for each frequency or use of technology, for example, third generation (3G), Fourth generation (4G), Long Term Evolution-Advanced (LTE-A) and the fifth generation (5G) [39].

Table 3.1: Global spectrum bandwidth allocation, adapted from [12]

Band	Uplink (MHz)	Downlink (MHz)	Carrier Bandwidth (MHz)
700 MHz	746-763	776-793	1.25-10
AWS	1710-1755	2110-2155	2-15
IMT Extension	2500-2570	2620-2690	2-20
GSM 900	880-915	925-960	1.25-5
UMTS Core	1920-1980	2110-2170	5-10
GSM 1800	1710-1785	1805-1880	1.25-5
PCS 1900	1850-1910	1930-1990	1.25-5
Cellular 850	824-849	869-894	1.25-5

3.2 Millimetre Wave

Millimetre wave bands are allocated between 30-300 GHz, to which the waves are identified as Extremely High Frequencies (EHF), are commonly used in broadband communications without high speed wire.

The Millimetre wave (mmWave) are allocated in the range of unlicensed spectra, so the possibility of use is wide, especially for Wireless Communication (WLANs) or high-speed point-to-point communication. Millimetre Wave communication is setting a new era for 5G wireless communication. Millimetre wave offer a much higher communication bandwidth compared to those used in today's wireless communication systems [40].

The main challenge of Radio Frequency Energy Harvesting (mmRF-HARVESTING) for Millimetre Waveband Wireless Sensor Networks with Cognitive Radio Capabilities is to develop and test a Wireless Sensor Network (WSN) operating at the Millimetre wavebands. WSNs typically communicate in the 800 MHz, 900 MHz and 2.4 GHz Industrial, Scientific and Medical (ISM) bands. In the mmRF-HARVESTING proposal, we aim for very high throughput and short distance networks, which is conceivable for the 5 GHz band and millimetre wavebands (e.g., 40 and 60 GHz) [12]. Such high frequency bands are not very used because corresponding communications are more affected by signal degradation than in lower frequency bands, and the signal can only be appropriately received in the close vicinity of the transmitter. However, broadband allows for values of the throughput, of the order of multi-Gbps within a bandwidth of some GHz. The focus on area spectral efficiency is a result of extremely limited bandwidths available in the UHF and microwave frequency bands where cellular systems are deployed, as illustrated in Table 3.1. Millimetre Wave cellular will change the current operating paradigm using the untapped mmWave spectrum [12].

3.2.1 Spectrum in Millimetre Wave

Using millimetre wave frequency communications, where the spectrum is less congested, it enables greater bandwidth availability and provides very high throughput. Millimetre Wave technology can be used to overcome the limited bandwidth constraint associated with large-scale communication systems such as MIMO and Massive MIMO. However, with the increased frequency band used, some propagation problems, channel model and hardware increase [40]. Nowadays, most of the mobile communication systems use spectra below the 3 GHz frequency, which are the most common and most requested. So with the increasing demand for better capacity, reliability and performance, the spectrum below 3 GHz are no longer able to meet the increasing demands of future 5G systems. As can be seen in Figure 3.1, mmWave communications are based on scanning the 3-300 GHz band spectrum and therefore the problem of limited available bandwidth is apparently solved by the vast increase in bandwidth.

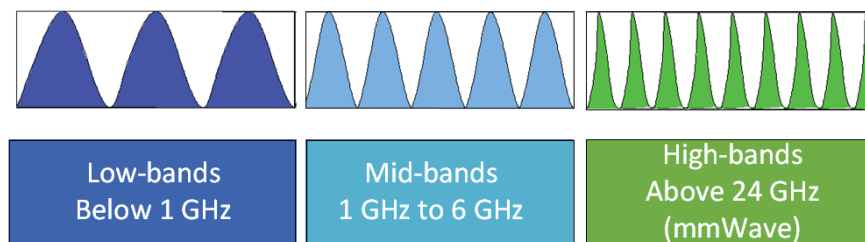


Figure 3.1: Millimetre wave spectrum

Today's wireless networks have run into a problem: More people and devices are consuming more data than ever before. However, it remains crammed on the same bands of the radio-frequency spectrum that mobile providers have always used. That means less bandwidth for everyone, causing slower service and more dropped connections [41].

One way to get around that problem is to simply transmit signals on a whole new swath of the spectrum, one that's never been used for mobile service before. This is the reason why providers are experimenting with broadcasting on millimetre waves, which use higher frequencies than the radio waves that have long been used for mobile phones.

Millimetre waves are broadcast at frequencies between 30 and 300 GHz, compared to the bands below 6 GHz that were used for mobile devices in the past. They are called millimetre waves because they vary in length from 1 to 10 mm, compared to the radio waves that serve today's smartphones, which measure tens of centimeters in length [41], [42].

Until now, only operators of satellites and radar systems used millimetre waves for real-world applications. Now, some cellular providers have begun to use them to send data between stationary points, such as two base stations. But using millimetre waves to connect mobile users

with a nearby base station is an entirely new approach.

There is one major drawback to millimetre waves, though they can not easily travel through buildings or obstacles and they can be absorbed by foliage and rain. That is why 5G networks will likely augment traditional cellular towers with another new technology, called small cells [42].

With millimetre waves and other 5G technologies, engineers hope to build the wireless network that future smartphone users, VR gamers, and autonomous cars will rely on every day. Already, researchers and companies have set high expectations for 5G by promising ultra-low latency and record-breaking data speeds for consumers. If they can solve the remaining challenges, and figure out how to make all these systems work together, ultra-fast 5G service could reach consumers in the next years [41], [42].

In World Radio Communications (WRC) conferences was discussed the possibility of allocating mmWave bands for 5G. Some of the bands discussed were 6 GHz, 18 GHz, 28 GHz, 48 GHz, 60 GHz or 70 GHz, with contiguous 300 MHz of spectrum [43]. There are already some protocols designed to explore the large bandwidth in the mmWave band to reach very high transmission rates, for indoor environments. With the 802.11n and 802.11ac protocols, which communications at 5GHz, allows achieving significantly higher maximum data rates, when compared with the older protocols 2.4 GHz [44]. The first IEEE wireless standard for data rates over 1 Gbit/s was the 802.15.3c, using between 57 GHz and 66 GHz band. In [45] were tested 3 modes for this protocol and with the video streaming and multivideo streaming mode the 802.15.3c allowed to reach 3.8 Gbit/s for video streaming and multivideo streaming. More recently, the 802.11ad protocol resulted from research works when trying to achieve multigigabit speed levels (up to 7Gbit/s) on WLANs, using signal transmission at 60 GHz [46]. However, the constraint associated to these protocols based on mmWave is the fact that they are only available for short-range services and normally designed for enclosed spaces.

3.2.2 Millimetre wave for 5G future

The tremendous breakthrough of industrial research to deploy new wireless technologies are more efficient, the wireless industry, always suffer from the huge capacity demands for their wireless technologies implemented, as a result of continuous advances and discoveries in communications systems and the emergence of new handsets and use cases, as mentioned the need to access the high-speed internet becomes increasingly sought after by users and applications. The trend tends to occur in the coming years for the 4G LTE technologies and later the 5G technology, some operated are already predicting this concept of 5G and implementing in their devices systems that are compatible with the technology, and the total implementation the

wireless networks will face congestion, as well as the need to implement new technologies and architectures to adequately meet the continuous demands of operators and customers. The life cycle of each new generation of cellular technology is usually a decade or less (as shown earlier) due to the natural evolution of computing and communication technology.

Recent research has worked to make possible a wireless future where mobile data rates expand into the range of multiple gigabits or maybe terabits per second, thus enabling the use of directional antennas and the wave spectrum of mm to which they are supported simultaneously with mobile and backhaul communications, which may interact with cellular and Wi-Fi services. Recent studies on mmwave frequencies have described that millimetre waves can be used to significantly increase the radio spectrum bands that are currently saturated in the frequencies of 700 MHz to 2.6 GHz for wireless communications [47]. The combination of low cost CMOS technology that can operate well in the mmwave frequency bands and high gain directional antennas in the mobile station and base, strengthens the viability of mmWave wireless communications [48]. The frequencies carrying mmwaves allow for larger bandwidth allocations, which translate directly into higher data transfer rates. The mmwave spectrum would allow service providers to significantly expand channel bandwidths far beyond the current 20 MHz channels used by 4G clients [38]. By increasing the bandwidth of the RF channel to mobile radio channels, data capacity increases dramatically, while the digital traffic latency decreases considerably, thus supporting Internet access and much better applications that require minimal latency. The mmWave frequencies, due to the much shorter wavelength, can exploit polarization and new spatial processing techniques, such as massive MIMO and adaptive beamforming [49]. Given this significant leap in bandwidth and new capabilities offered by mmWave, base station-to-device links as well as backhaul links between base stations will be able to handle much larger capacity than current 4G networks in highly populated areas. In addition, as operators continue to reduce cell coverage areas to exploit spatial reuse and implement new cooperative architectures, such as cooperative MIMO, retransmission and mitigation of interference between base stations, the cost per base station will decrease as it becomes more common and widely distributed in urban areas, thus making wireless backhaul an essential part of rapid deployment. Unlike the dis-articulated spectrum used by many cell phone operators today, at which cell site coverage distances range between 700 MHz and 2.6 GHz, the millimetre wave spectrum is in relatively high spectral allocations, making the propagation characteristics in different homogeneous millimetre wavebands. The 28 and 38 GHz bands are currently available for spectrum allocations of more than 1 GHz bandwidth. Originally intended for the use of Local Multipoint Distribution Service (LMDS) in the late 1990s, these licensees could be used for both cellular and backhaul [50].

3.3 Millimetre Wave Propagation and Channel Models

Electromagnetic waves can undergo reflection, diffraction and scattering. Often Direct Sighting Line (LVD) communication is impractical due to buildings or elevations. The signals referring to the various reflections occurred interfere causing a change of amplitude and phase in the signal, causing it to fade. Traditional models will seek to determine the value of the received signal at a certain distance from the transmitter. These models are useful for establishing the coverage area of a given communication system. In a mobile communication system the possibility of rapid fluctuations of the signal, giving rise to fading. Propagation aspects are unique in mmWave due to the very small wavelength when compared to the size of most objects in the environment. Understanding the characteristics of these channels is fundamental for the development of signal processing algorithms for the transmitter and receivers.

3.3.1 Distance Based Path Loss

For free-space propagation, the transmit power, P_t , and far-field receive power, P_r , are related by the Friis' Law [51]:

$$P_r = \frac{G_r G_t}{L_0} \left(\frac{\lambda}{4\pi d} \right)^2 P_t \quad (3.1)$$

- $P_r(d)$ is the power received as a function of distance;
- P_t is the transmitter power;
- λ is the wavelength of the signal;
- d is the distance T-R (Transmitter-Receiver);
- G_t is the transmitter gain;
- G_r is the gain of the receiver;
- L_0 represents the losses.

Where I fear the powers in linear scale, where the Law of Friis implies that the loss of the isotropic path at which the relation between transmitted power and received power (P_t/P_r) as the unit gain of the antenna, being $G_t = G_r = 1$, with its increase being inversely proportional to the wavelength squared, λ^2 . In the absence of gain in the directional antennas, the propagation of mmWave will suffer a more significant loss in the trajectory in relation to the lower frequencies. For any aperture of a physical antenna, the maximum directional gains are usually scaled

with the ratio of $G_r, G_t \propto \lambda^2$ [52]. Since more amount of antennas can be allocated in the same physical area. Consequently, antenna sizing can gain more than can be compensated for most of the free-space trajectory losses allocated to mmWave frequencies. Having thus compensated for the loss of trajectory in some way, however, directional transmissions with high-dimensional antenna arrays such as 64×64 , where it can be seen in MIMO which is a defining feature for millimetre wave communications. Although the propagation in free space can be predicted by the Law of Friis, already the loss of trajectory in general environments and dependent on the position in which are the objects or obstacles that can attenuate, to diffract and to reflect the propagated signals. There is also a large amount of work in the development of mmWave statistical models that describe the distribution of trajectory losses in a set of environments [53], [54].

We can define the losses L as being:

$$L = 10 \log\left(\frac{P_t}{P_r}\right) \quad (3.2)$$

Relating the Friis equation:

$$\left(\frac{P_t}{P_r}\right) = \left(\frac{4\pi d}{\lambda}\right)^2 \quad (3.3)$$

Associating the equation (3.2) with the(3.3), we will have:

$$L = 10 \log\left(\frac{4\pi d}{\lambda}\right)^2 \quad (3.4)$$

$$L = 20 \log(4\pi) + 20 \log\left(\frac{d}{\lambda}\right) \quad (3.5)$$

$$L = 21,98 + 20 \log\left(\frac{d}{\lambda}\right) \quad (3.6)$$

3.4 What is Massive MIMO?

Massive MIMO is a form of Massive Multiple Input Multiple Output (MU-MIMO) systems where the number of BS antennas and the numbers of users are large. In Massive MIMO, hundreds or thousands of BS antennas simultaneously serve tens or hundreds of users in the same frequency resource. Massive Multiple Input Multiple Output systems with multiple antennas at the transmitter and receiver are already used to achieve higher capacity and link reliability by the

exploitation of both spatial multiplexing and diversity. In order to deliver the required data rates, the use of antenna arrays with a very large number (tens to hundreds) of elements might become a reality. This technology will allow a much higher spectral efficiency with decreased energy levels, whilst serving a large number of users at the same time in Figure 3.2.

