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Técnicas de Equalização Iterativas no Espaço-Frequência para o LTE

Iterative Space-Frequency Equalization Techniques for LTE

Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Prof. Dr. Adão Paulo Soares da Silva, Departamento de Eletrónica, Telecomunicações e Informática, Universidade de Aveiro; e do Prof. Dr. Atílio Manuel da Silva Gameiro, Departamento de Eletrónica, Telecomunicações e Informática, Universidade de Aveiro.

Dedico esta Dissertação aos meus pais e irmão por todo o apoio e dedicação.

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Palavras-chave LTE, OFDMA, SC-FDMA, MIMO,ZF, MMSE, IB-DFE

Resumo

As comunicações móveis tiveram um grande avanço na sua evolução na última década devido ao constante aumento dos requisitos dos utilizadores. O *Long Term Evolution* é a nova tecnologia desenvolvida para dar resposta às necessidades de uma crescente comunidade de comunicações móveis, oferecendo taxas de transmissão de dados muito mais elevadas, melhor eficiência espectral e menor latência quando comparado a tecnologias anteriores, incluindo também largura de banda escalável, interoperabilidade e *roaming* simples. Todas estas vantagens são possíveis devido à implementação de novas arquiteturas de rede, como a rede de acesso E-UTRAN e a rede *core* EPC, o uso de sistemas MIMO, e novos esquemas de múltiplo acesso: OFDMA para o *downlink* e SC-FDMA para o *uplink.*

Esta tese centra-se na comunicação no sentido ascendente desta tecnologia onde o esquema utilizado é o SC-FDMA, mais especificamente na aplicação de *Iterative Block Decision Feedback Equalizers* (IB-DFE) onde tanto a matriz de *feedback* como a de *feedfoward* do equalizador são aplicadas no domínio da frequência. Dois esquemas IB-DFE foram implementados utilizando processamento baseado em cancelamento de interferência em paralelo (PIC) e em serie (SIC). Foi considerado um cenário ascendente onde alguns utilizadores (UEs) partilham o mesmo canal físico para transmitir a sua informação para a Estação Base (BS). È também assumido que a BS está equipada com múltiplas antenas, e os terminais dos utilizadores com uma antena apenas. O objetivo dos esquemas iterativos estudados é remover eficientemente a interferência entre utilizadores e entre portadoras, permitindo entretanto um ganho de diversidade no espaço quase ótimo.

Os resultados obtidos mostraram que tanto a implementação PIC como a SIC apresentam melhor eficiência do que os habituais equalizadores lineares sub ótimos ZF e MMSE. Ambas as soluções eliminam a interferência entre utilizadores, embora o esquema SIC apresente um melhor desempenho que o PIC, aproximando- se do atingido com o *Matched Filter Bound (MFB)*.

Keywords LTE, OFDMA, SC-FDMA, MIMO,ZF, MMSE, IB-DFE

Abstract

Mobile communications had a huge leap on its evolution in the last decade due to the constant increase of the user requirements. The Long Term Evolution is the new technology developed to give proper answer to the needs of a growing mobile communications community, offering much higher data rates, better spectral efficiency and lower latency when compared to previous technologies, along with scalable bandwidth, interoperability and easy roaming. All these advantages are possible due to the implementation of new network architectures like the E-UTRAN access network and the EPC core network, the use of MIMO systems, and new multiple access schemes: OFDMA for downlink and SC-FDMA for uplink.

This thesis focuses on the uplink communication of this technology with SC-FDMA, specifically on the use of Iterative Block Decision Feedback Equalizers (IB-DFE) where both the feedback and the feedforward equalizer matrices are applied on the frequency domain. Two IB-DFE schemes were implemented using both Parallel Interference Cancellation (PIC) and Serial Interference Cancellation (SIC) based processing. We considered the uplink scenario where some users share the same physical channel to transmit its own information to the Base Station (BS). Also, we consider that the BS is equipped with multiple antennas and the user terminals (UT) with a single antenna. The aim of the studied iterative schemes is to efficiently remove both the multi-user and inter-carrier interferences, while allowing a close-to-optimum space-diversity gain.

The results obtained showed that both PIC and SIC implementations presented better performance than the conventional used linear multi-user sub optimal equalizers ZF and MMSE. Both solutions efficiently eliminate the multi-user interference, although the SIC based scheme slightly outperforms the PIC approach, with a performance close to the one achieved by the Matched Filter Bound (MFB).

Contents

List of Figures

List of tables

Acronyms

1G	First Generation.
1xEV-DO	One Carrier Evolved-Data Optimized.
2G	Second Generation.
3G	Third Generation.
3GPP	Third Generation Partnership Project.
3GPP2	Third Generation Partnership Project 2.
4G	Fourth Generation.
8-PSK	8-Phase Shift Keying.
ADC	Analog to Digital Converter.
AMPS	Analogue Mobile Phone System.
AS	Access Stratum.
AuC	Authentication Center.
BER	Bit Error Rate.
CDMA 2000	Code Division Multiple Access 2000.
CDMA	Code Division Multiple Access.
CP	Cyclic Prefix.
CS	Circuit Switched.
CSI	Channel State Information.
CTC	Convolutional Turbo Code.
CW	Continuous Wave.
DAC	Digital to Analog Converter.
DECT	Digital Enhanced Cordless Telecommunications.
DFE	Decision Feedback Equalizer.
DTF	Discrete Fourier Transform.

DwPTS	Downlink Pilot Time Slot.