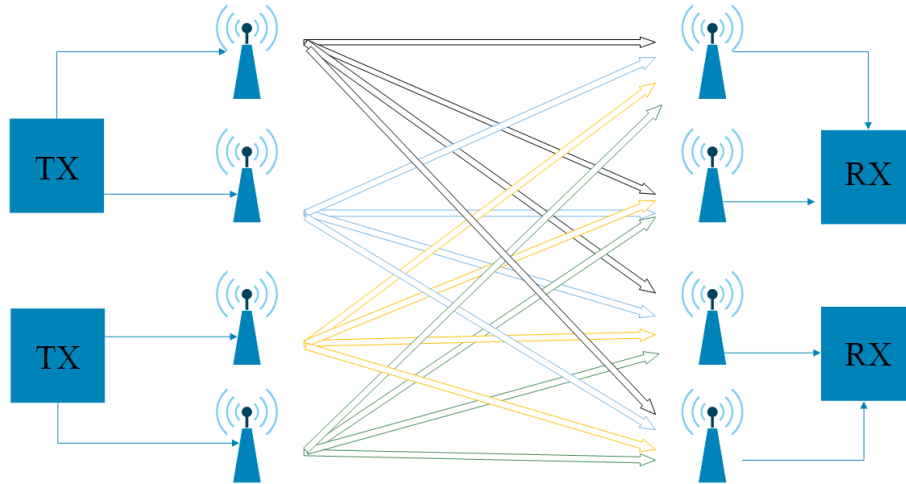


Figure 3.2: Massive MIMO

Although the potential capacity gains can be very high, the implementation complexity of MIMO systems grows very fast with the number of antenna elements. Therefore, massive MIMO systems cannot be regarded as a scaled version of conventional MIMO schemes, and low-complexity implementations are required [49]. In massive MIMO the number of transmitters is large, so a Time Division Duplexing (TDD) is preferable in opposing to a Frequency Division Duplexing (FDD), because that with TDD adding more antennas does not affect the resources needed for the channel estimation. Because of the large number of BS antennas and the number of users are large, the signal processing at the terminal end must deal with large dimensional matrices/vectors. Thus, simple signal processing is preferable. In Massive MIMO, linear processing, linear combining schemes in the uplink and linear precoding schemes in the downlink, is nearly optimal. Massive MIMO is scalable. The BS learns the channels via uplink training, under TDD operation. The time required for channel estimation is independent of the number of BS antennas. Therefore, the number of BS antennas can be made as large as desired with no increase in the channel estimation overhead. Further more, the signal processing at each user is very simple and does not depend on other users' existence, i.e., no multiplexing or de-multiplexing signal processing is performed at the users. Adding or dropping some users from service does not affect other users activities [9].

In Massive MIMO, the Time Division Multiple Access (TDMA) operation is preferable. During a consistency interval, there are three operations: channel estimation that includes uplink training and downlink training, as well as uplink data transmission and downlink data transmission.

A TDD protocol for massive MIMO systems can be observed in Figure 3.4. As with all data transmission and reception systems, it is always necessary to obtain a channel estimate and is no different for massive MIMO systems.

In systems with TDD operation, such as FDD, channel estimation depends on the number of antennas BS, M . In contrast, with TDD, the channel estimation is independent of M , driven by the need to acquire channel-state information between numbers at the ends of the antennas and having a much smaller number at the terminals. Uplink pilots are independent of the number of antennas, while the time needed to transmit the direct link pilots is proportional to the number of antennas. The matrix of propagation in the uplink, G , is sized by $M \times K$, being the product of a matrix $M \times K$, H , to which we can represent the small scale fading, that is, the change in the intervals of a wavelength and $K \times$ diagonal matrix K , $D1/2\beta$, whose diagonal elements constitute a vector $K \times 1$, having a large scale fading coefficients [55]. In MIMO mass, M , and considerate by a large number of antennas, to which it makes good use for TDD systems. However, we can assume that the coherence interval is $T = 200$ symbols for which we have a coherence bandwidth of 200 kHz and an estimated coherence time of 1ms. Considering this, we can say that in FDD systems, the number of BS antennas and the number of users are limited by a $M + K < 200$, where K are considered the numbers of users, whereas in TDD systems it creates a restriction in M and K can be considered $2K < 200$. Figure 3.3. shows the viability regions (M, K) in the FDD and TDD systems. We can see that the FDD region is much smaller than the TDD region. With TDD, adding more antennas does not affect the capabilities required for channel estimation [56]. With TDD, adding more antennas does not affect the resources needed for channel estimation [56], [55].

3.4.1 Channel Estimation

The Base Station needs Channel Status Information to detect the signals transmitted by the users in the uplink and to precode the signals in the downlink. This CSI is obtained through uplink training. Each user receives an orthogonal pilot sequence and sends that pilot sequence to the BS. The BS knows the sequences of pilots transmitted from all users and estimates the channels based on received pilot signals. In addition, each user may need partial knowledge of the CSI to consistently detect transmitted BS signals. This information can be acquired through downlink training or some blind channel estimation algorithm. Since the BS uses linear precoding techniques to send signals to users, the user only needs the effective channel gain (which is a scalar constant) to detect the desired signals [57]. Therefore, the BS can spend a little time to train pilots in the downlink for the acquisition of the CSI for the users.

MIMO has become a key technology for future communication systems, as the system calls for a

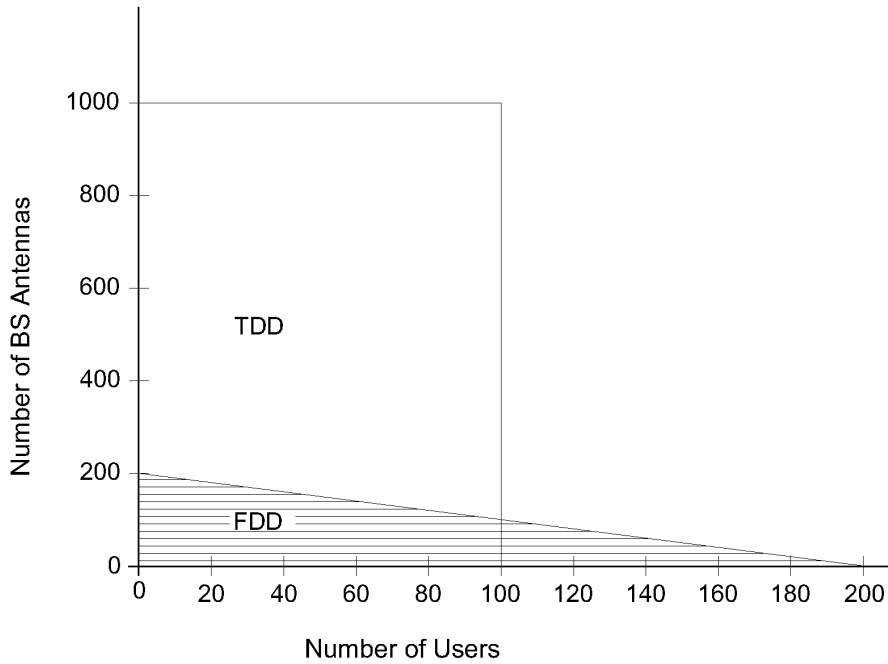


Figure 3.3: Transmission protocol of TDD Massive MIMO, adapted from [9]

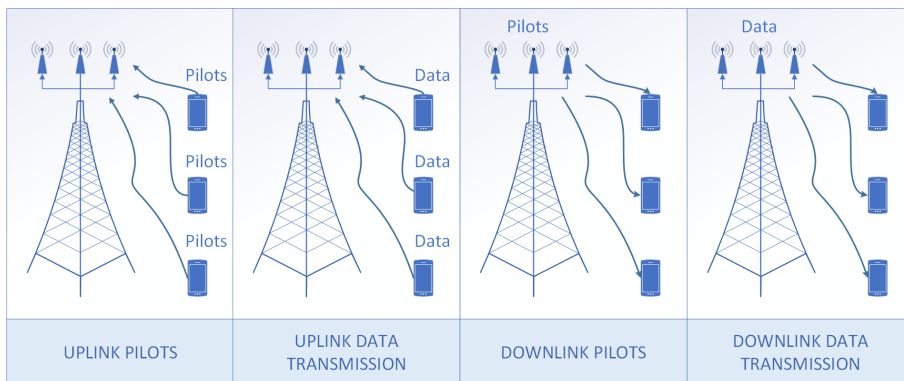


Figure 3.4: Transmission Protocol of TDD Massive MIMO, adapted from [9]

greater number of wireless services and having to increase over time, we have to keep in mind that the spectrum is finite. Given this large spectral request, it has had a more pronounced study conducted in the field of communication in multiuser MIMO systems, where the relevant systems are termed as massive MIMO or large-scale MIMO systems [56]. Massive MIMO systems can be defined as an array of MU-MIMO systems in which they are deployed in large quantities of antenna elements in BSs and large quantities of antennas in the transmit and receive terminals. Massive MIMO systems can improve the capacity of communication systems in several times due to their characteristics and energy efficiency and maximized in several times. The increase in capacity enabled by massive MIMO systems is due to the large number of antennas that are implemented. However, the use of a large number of antennas causes interference problems, which can be attenuated with the deployment of beamforming antennas instead of conventional

antennas [56].

3.4.2 Uplink Data Transmission

Transmission on Uplink systems is the scenario where K users transmit signals to the BS. A portion of the coherence interval is used for the uplink data transmission. Since K users share the same time frequency resource, the received signal vector ($M \times 1$) in BS is the combination of all signals transmitted by all users K . In the uplink, all K users transmit their data to the BS in the same time frequency resource. The BS then uses channel estimates along with linear combination techniques to detect signals transmitted from all users.

3.4.3 Downlink Data Transmission

Downlink transmission on base station systems. BS transmits signals to all users K on the same time frequency resource. More specifically, BS uses its channel estimates in combination with the symbols intended for users K to create to create M pre-coded signals which are then fed to M antennas.

3.5 Continuous Aperture Phased MIMO

With the accelerated evolution and the uncontrolled increase in the use of wireless applications, it is increasingly necessary to release a demand for data to supply the requested demand, due to this fact, the need for greater power and efficiency of width bandwidth on wireless transceivers becomes increasingly demanding. Two of the main technological trends, if so we can call them, where recent offers complex opportunities to meet the demands of increasing wireless capacity, being the use of Multiple Input Multiple Output (MIMO) systems to exploit matrix's of multiple antennas for simultaneous multiplexing of multiple data streams which has been previously seen in more detail, and the use of millimetre Wave Communication (mmWave) systems operating in the range of 6-300 GHz which provide much larger bandwidths than conventional ones that are allocated between 700 MHz and 5 GHz. One of the main advantages of mmWave systems is the possibility that they offer the operation in high dimensional MIMO systems with relatively compact matrices [21], [58].

Transceiver architecture for Continuous Aperture Phased MIMO (CAP-MIMO) opening systems that combine elements MIMO, continuous aperture antennas and phase matrices for completely improved performance. The CAP-MIMO can be defined as a system based on a hybrid analogue-digital transceiver architecture with which a new array of antenna arrangements is employed,

to which each uses a high-resolution Discrete Lens Array (DLA) [59], has as main function, to allow the operation with MIMO systems of almost continuous phase of opening. The DLA based analogue-digital interface also allows for a low complexity alternative coupled with a low cost related to high-dimensional phase arrangements that employ digital beamforming for communication, having the disadvantage of being too complex and more expensive to be developed and implemented at this time. In the context of Gigabit Line of Sight (LOS) communication links, CAP-MIMO systems combine the attractive features of state-of-the-art conventional designs by combining a power gain of dish systems and multiplexing gain of MIMO systems, thus providing a the most significant capacity of proportional gains in bandwidth-dependent power efficiency [21], [58]. However, the analogue-digital hybrid architecture provides a possibility to control the spatial beams with certain precision and consequently generate a link optimization and P2P operation, as can be show in the Figure 3.5.

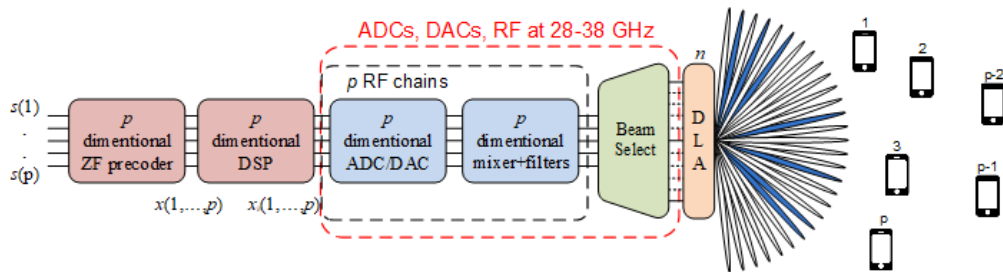


Figure 3.5: DLA-based beamforming CAP-MIMO transceiver, adapted from [10]

CAP-MIMO using a lens array for beamforming allows multiplexing data and multiple beam directions by generating p -beams and data multiplexing in them through the matrix-based front-end antenna lens. Different data bundles are generated by different feed antennas, where there is multiplexing in the data feeds which is achieved through a mm-wave beam selector that drives the complexity of the CAP-MIMO transceiver.

When using a high resolution DLA, i.e, a microwave lens with a suitably designed near continuous phase profile, having as the radiant aperture which is excited by feed elements on an associated focal surface [21], [58]. In the CAP-MIMO, appropriately developed data flows digitally coordinate the feed elements at the focal surface and the signal propagation of the focal arc to the aperture affects a spatial transform. The basic mathematical framework for implementation of CAP-MIMO systems are dependent on a discrete representation of continuous-aperture antennas or radiant surfaces. Where the number of critical samples, where n represents the maximum number of analog space modes that are excitable at the aperture of each set of antennas.

The CAP-MIMO structure may be applicable to certain class of communication links, such as short-range or long-range, LoS or multi-path propagation, P2P or network links. In any case, the use of high frequency mmWave, high rate 1-1000 Gbps in LoS links, which may be short range, such

as in high rate internal applications such as HDTV or long range, such as in wireless backhaul. In such applications, n possible analog modes, only the digital modes p_n couple the transmitter and receiver and can be used for simultaneous transmission of data streams p . The CAP-MIMO theory allows us to characterize the capacity of any LoS link and the DLA-based analog-digital architecture, thus allowing us to approach link capability with a significantly lower complexity when compared to traditional architectures [21], [58].

3.5.1 Overview of CAP-MIMO

The CAP-MIMO theory can be said to be based on a representation of the finite-dimensional system to which critical sampling is induced at the antenna apertures in MIMO array systems. The sampled representation provides a more complex model for the baseband systems, which serve as a basis for theoretical, computational and experimental design and analysis for CAP-MIMO systems. However propagation in LoS systems has provided important performance when applied in conjunction with millimetre wave frequencies. Because of the LoS being well accepted and having an acceptable combination when applied in CAP-MIMO systems mainly in the simplest configuration as we can exemplify point-to-point (P2P) link systems, as can be seen more emphatically in the [60], [21], to which a linear aperture of length L operating at a Carrier Frequency (FC), with wavelength λ , being able to excite n orthogonal spatial modes, having as the "space dimension" spatial signal, thus obtaining a critical sampling of the aperture:

$$n_{1D} = \frac{2L}{\lambda} \quad (3.7)$$

The LoS link systems that are implemented consist of allocating a Transmission Length (LT) antenna, a receiving antenna of length L_r and having a link length $R \ll L_t, L_r$, the modes p and d are firmly coupled to the transmitter to the receiver [21].

$$p_{los,1D} = \frac{L_t L_r}{R \lambda}, p_{los,1D} \ll n \quad (3.8)$$

Where we can define p_{LoS} as being a fundamental quantity known as the Fresnel number in optics, conceptually we can say that p_{LoS} and the number of half-period zones in a wavelength range, which can be meditated from the center to the edge of a an example that can be analyzed would be to observe from the point of view of an observer that is in the center of an image screen, where a part-period zone is defined as the wavefront phase change, when the zone

we have a definition equivalent to what the Fresnel number being the difference expressed in half wavelength, that is, between the distance from the observation point to the center of the aperture. Similarly it can be considered for 2D square antennas with area A [61].

$$n = n_{2D} = \frac{4A}{\lambda^2}, \quad (3.9)$$

$$p_{LoS} = p_{LoS,2D} = \frac{A_t A_r}{R^2 \lambda_c^2} \quad (3.10)$$

When we consider a LoS link system with R being the length and having AT the size of the transmitting antenna and AR as the size of the receiving antenna. It results in a critical sampling as a function of the dimensions of the signal spacing n_T and n_R and $p_{LoS} \ll n_T, n_R$ modes of communication. In the open domain, a single digital transmission can be modeled according to equation (3.11);

$$r = Hx + w \quad (3.11)$$

Where $x = [x(1), \dots, x(n_T)]^T$ can be described as the domain signal vector of the aperture of the transmitted antennas, $r = [r(1), \dots, r(n_R)]^T$ is the domain signal vector of the aperture of the pickup antennas, H is the aperture domain channel matrix $n_R \times n_T$ where representing the propagation channel coupling the transmitting and receiving antennas, and w is a vector of $n_{Rx} \times 1$ which is representing noise and interference at the receiver. The model expressed in (3.11) serves as a direct representation for conventional MIMO systems with discrete antenna arrays where they are critically spaced, however the system may be a virtual model for other continuous aperture systems, such as the CAP-MIMO systems, which according to [61],[62] can be applied because there will be no such significant losses in the information. The performance of LoS link systems is managed by the characteristics of the H channel matrix, in particular, p_{LoS} can be treated as an approximate indicator of the H matrix, the number of dominant communication modes supported by the link and $p_{los} \ll n_T, n_R$. We can exemplify how, $n = n_T = n_R = 160000$ and $p_{los} = 4$ for a 100 m LoS backhaul link formed by antennas of $1m \times 1m$ to $f_c = 60GHz$ [58].

The Shown in Figure 3.6 a propagation link of the 1D Line of Sight (LoS) in antennas of the transmitter and receiver, has a linear aperture of length A and is separated by a distance R , over time, we can assume that A is much smaller than R . Let $\lambda_c = \frac{c}{f_c}$, where the frequency ported is expressed by f_c . For a carrier frequency f_c in the range of 60-100 GHz, λ_c is comprised between 3-5 mm.

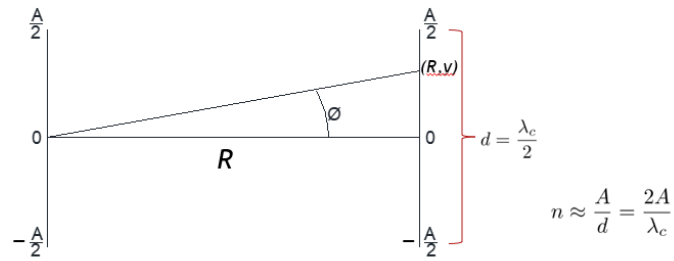


Figure 3.6: Line of Sight Propagation.

For a given LoS link system characterized by the physical parameters (A, R, λ_c) , as shown in Figure 3.6, the CAP-MIMO system framework questions some fundamental concepts related to system capacity in link, to which any operational Signal to Noise Ratio (SNR) can be implemented. The theory for CAP-MIMO systems aims to characterize which fundamental limits and the realization of the CAP-MIMO system, based on DLA, would better approach this limit if applied in practice. Some DISH and MIMO projects are special cases of great complexity of the CAP-MIMO structure, which seek to answer such questions.

The DLA-based hybrid digital-analog architecture of a CAP-MIMO system to efficiently access the information that transports the digital modes applied to analog space beamforming systems.

3.6 Conclusions

This chapter presents an overview of millimetre wave technology and the use of massive MIMO and CAP-MIMO systems. The immense unlicensed bandwidth, coupled with higher allowable transmission power, are small factors that can thus collaborate on advances in integrated circuit technology, making the use of mmWave systems one of the most promising for implementation in systems with multigigabit, and its main use in multiple MIMO systems. I try as intense efforts for its implementation, of which they are much studied. The use of the unlicensed spectra along with the massive MIMO has been well studied and as it significantly increases the speed of transmission and reception and having an increase in reliability, it has been well seen for the use of over streaming video in establishing a link of reliable communication for millimetre waves.

The importance of the system of multiple antennas, provide sufficient power margin through matrix gain, as in the case of its use in conjunction with beamforming systems, it can further modify the signal transmitted in other significant paths, such as would be the case of block by human, in the course of the main trajectory of the signal. Despite the clear advantages of mmWave systems, technical challenges still need to be studied for more consistent use. The

issues of propagation and implementation are the two aspects that require further optimization and research in order to obtain a more efficient and low cost millimetre wave communication system. Taking these aspects into consideration, the implementation of CAP-MIMO and massive MIMO systems has been a great help, since its technologies vision the use of several antenna arrangements to reduce complexity, increasing efficiency and reducing the cost of its implementation.

Chapter 4

Implementation of transmitter and receiver with USRP B210

4.1 Introduction and Objectives

The MIMO concept begins with the use of multiple antennas. However, to apply the modulation, we must first understand and implement less complex systems in Matlab. Firstly, the code for Single Input Single Output (SISO) transmission and reception modulation was implemented in order to make the flow of the transmitter to the USRP available from the receiver.

In this first step, the code will be sent through SMA-M (6 GHz, 1 m long) or 900/2600 MHz coaxial cable antennas. The first ensures the signal of two types of coaxial cable reading, to ensure that the attenuation of the signal is as small as possible, while communication via 900 MHz antennas allows observing the transmitted signal and the signal received through a spectrum analyzer. The main objective this hardware implementation is to explore a simplified version of massive MIMO with a few Universal Software Radio Peripherals (USRP), where each of them can implement a 2x2 MIMO. By synchronizing them and using appropriate signal processing techniques and algorithms, we propose to have a low-complexity version of massive MIMO when implementing the analog hybrid digital solutions we are proposing in our research.

The main bottleneck in implementing Massive Array (MAAS) systems on mmWave frequencies (or even lower frequency bands for demonstration purposes) is the complexity of hardware and software. The increase in the number of antennas implies more analogue-to-digital converters (ADCs) and energy-intensive radiofrequency (RF) strings. The imagined solution is to use analog-to-digital hybrid transceiver architectures that, along with proper signal processing and modulation design, can lead to a large reduction in hardware and software complexity and power consumption. Since obtaining state-of-the-art (CSI) information in MAAS (Massive Antenna Array Systems) is challenging, signal processing schemes will be designed to simplify CSI estimation but also to reduce the CSI requirement. The goal of MIMO Optimization is to achieve the highest possible throughput and connectivity within the network and within a given environment by leveraging the multipath potential of that environment. With the aid of a concept-based multiplexing protocol of antenna diversity, with code developed in Matlab, implemented with the aid of USRP hardware, we have as expectations in the experimental researches in massive MIMOs and pre-coding hybrid analog-digital schemes.

In this first part of the code implementation with USRP were synchronized from a SISO communication system. This is the appropriate intermediate step to grow to a low-complexity version of massive MIMO. Another concept studied was the use of a platform based on programming language with the help of the system `openairinterface5g` (from Eurecom) to configure the LTE eNBs and EPC (Evolved Packet Core) OpenAir-core (CN) network. The entire configuration and hardware project will be programmed into Linux platform code lines and then transferred to the USRP. Within this configuration, the transfer of data between eNB and receivers, in the same pattern, in a more advanced context is being considered the use of compatible phones (only the assumptions for their operation) within the frequencies of the systems under study, to simulate emulate) the new mmWave environments, thus creating an independent internal network, to which the SIM cards will be configured to be used according to the programming of the transmitters and receivers.

4.2 Description of the work carried out

The main carried out activities are as follows:

- Definition of the main programming tasks for the SISO transmitter and receiver;
- Conceptually addressing how to evolve from SISO to MIMO and massive MIMO.
- Creation of a transmitter that considers just QPSK or 16-QAM and 64-QAM;
- Creation of the receiver, in another USRP, by considering these simple modulations, and addressing synchronization issues;
- Solving the challenge of synchronizing the receiver with estimates for the phase of the power of the received signal [63], [64];
- Initial laboratory tests with a spectrum analyzer while obtaining the spectrum of the transmitter and receiver signals;
- Development and testing of the eNBs and EPC OpenAir-core network (CN) with the goal of operating our own LTE network.
- Achievement of the initial synchronization in SISO system;
- Hardware tests for the achieved solution, performance evaluation, and preparation of the draft report;

- Preparation of next steps, solving the last issues in terms of synchronization, applying matrix's to implement a simplified version of MIMO, addressing how to synchronize to achieve a simplified version of massive MIMO.

The architecture of the communication system is formed by the transmitter (one USRP), the receiver (another USRP) with antennas. The two USRP can communicate either through the air interface or via a coaxial SMA-M-to-SMA-M cable. Matlab code has been developed for the transmitter, receiver and synchronization parts. A digital communications library [65] developed by Instituto de Telecomunicações - Aveiro site (in Portugal) was considered. Based on the preliminary effort to bring these libraries together throughout the investigation, the code in Matlab for the two peer devices was developed. The first code is responsible for implementing the TX antenna system on the transmitter of the USRP while the second part of the code is responsible for receiving the transmitted signal through the antenna systems connected in the RRS channel of the URSP while the programming work in progress considers the receivers and the synchronization methodology proposed in [63], [64], as shows in Figure 4.1 gives an overview of the hardware elements.

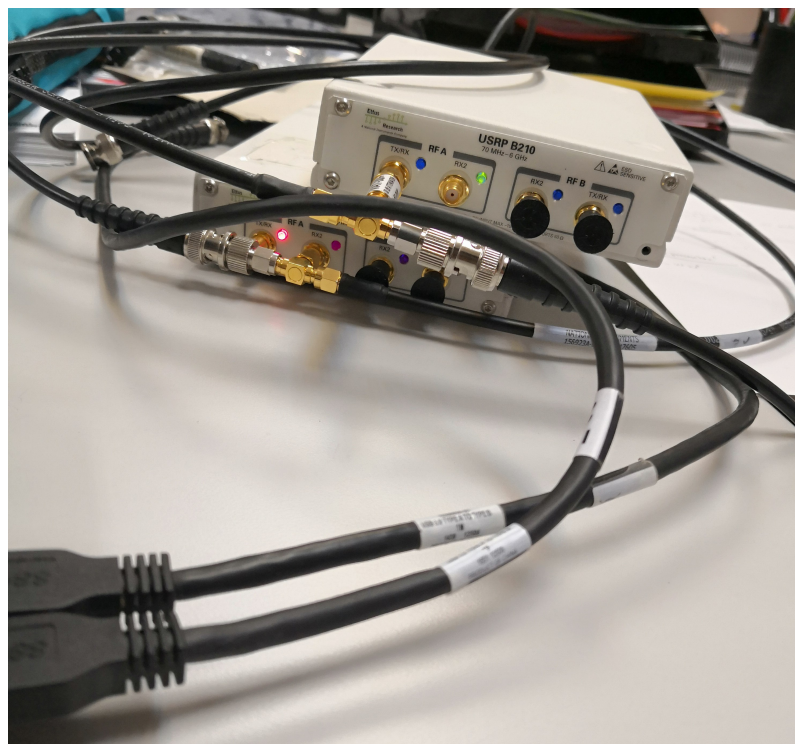


Figure 4.1: Overview of the hardware elements

4.3 Hardware Implementation with USRP

The MIMO Concept starts from the use of several antennas. However, to apply modulation we need to first understand and implement less complex systems in the Matlab. Firstly, the code for the modulation for Single Input Single Output (SISO) transmission and reception has been implemented, in order to make the transmitter stream available to the USRP from the receiver. In this first step, the code will be send either through coaxial cable SMA-M or 900/2600 MHz antennas. The former ensures that the signal two types of coaxial cable reading, to ensure that the signal attenuation is as small as possible, while communication via 900 MHz antennas enables to observe the transmitted signal and the received signal through a spectrum analyzer.

4.3.1 USRP and its Programming with Matlab

Universal Software Radio Peripheral (USRP) shown in Figure 4.2 was developed for digital radio systems, providing a complete infrastructure for signal processing. In the USRP. More than one antenna can be attached to the device, depending on user requirements. For example, it is possible to connect three antennas in order to transmit different stations. It is also possible to perform a reverse procedure, i.e, receive several frequencies at the same time. Another possibility is the simultaneous connection of antennas to transmit and receive signals using MIMO. The USRP works with signal strengths whose power is in between 50 and 200 mW. It has a high-speed serial interface for integration with other boards, allowing the development of MIMO systems [11],[66].

The generalized architecture of the URSP is composed of antenna, daughter board and motherboard. Regarding antennas, a modern technology called Multiple Input Multiple Output (MIMO) can be applied, consequently the peripheral becomes more flexible, as a number of analysis structures are incorporated. One of them is the evaluation of two or three distinct signals for different applications, as well as signal transmission, allowing the formation of cognitive networks [67]. Successively, the daughter boards are responsible for performing the conversion of the received signals to baseband, as well as the reverse conversion, that is, they act as the front end of the USRP. On the other hand, the architecture also consists of the motherboard, which has D/A and A/D converters, FPGA, interface to the computer and interfaces that allow the communication of the same with the other peripherals. In this work the model of USRP B210 is approached. The shown in Figure 4.2 the architecture of USRP B210. Basically, its characteristics are: range of 70 MHz - 6 GHz, sampling frequency of 56MHz, uses USB 3.0 port for communication between the board with the USRP, whose model is a Spartan 6XC6SLX150 FPGA.

It is also full duplex and has extension for MIMO system support (2TX and 2RX). However, it operates only with GNU Radio and OpenBTS. The is Figure 4.3.



Figure 4.2: Universal Software Radio Peripheral(USRP) [11]

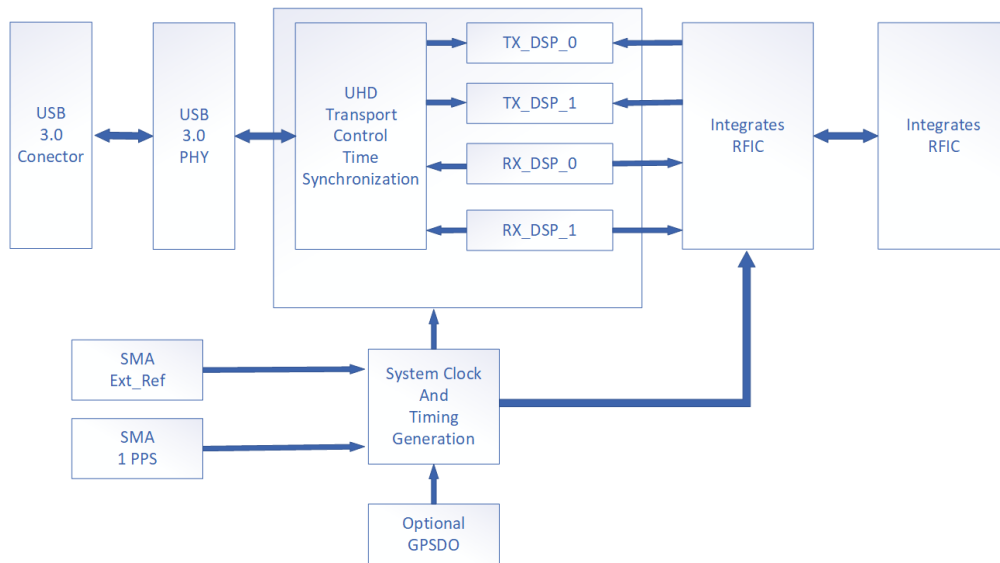


Figure 4.3: Architecture USRP-B210 adapted from [11]

The USRP can be connected to Matlab via USB 3.0 cable, compatible with Windows 10 system or with Linux Ubuntu 14.04 or higher. When the USRP is used with Matlab a support package is needed that contains the basic tools for the communication system that are necessary for the implementation of the Matlab code that will be emulated by Universal Software Radio Peripheral (USRP), and will ensure the communication between the transmission and reception system [68]. Communication between the transmitter and the receiver can be done by coaxial cable or antennas operating at different frequencies. The most common ones are the 900 MHz and 2450 MHz antennas. The Matlab support package for the USRP radio has a support module in both code

lines and Simulink-based project creation. The proposed project was implemented in code lines, thus having a somewhat more complex hardware complexity. USRP hardware supports not only Single Input Single Output (SISO) but also Multiplexed Multiple Input Multiple Output (MIMO) up to 2x2 array. Taking into account that several USRP can be used, together, we can get a massive MIMO (mMIMO) system, which considerably improves the transmitter and receiver bit rate. The programming of the USRP with in Matlab is initiated from base parameters such as gain, carrier frequency, clockRate, which is responsible for the amount of operations that can be performed at a given time. The corresponding interpolation Factor can increase the sampling rate by a factor multiplication in relation to the amount of sampling (nBloscks). There is a difference between the of transmitter (TX) at which the Sampling Frequency (FS) and is considered in the Digital Analog Conversion (DAC), and the in receiver where the Sampling Frequency (FS) and in the one from the Analog Digital Conversion (ADC). After configuring the interfaces, we request the USRP connection a by applying the *'findsdru'* command, which is responsible for synchronizing the USRP with Matlab. The connection made by the system generates equipment IP data, connection status, and the identification of the equipment and port to which it was connected. In order to be able to identify the behavior of the synchronism between a transmitter and a receiver, the major greatest difficulty is the implementation of multiplexing into the USRP. It was decided to start TX and RX code by a low complexity communication, in Matlab, and precisely the synchronization, the code allows for generating a signal with a fixed gain and fixed frequency. The transmitter/receiver has a dependence on the digital modulation. The receiver has the possibility of recognizing the signal emitted and which can be received in the most adequate work, taking into account that there is path loss plus noise/interference. The configuration of the modules is as shown in Figure 4.4. It implements SISO, with only one transmitter and one receiver.

4.3.2 Transmitter implemented in USRPs

The transmission in an USRP system considers a number of simulated symbols. First during the QAM data by stipulating a value to be used as a reference in the 16-QAM calculations and the loading of the USRP parameters. This facilitates to determine the parameters that will be used to calculate the transmission data, as shown in Figure 4.5.

Quadrature amplitude modulation (QAM), enables to increase the bit rate, the QAM technique was developed to encode digital data in an analogue signal through modulation in which two different components are combined in a single signal by orthogonal modulation of these two components, thus avoiding interference; hence this is the justification of the use of the term quadrature. The technique employed is the combination of Phase Shift Keying (PSK), Amplitude

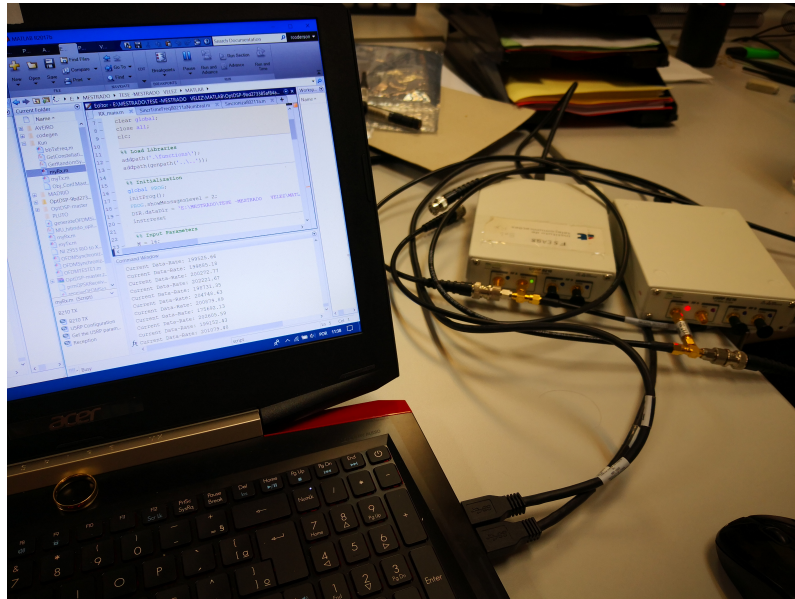


Figure 4.4: USRP connection to the PC via USB cable

```
%% Get TX Parameters
nSyms = symRate/USRP_Tx.Fs_DAC*2^14;
TX = presetTXparams_USRP_B210(M, symRate, OH, nSyms, rolloff, USRP_Tx.Fs_DAC);
```

Figure 4.5: Get TX Parameters

Modulation (AM), to create a constellation of signal points, each representing a unique combination of bits. It is widely used in digital conversion and other systems that require a high data transfer rate 4.6 shows the constellation diagram for 16-QAM, where Q and I are representations of the modulated (phase and amplitude) signals. The constellation consists of a square plot of signal points.

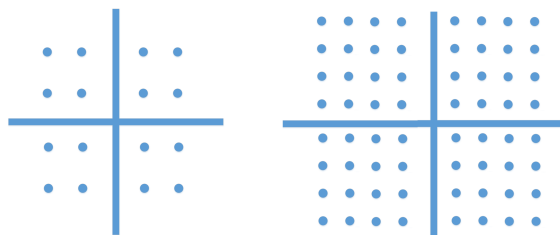


Figure 4.6: Constellation diagram of a set of QAM signals ($M = 16$ and 64)

The general form of a QAM-M signal can be expressed from equation (4.1).

$$S_i(t) = \sqrt{\frac{2E_m}{T_s}} a_i \cos(2\pi f_c t) + \sqrt{\frac{2E_m}{T_s}} b_i \sin(2\pi f_c t) \quad (4.1)$$

Transmission antennas are components that are effectively responsible for transmitting information. In the USRP, more than one antenna can be connected to the device, according to the

user's need. For example, we could connect three antennas and transmit three different radio stations, each at a given frequency. We could also perform the inverse procedure, receiving multiple signals of different frequencies. Another possibility is the simultaneous connection of antennas for the transmission and reception of signals, which could be used, for example, in the modern MIMO systems for wireless communications in cellular telephony [68], as shown in Figure 4.7.



Figure 4.7: USRP Simultaneous connection of antennas for the transmission and reception of signals

Figure 4.8 shows how the interconnection of the transmitter to receiver USRP. These connections can be made by SMA-M cable to SMA-M, in the low loss coaxial model for 6 GHz, 1 m length.



Figure 4.8: USRP Cable Connection

4.3.3 Implementation of the Receiver and Aspects of Synchronization

The operation of the system in the receiving mode is followed by a few steps, the receiving process begins when the RF signal is captured by the antenna and driven to the RF block, the received RF signal spectrum is shifted to the baseband in the RF block, where the analog baseband signal is scanned by an ADC, which has the code applied in Matlab (USRP_Rx.Fs_ADC), then the sampling rate in the block is decreased [69]. The implementation of the reception code is based on interpreting the signal sent by the transmitter, in a certain time, upon receiving the data in wireless communication, by means of either antennas connected to the USRP or by means of connection by cable. Receiving the signal is conditioned to frequency modulation and phase shift, and timing of the frame offset. Synchronization occurs only when the same modulation frequency is obtained on the transmitter and receiver. After the data begins to be received by the USRP, the initial data is stored and copied according to the amount of information sent.

4.3.4 Tests and preliminary experimental results

The hardware for the over the radio tests is the following:

- 2x USRP B210;
 - USB 3.0 interface;
 - Xilinx Spartan 6 C6SLX150 FPGA;
 - A Cypress EZ-USB FX3 High-speed USB 3.0 controller;
 - Analog Devices AD9361 RFIC;
 - Coverage from 70 MHz- 6 GHz RF;
 - Flexible rate 12 bit ADC/DAC;
 - 2 TX, 2 RX, Half or Full Duplex;
 - Fully coherent 2x2MIMO capability;
 - Up to 56 MHz of real-time bandwidth 1x1;
 - Up to 32 MHz of real-time bandwidth 2x2.
- 2x Notebook with Matlab 2017b;
- 2x Antenna 900 MHz;
- 1x coaxial cable.

The test was done based on the SISO systems that corresponds to transmit a signal by a TX system that is in the USRP connected to a notebook and receive the signal by another USRP

with connection in the RX system connected to another notebook, simulating the station base, and co, as shown in Figure 4.9, the signal was modulated with the input parameters in the TX, 16-QAM that is the size of the sync constellation, 50×10^3 symRate which is the total gross rate of modulated symbols, and with parameters of the URSP having a gain of 20dB, carrier frequency 900MHz which will be the carrier frequency, and having a 1×10^6 as interactions (nBlocks) and a DAC frequency of 200×10^3 . Shown in Figure 4.9 the interconnection of USRP TX/RX.

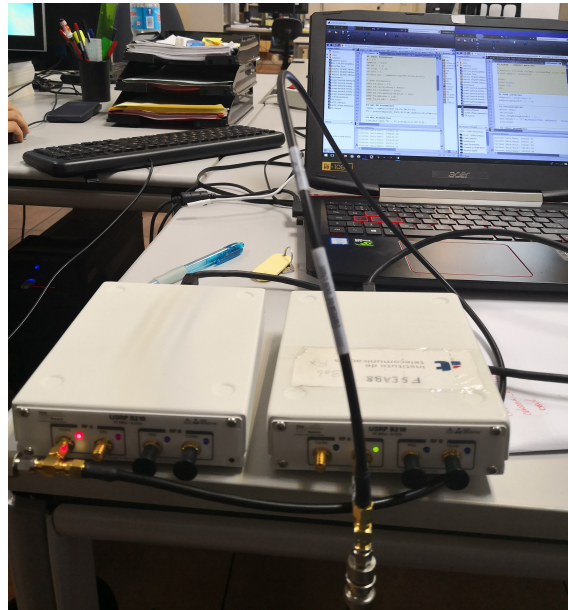


Figure 4.9: USRP TX / RX connection

The Power Spectral Density (PSD) is the ratio between the Power and Frequency (dB/Hz). Shown in Figure 4.10 the PSD of the received signal. The signal is simulated by using the code, as shown in Figure 4.11. The code to obtain the signal received at the RX is presented in Figure 4.12, the Power Spectral Density (PSD) of the received signal as shown in Figure 4.13, Figure 4.14 shows the modulated signal after the ADC conversion. The modulated signal is slightly shifted from the central point. There is a delay in the conversion due to a possible synchronization mismatch.

We are considering the formulation from [64] to implement the synchronization procedure, as follows. The main difference between the two halves of the first training symbol will be a phase difference of $\Phi = \pi T \Delta f$ which can be estimated by $\hat{\Phi} = \text{angel}(P(d))$ near the best timing point. If $|\hat{\Phi}|$ can be guaranteed to be less than π , then the frequency offset estimate is $(\hat{\Delta}f) = \hat{\Phi}(\pi T)$ and the even PN frequencies on the second training symbol would not be needed. Otherwise, the actual frequency offset would be $\frac{\Phi}{\pi T} + \frac{2z}{T}$ where z is an integer. By partially correcting the frequency offset, Adjacent Carrier Interference (ACI) can be avoided, and then the remaining offset $2z/T$ of can be found. More details are given in to [64].

The behavior of the transmitter signal at 900 MHz in the Digital Storage Oscilloscope is shown

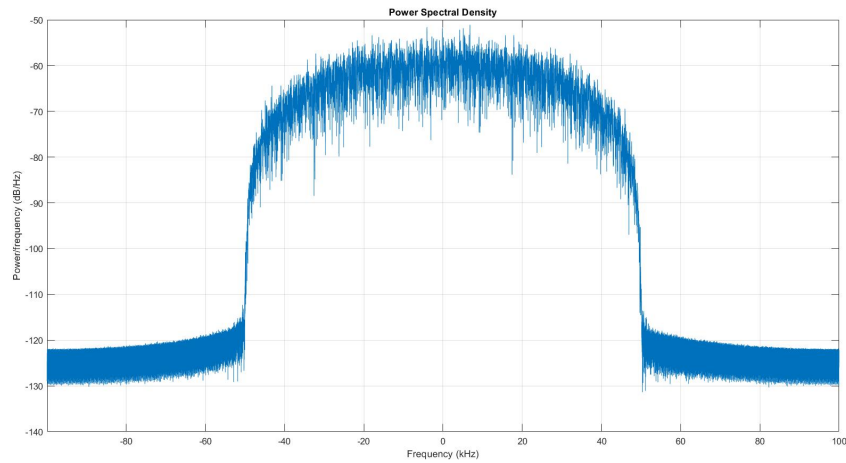


Figure 4.10: Transmitter signal (TX)

```

%% Transmit Signal
n = 1;
dataRate_Tx = NaN(1,USRP_Tx.nBlocks);
while n < USRP_Tx.nBlocks
    tic
    step(radioTx, Stx);
    dataRate_Tx(n) = numel(Stx)/toc;
    fprintf('\nCurrent Data-Rate: %1.2f',dataRate_Tx(n));
    n = n + 1;
end

```

Figure 4.11: Code for the transmitter Signal

```

%% Receive Signal
n = 1;
len = 0;
dataRate_Rx = NaN(1,USRP_Rx.nBlocks);
while n <= USRP_Rx.nBlocks
    tic
    while len <= 0
        [Srx(:,n), len] = step(radioRx);
    end
    dataRate_Rx(n) = numel(Srx(:,n))/toc;
    fprintf('\nCurrent Data-Rate: %1.2f',dataRate_Rx(n));
    len = 0;
    n = n + 1;
end

```

Figure 4.12: Received Signal

in Figure 4.14.

Figure 4.15 shows the comparison between the transmitter signal and the receiver signal.

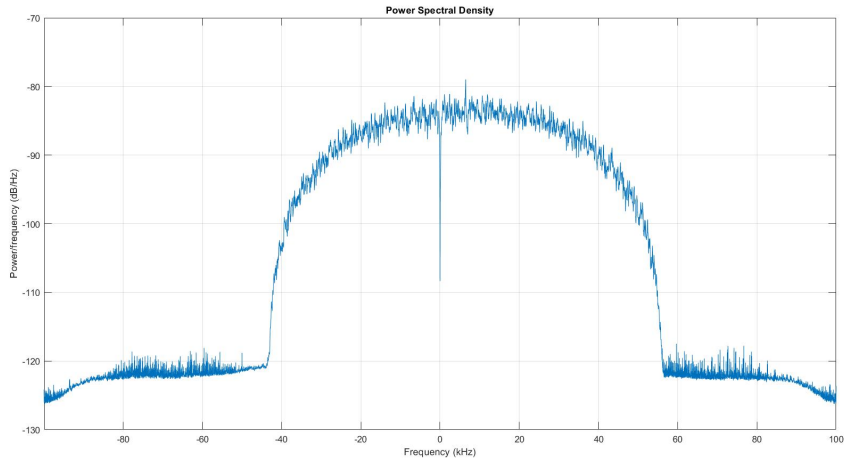


Figure 4.13: Signal received RX

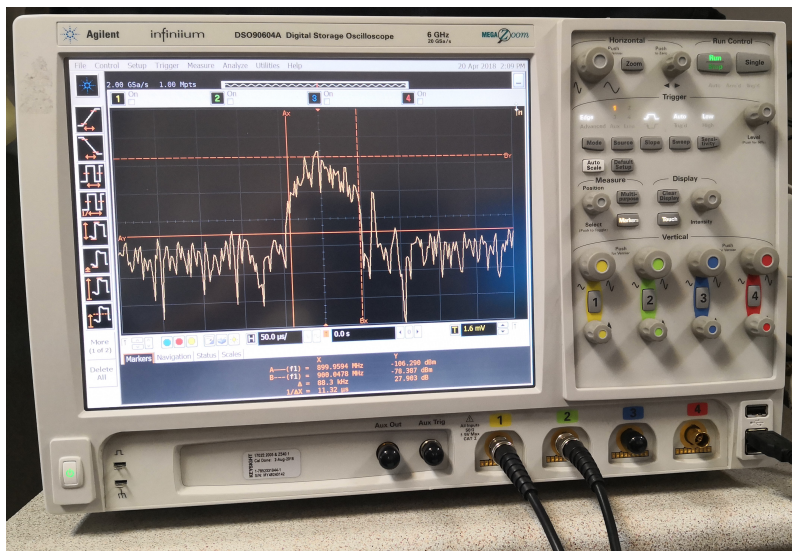


Figure 4.14: Transmitter signal at 900 MHz in the Digital Storage Oscilloscope

4.4 Testing the connection with NARDA SRM 3006

SRM-3006 Selective measurement of high-frequency electromagnetic fields being an easy-to-use test system, consisting of a basic unit of measurement antennas for a non-directional detection field and operating in the 9 kHz to 6 GHz frequency bands.

Main technical characteristics of the NARDA SRM 3006 is a selective frequency field measurement system for fast, reliable and reliable evaluation are as follows:

- Dimensions: 213 X 297 X 77 mm;
- Weight with antenna mounted: 3300g;
- 7 inch TFT-LCD display, 800 X 480 pixels;
- Frequency range: 9 kHz to 6 GHz;

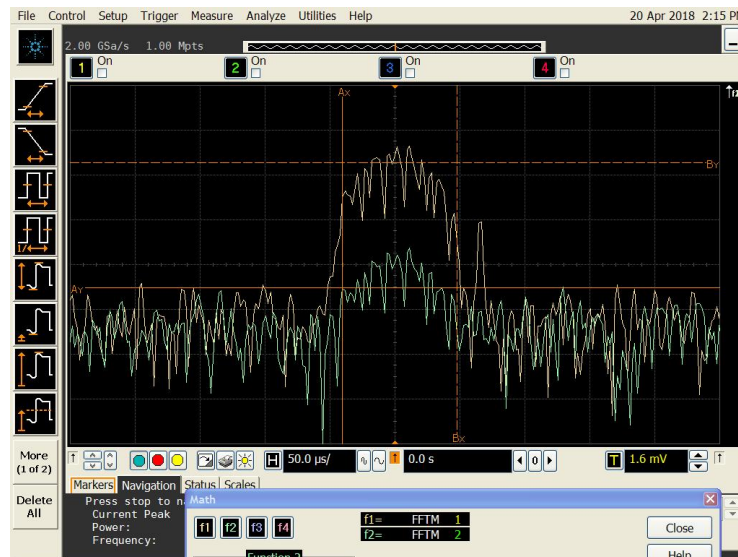


Figure 4.15: Comparison between the transmitter signal and the receiver signal at a frequency of 900 MHz



Figure 4.16: NARDA SRM 3006

- Supported temperature: -10° to $+50^{\circ}$ C;
- Operating time with internal battery: 3 hours +/- 15 minutes.

To verify the veracity of the data collected in the simulation / emulation of the SISO system implemented in conjunction with the USRP, to which the tests were done the portable frequencies have been altered to verify the stability of the synchronization, both via SMA cable, or using antennas. NARDA SRM -3006 was used to collect data from both the transmitter antenna and the receiver antenna. With the data collected it was possible to verify that the data is being adequately transmitted and received, as can be seen in Figures 4.17, 4.18.

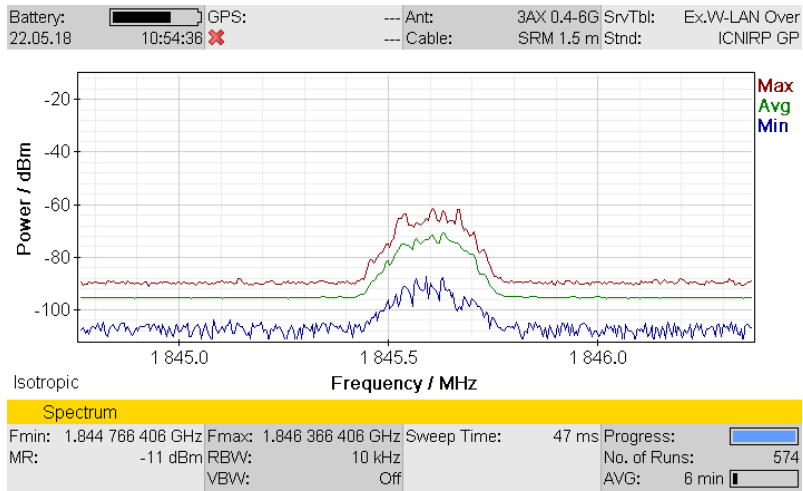


Figure 4.17: Comparison between the transmitter signal and the receiver signal at a frequency of 1846 MHz

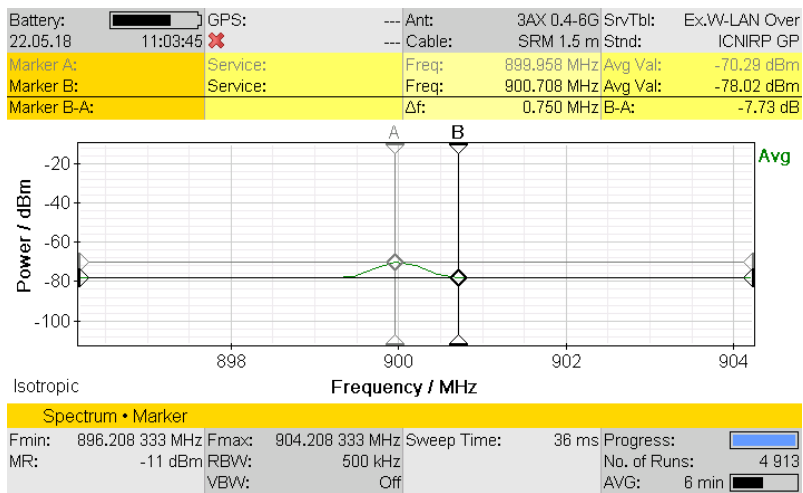


Figure 4.18: Comparison between the transmitter signal signal at a frequency of 900 MHz

4.5 Creation of an LTE network with OpenAirInterface

OpenAirInterface (OAI) [70] is a powerful and flexible wireless technology platform based on the 4G ecosystem. This platform offers an open-source software-based implementation of the Long-Term Evolution (LTE) system spanning the full protocol stack of the Evolved Universal Terrestrial Radio Access (E-UTRA) and the Evolved Core Network (EPC), defined in the 3rd Generation Partnership Project (3GPP) standard. Therefore, we can deploy a LTE Evolved Node B (eNB), an User Equipment (UE) and the Evolved Packet Core (EPC) on different PCs. Additionally, we can also connect Commercial Off-The-Shelf (COTS) UEs to our platform.

In an exchange with the Universidad Carlos III de Madrid, a research was begun to evaluate the OAI platform to know its capabilities. As we mentioned earlier, this platform emulates a real LTE system, so it is not only complex to configure, but also requires expensive hardware boards that are not available to everyone. In addition, we will take this opportunity to change

the LTE waveform in DL. In this joint action, it was possible to perform tests with the OAI, which will provide more realistic measurements of the physical link, which will give us a better understanding of the behavior of the system when interconnected to a URSP. In addition, we also look at the overall performance of an LTE system. The project was developed to represent the behavior of wireless access technology in a real network configuration, obeying the temporal structure parameters of the air interface.

4.5.1 OAI Set-up: Connect EPC + eNB with COTS UE

The OAI System Configuration consists of: Connect EPC + eNB with EU COTS, OAI brings different configurations to users. In this specific case, we select the most modular one, which consists of deploying the EPC and eNB in different PCs as can be seen in Figure 4.20. The reason for this choice is to facilitate the integration of commercial EPC or eNB in the future. In addition, we selected a commercial UE for our testbed to verify that the OAI platform is fully compliant with the LTE standard. OAI also supports different hardware, in our case, we use the following components:

- Two Intel Core-i7-3.5GHz host PCs with UBUNTU 14.03.02 and low-latency kernels suitable for real-time processing;
- Ettus Universal Peripheral Radio Peripheral (USRP) B210. This board has two independent radio frequency (RF) strings that cover from 70MHz to 6GHz, in Figure 4.19 shown. OAI strongly recommends the use of this terminal due to the quality of its RF chain;
- VERT900 Antenna, in Figure 4.19 shown;
- 4G Android phone;
- Programmable SIM cards for test: sysmoUSIM-SJS1;
- Card reader: Omnikey CardMan 3121 USB CCID reader;

After installing the operating system and any additional programs required, the steps for installing and configuring the platform are summarized as follows:

- We must correctly configure the IP address of each component. Each block should be able to communicate with others;
- in the Home Subscriber Server (HSS), we have to add the user information in the database using MySQL commands;



Figure 4.19: USRP B210 and antennas vert900

- in the Packet Data Network Gateway (PGW), we have to set the IP address of our Internet access;
- in eNB, we have to define the physical parameters of LTE radio, such as: bandwidth, carrier frequency, transmission modes;
- on the SIM card, we have to program the same information that we added in the HSS;
- in the mobile phone, we have to configure the Access Point Name (APN) of our system.

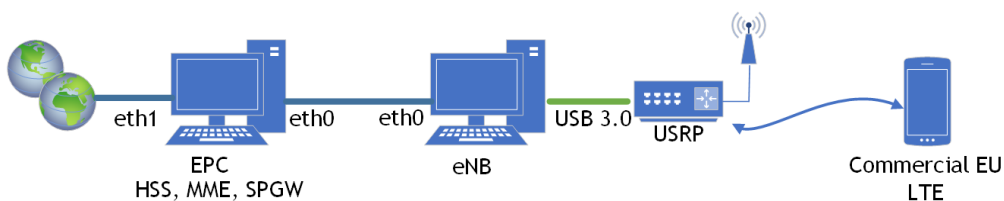


Figure 4.20: OAI scenario: EPC + eNB + COTS UE

The configuration is the OAI system, when connected with EPC + eNB with COTS UE.

Once the commercial UE has attached to the or OAI platform, we generate dummy data using any speed test application installed in the UE, additionally we can get the data rate of the radio

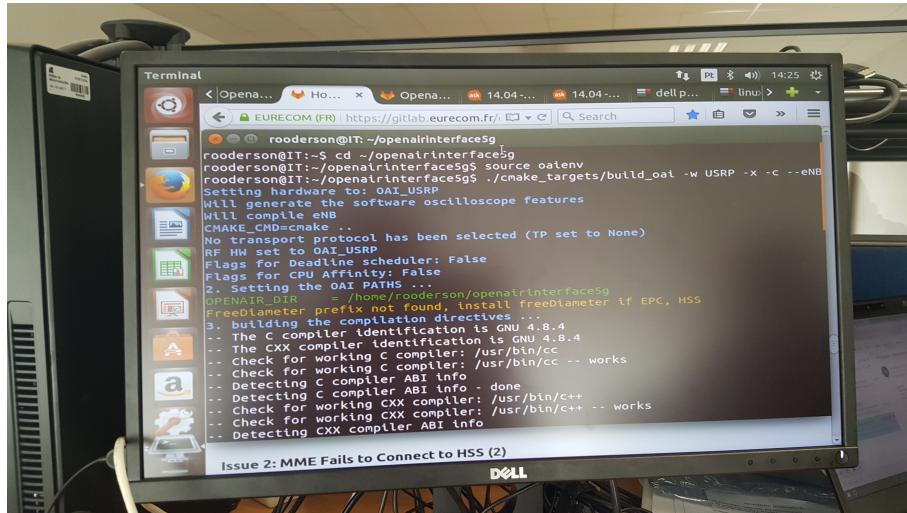


Figure 4.21: Configuration sistema of OpenAirInterface

link for both down-link (DL) and up-link (UL). In our host PC we can observe the performance of UL. In Figure 4.22 and 4.23, we can see different measurements provided by the OAI scope. Due to the proximity of our cell-phone to the USRP, the frequency channel response is flat and the selected constellation is 16- QAM. We also see the effects of the Additive white Gaussian noise (AWGN) which shifts the transmitted constellation. Details on the installation and configuration of a 4G system with OpenAirInterface is give in appendix A.



Figure 4.22: Interface scope of the UL

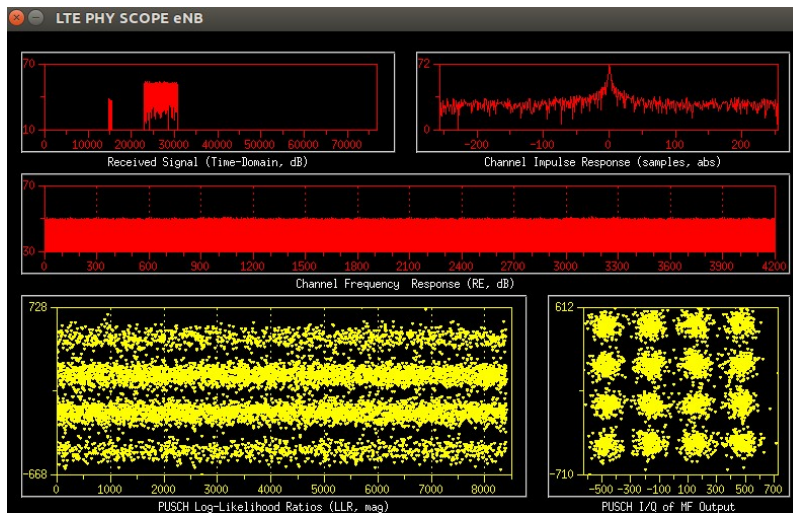


Figure 4.23: Scope of the UL

4.6 MIMO with USRP

With MIMO, wireless system performance can be increased without increasing power consumption. When using multiple antennas, the transmitted signal travels through different wireless channels (from transmitter antennas to receiver antennas), thus creating a capacity gain by exploiting the diversity of channels, more details can be seen in Figure 2.13, where the capacity of the MIMO channel is shown. In the tests for implementation of the MIMO system, first we went through the implementation of the code in Matlab for the transmission system and the Simulink code. The main difficulty in creating the code was to get Matlab to recognize the two TX and RX antennas of the USRP in the same code. After defining parameter through the line of code (`rxradio.ChannelMapping = [1 2];`) it causes Matlab to recognize that the USRP has 2 channels (transmitter and receiver). The developed code provides the possibility to change transmission parameters, such as system gain, number of simulated blocks, carrier frequency, among others, while giving a flexibility for future tests with other frequencies. In appendix B is seen details of the code in Matlab to implement the MIMO transmission in USRP. The receiver was implemented in Simulink, by considering the same parameters of the transmission system, aiming at having the least possible attenuation when receiving the data through different channels. The blocks in Simulink, are very interactive and adheres to the same principles of the code in the transmitter side.

Figure 4.24 shows the signal transmitted by the TX1 antenna from the USRP and is very similar to the signal from the TX2 antenna in Figure 4.25. Figure 4.26 shows an overlapping of the transmitted and received signals.

Figure 4.27 shows the signal received by RX1 antenna in the USRP is very similar to the signal

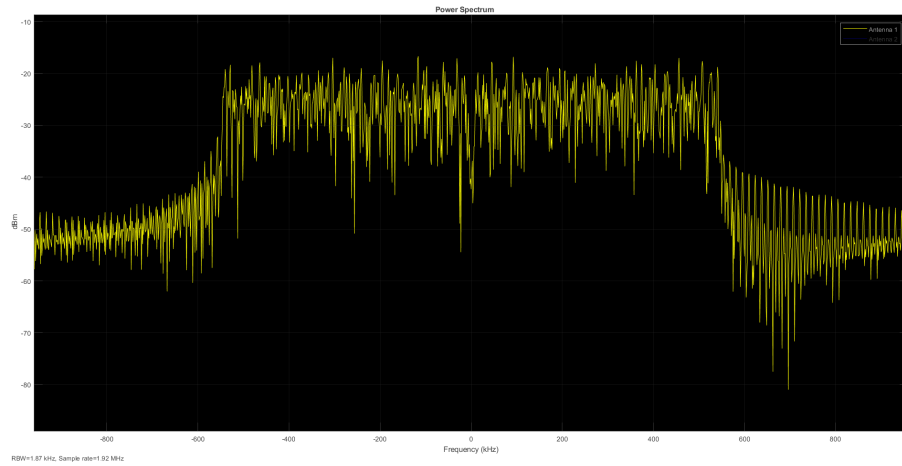


Figure 4.24: Signal Transmitter MIMO 2x2 TX

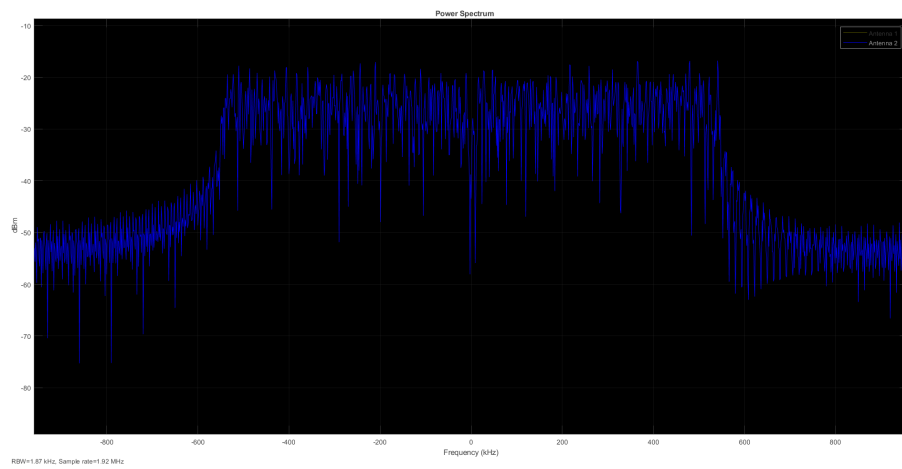


Figure 4.25: Signal Transmitter MIMO 2x2 TX1

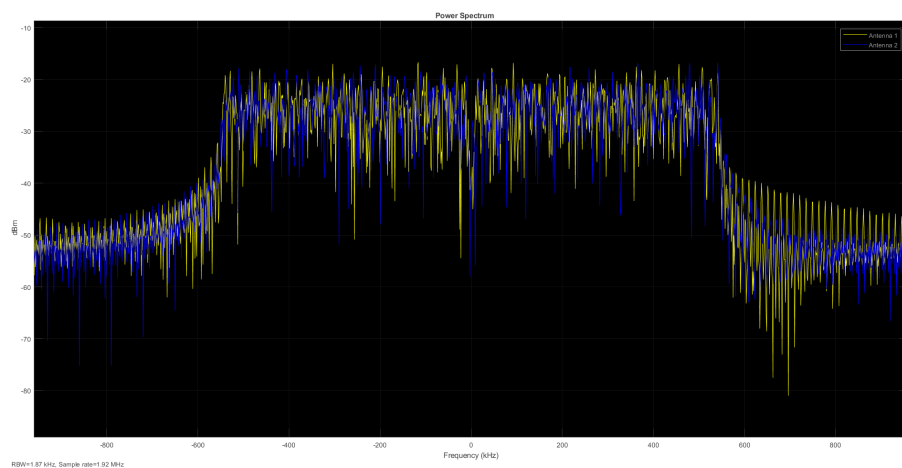


Figure 4.26: overlapping of the signals transmitted by the TX1 and TX2 antennas

of the RX2 antenna in Figure 4.28. Figure 4.29 shows an overlap of the signals received in the two RX antennas. As shown in Figure 4.29 the signal received by the antennas contains a considerable amount of noise, and it is still possible to verify that the received signal is very similar to the transmitted signal. However, in order to reduce the considerable amount of noise,

the implementation of a filter on the side of the receiver is being considered.

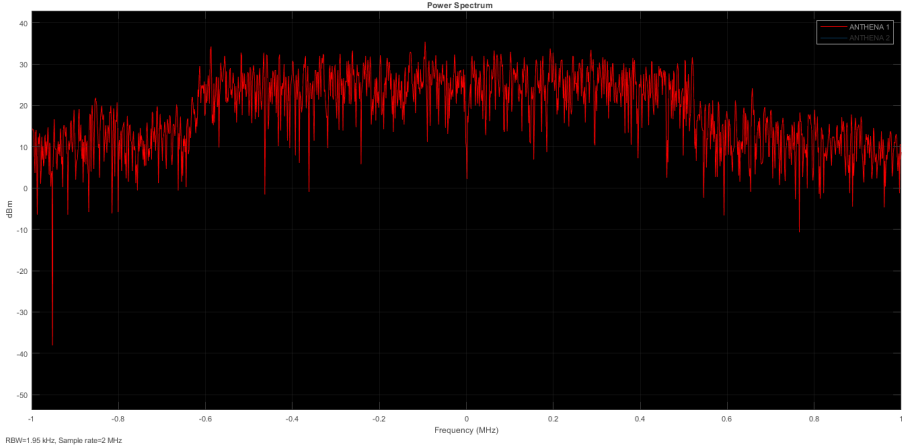


Figure 4.27: Signal Received in MIMO 2x2 RX1

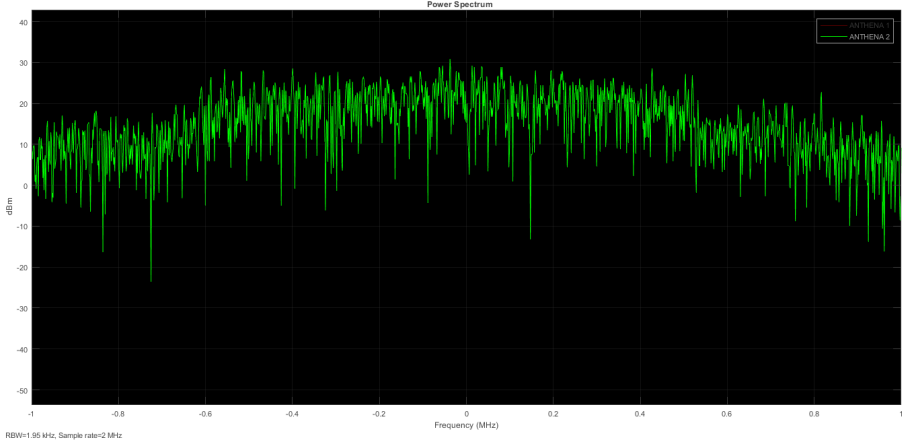


Figure 4.28: Signal Received in MIMO 2x2 RX2

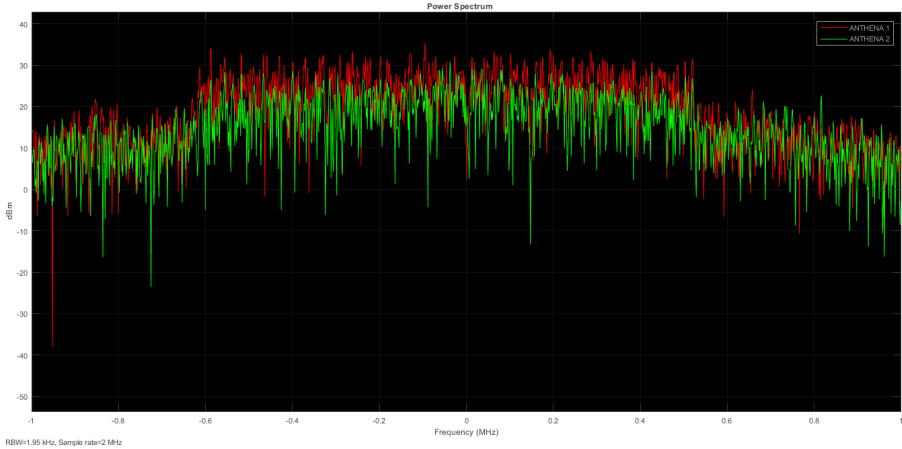


Figure 4.29: Signal Received in MIMO 2x2 RX (overlaped signals)

The receiver parameters can be changed in the USRP block as shown in Figure 4.30.

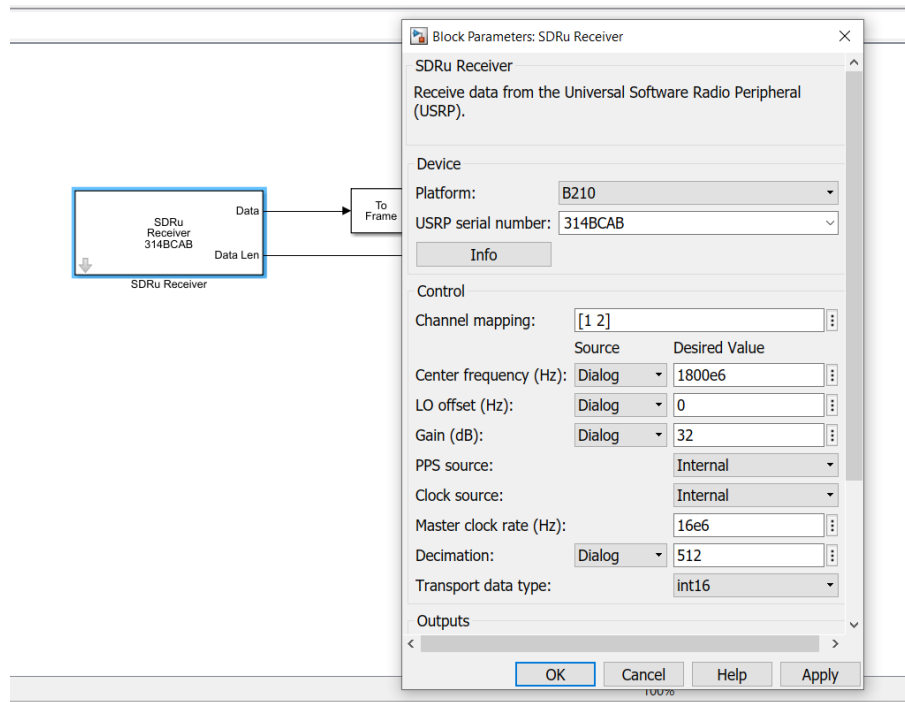


Figure 4.30: Configuration of parameters in block USRP RX

4.7 Conclusions

This chapter covers the work done and the results obtained. It begins by presenting the system model, describing the scenario, the receiver and transmitter architecture, and the channel model. However, in addition to the proposed project, it also intends to show and compare the results obtained for different frequencies. An overview shows that the performance and behavior of the implemented system, for the tests that have been done with different frequencies. It can be observed that the higher the gain in the transmitter is the better the performance is. Measurements have been performed with the NARDA spectrum analyzer so that the signal can be monitored, thereby proving the code stability and the synchronization of the USRP. During the elaboration of the work, in conjunction with Universidad Carlos III de Madrid, the OpenAir-Interface platform has been considered. In conjunction with the USRP to verify the compatibility and stability of a LTE network system. It was possible to implement a 4G network while communicating through real 4G cell phones of common use together with a configurable SIM-Card. The EPC and eNBs support a full functionality 4G network.

Chapter 5

Conclusions and Future Research

5.1 Conclusions

This dissertation proposes the capacity calculations of the SISO and MIMO systems in different channel hypotheses, where the Shannon capacity formula is presented, with which simulation is performed and we compare the results with the formulas of channel capacity MIMO 2x2, MIMO 3x3 and MIMO 4x4. With the simulation result it can be observed that the channel capacity increases linearly when using MIMO systems. The concept and statistical analyses of the MIMO channel matrix are discussed, where the channel capacity formulas can be verified in terms of their own vectors and singular vectors. The use of MIMO systems can be interpreted as the sum of many parallel SISO channels being conceptualized by the MIMO capability. Millimeter-wave communication is defining a new era of wireless communication, where the use of these mmWave bands offers a wider range of communication channels than bandwidth compared to those currently used. Taking this as a basis point, the millimeter wave signal processing is of paramount importance to the next generation of communication as the 5G. However, immersion in mmWave bands must be applied to a wide range of antenna sets in the transmitter and receiver, combined with radiofrequency and mixed signal restrictions, new signal processing techniques require multiple multiple input (MIMO) signals. Because of the wide bandwidth, low-complexity transceiver algorithms are extremely important. Studies have provided us with the possibilities of exploring techniques such as compressed detection for channel estimation and beamforming, which are now quite common in the implementation of more complex MIMO systems, such as massive MIMO systems, which rely on grouping a large number of MIMO antennas. More when we say millimeter wavebands and a revolution for new technologies, it is not simply a matter of just changing the operator's frequency [40]. The use of massive MIMO systems has become increasingly demystified with current practice through the use of a large amount of antennas in the laptops and the time division duplex operation. The set of additional antennas collaborates to concentrate more energy in much smaller dimensions, aiming, therefore, improvements in the efficiency and efficiency of the irradiated energy. Massive MIMO provides benefits that are of paramount importance to future technology, ie the extensive use of low-power components, reduced latency, and reduced system complexity. This paper proposes the implementation of a mathematical solution to simplify the more complex structures of multiple

input and output systems using mathematical methods implemented in Matlab for the synchronization of the USRP. It started by considering transmission techniques and reception-based single input single output (SISO) techniques to refine the synchronization, thus facilitating the future implementation of the MIMO system. Implemented through the quadrature amplitude modulation (QAM) constellation with 16 variants, or 16-QAM, was proposed for synchronization. However, it is being studied, a solution that makes it possible to further simulate the complexity of the code being studied and the implementation of a preamble structure in the synchronization pilot in the constellation to improve synchronization performance [64]. With the results obtained in the tests implemented using the 16-QAM modulation together with the synchronization, it is possible to verify that an attenuation occurs in determined moments of time. With the implementation of the preamble, we think that this mitigation can be extinguished. For the implementation of the MIMO system using the USRP in conjunction with Matlab, the main difficulty is in getting Matlab to identify and interpret the 2 channels of the USRP simultaneously in a unique interface of the software. With the Matlab code implemented it is possible to configure the parameters that make it easier to vary the frequency, gain and obtain new results, for different modulations and different carrier frequencies. For the implementation of the MIMO system using the USRP in conjunction with Matlab, the main difficulty was getting Matlab to identify and interpret the 2 channels of the USRP simultaneously in a single interface of the software. For this purpose, the MIMO communication was performed using a code written in Matlab to operate the trapping system with 2 TX antennas, and a Simulink / Matlab code for the RX receiving antenna system. With the Matlab code implemented it is possible to configure the parameters that facilitate the variation of the frequency, gain and obtain new results, for different modulations and different carrier frequencies. With the Matlab code implemented it is possible to configure the parameters that make it easier to vary the frequency, gain and obtain new results, for different modulations and different carrier frequencies. During the elaboration of the work, an analysis was carried out in conjunction with universidad Carlos III of Madrid, where it was tested the implementation of a code on the OpenAirInterface platform in conjunction with the USRP to verify the compatibility and stability of a LTE network system , to which it was possible to implement a 4G network and to use data transfer through a cell phone of common use together with a SIM-Card configurable, with the test it was possible to verify the carrier frequencies and the connection with the cell phone.

5.2 Future activities

This work considered the transmission of data by a USRP in concept of SISO system. As a future work, a more complex system will be implemented, as well as the use of a MIMO multi-antenna system with USRP hardware, to which it is possible to synchronize a 4x4 MIMO system using a single platform in Matlab to explore completely multi-user MIMO techniques. In addition, a more in-depth study will be done together with test, for the implementation of a mobile network using the OpenAirInterface board in conjunction with USRP B210. We did tests for UHF bands but future work will involve mmWave. Many companies and research institutes are examining possible new standards for upcoming 5G networks to overcome existing constraints and believe that the use of massive MIMO and CAP-MIMO will be of great help in the development of these technologies. It is hoped that our future work will follow this line of action.

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Appendix A

4G system with OpenAirInterface: Installation and configuration

A.1 Overview of OpenAirInterface

OpenAirInterface (OAI) is an open source experimentation and prototyping platform for wireless communications systems, launched under GPLv3 by the Eurecom Mobile Communications Department. Its main objective is to provide methods for protocol validation, performance evaluation and pre-implementation system testing for LTE and LTE-Advanced. The OpenAirInterface platform can be used for link-level simulation, system emulation and real-time Radio Frequency testing. The platform comprises the entire LTE protocol stack, including implementations compatible with 3GPP LTE standards for eNB and EPC and a subset of the 3GPP LTE protocols, and can be adopted as a platform for performance evaluation and emulation for LTE/Systems LTE-A [70].

OAI is based on a fronted architecture of software hosted on PC. With OAI, transceiver functionality is performed through a software radio front end connected to a host computer for processing. OAI is written in C standard for several variants of Linux in real time being optimized for Intel TM x86 processors and released as free software under the OAI license model. OAI provides a rich development environment with a number of integrated tools such as highly-realistic emulation modes, monitoring and debugging tools, protocol analyzer, performance profile, and configurable logging system for all tiers and channels [70].

The two main characteristics of OAI are:

- An open implementation of a 4G and future 5G system [71], fully compliant with 3GPP LTE standards and comprising the entire protocol stack, which can inter-operate with commercial terminals and can be used for real-time experimentation;
- An integrated emulation feature that can be used to test repetitive scenarios in a software-only environment and easily switch between emulation and real-time experimentation. Fast prototyping of 3GPP-compatible use cases as well as new concepts for 5G systems ranging from Machine-to-Machine (M2M), Internet of Things (IoT) networks and software-defined networks to cloud-RAN and massive MIMO.

A.1.1 Requirements for installation

In order to use the OAI it is necessary to follow some procedures designed to configure the OAI eNB and OAI EPC to which the connection to the eNB is allowed. You need 2 machines configured with Ubuntu, each machine has a specific configuration, settings that will be exposed during the analysis [72].

A.1.1.1 Hardware

Hardware necessary for installation:

- At least 2 physical machines;
- Ettus USRP B210 and Antenna;
- Blank USIM cards;
- Intel Architecture;
- USB 3.0 interface;
- Computer with i5/i7 5th generation processor with at least four CPU cores (for ENB).

A.1.1.2 Software

Software necessary for installation:

- Ubuntu 14.04 (64-bit recommended).
- Ubuntu low-latency kernel higher 3.19 or Preemptive-rt kernel higher 3.1 and Kernel Setup Instructions in [73].

A.1.1.3 ENB BIOS setting

The settings executed in the BIOS and only for the machine that will be used for ENB, it is not necessary to define the EPC machine. Remove all power management features in BIOS or GRUB [72].

- turned off C-States.
- Enhanced Intel Speedstep.

A.1.1.4 ENB CPU Setting : Maximize CPU frequency

For the system to flow in a stable manner and necessary to perform a configuration that 100% release the processor, such configuration can be done following the following steps:

- Install cpufrequtils code “*sudo apt - getinstallcpufrequtils*”;
- Then edit the following file (if it doesn't exist, create it) code
(*sudo vim/etc/default/cpufrequtils* or *sudo vim/etc/init.d/cpufrequtils*);
- Add the following line into it code “*GOVERNOR = "performance"*”;
- Disable ondemand daemon, otherwise after you reboot the settings will be overwritten code “*sudo update - rc.dondemanddisable*”;
- You can check your settings with code “*cpu freq - info*” It will show a block of information for every core your processor has. Just check if all of them are in performance mode, and at the maximum speed of your processor.

A.2 Get the sources

ENB:

- *sudo apt - getupdate*;
- *sudo apt - getinstallsubversiongit*;
- *gitconfig - -globalhttpitem.sslverifyfalse*;
- *gitclone* (<https://gitlab.eurecom.fr/oai/openairinterface5g>).

EPC:

- *gitclone*(<https://gitlab.eurecom.fr/oai/openair-cn>).

A.3 Unitary Simulation of LTE PHY

Several unitary simulations for the OpenAir5G Physical Layer exist and are located in *cmake_targets/lte-simulators*. These firstly constitute the starting point for testing any new code/innovations in the basic PHY functionality. Secondly, these are the required tests to be performed before committing any new code to the repository, in the sense that all of these should compile and execute correctly [74]:

- pbchsim for PBCH;
- pdccsim for DCI/PDCCH;
- dlsim for DLSCCH/PDSCH;
- ulsim for ULSCCH/PUSCH;
- pucsim for PUCCH;
- prachsim for PRACH;
- mbmssim for MCH/PMCH;

- **Compiling:**

```
cdYOURopenairinterface5gDIRECTORY;
sourceaienv#(setthepaths);
cdmake_targets;
./build_oih#(-hmeanshelp);
./build_oiI#(-Imeanstoinstalladditionalpackets,runitonlyonce);
./build_oi - -phy_simulatorsx#(-xisthescope).
```

- The compiled program are placed at:

```
cdlte - simulators/build.
```

A.4 Execution

- *Inordertogetthehelp:*
- `./ulsimh;`
- `./dlsimh;`
- *theinformationisnotfullyavailablewithh,gothethesourcecodeandchecktheoptions;*
- `openairinterface5g/openair1/SIMULATION/LTEPHY.`

Examples:

- `./ulsimF#(FisfortheScope);`
- `./ulsim10u - B50r3n100;`
- `./dlsimX#(-XisfortheScope);`

- `./dlsimXgEm17 - s30`.

In the OpenAirInterface site you can find a more complete tutorial for installing the necessary devices and the settings for the implementation of the code [75].

In the "VTS PT Chapter/COST-IRACON Joint Winter School on Beyond 5G Networks operating in the Millimetre Wavebands enabled by Joint Analogue-digital Signal Processing", hosted by Instituto de Telecomunicações/Lisbon, from March 5th until March 9th, 2018, there was a lecture on training routine on OpenAirInterface guided by a researcher of the University Carlos III de Madrid as shown in Figure A.1, A.2. It covered aspects of the OAI interface and its application in conjunction with the USRP as a remarkable technology for 4G and the future 5G [71].

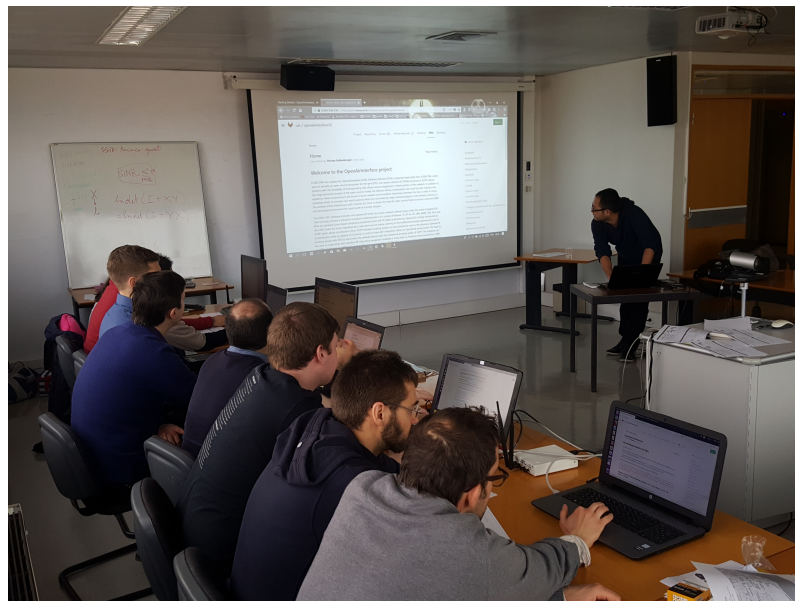


Figure A.1: Training OpenAirInterface (I)



Figure A.2: Training OpenAirInterface (II)

Appendix B

Matlab Code for the MIMO Transmitter

```
\% Check for presence of LTE System Toolbox
if isempty(ver('lte'))
error(message('sdru:examples:NeedLST'));
end
\% Generate LTE signal
rmc = lteRMCDL('R.12'); \% Base RMC configuration
rmc.CellRefP = 2; \% 2 transmit antennas
rmc.PDSCH.NLayers = 2; \% 2 layers
rmc.NCellID = 64; \% Cell identity
rmc.NFrame = 100; \% Initial frame number
rmc.TotSubframes = 8*10; \% Generate 8 frames. 10 subframes per frame
rmc.OCNGPDSCHEnable = 'On'; \% Add noise to unallocated PDSCH resource elements
rmc.PDSCH.RNTI = 61;
rmc.SIB.Enable = 'On';
rmc.SIB.DCIFormat = 'Format1A';
rmc.SIB.AllocationType = 0;
rmc.SIB.VRBStart = 0;
rmc.SIB.VRBLength = 6;
rmc.SIB.Gap = 0;
rmc.SIB.Data = randi([0 1],144,1); \% Use random bits in SIB data field.
trData = [1;0;0;1];
[eNodeBOutput, txGrid, rmc] = lteRMCDLTool(rmc, trData);
\%\% Plot Power Spectrum
spectrumAnalyzer = dsp.SpectrumAnalyzer;
spectrumAnalyzer.SampleRate = rmc.SamplingRate; \% 1.92e6 MHz for 'R.12'
spectrumAnalyzer.Title = 'Power Spectrum';
spectrumAnalyzer.ShowLegend = true;
spectrumAnalyzer.ChannelNames = {'Antenna 1', 'Antenna 2'};
step(spectrumAnalyzer, eNodeBOutput);
```

```

release(spectrumAnalyzer);
\% USRP Parameters:
txradio = comm.SDRuTransmitter
('Platform','B210','SerialNum','314BC6A','MasterClockRate',16e6,'CenterFrequency',
1800e6,'Gain',30,'InterpolationFactor',100)\cr
\% txradio.SamplesPerFrame=1000;
txradio.ChannelMapping = [1 2]
\%txradio.MasterClockRate = 16e6
mod = comm.DPSKModulator('BitInput',true)
\%\% Send Signal over Two Antennas
\% Scale signal to make maximum magnitude equal to 1
eNodeBOutput = eNodeBOutput/max(abs(eNodeBOutput(:)));
\% Reshape signal as a 3D array to simplify the for loop below\cr
\% Each call to step method of the object will use a two-column matrix
samplesPerFrame = 10e-3*rmc.SamplingRate;\cr
numFrames = length(eNodeBOutput)/samplesPerFrame;\cr

txFrame = permute(reshape(permute(eNodeBOutput,[1 3 2]), ...
samplesPerFrame,numFrames,rmc.CellRefP),[1 3 2]);
disp('Starting transmission')
currentTime = 0;
while currentTime < 3000 \% Run for 5 minutes
for n = 1:numFrames
\% Call step method to send a two-column matrix
\% First column for TX channel 1. Second column for TX channel 2
bufferUnderflow = step(txradio,txFrame(:,:,n));
if bufferUnderflow~=0
warning('sdru:examples:DroppedSamples','Dropped samples')
end
end
currentTime = currentTime+numFrames*10e-1; \% One frame is 10 ms
if currentTime ==3000
break
end
end

```

```
release(txradio);  
disp('Transmission finished')  
displayEndOfDemoMessage(mfilename)
```

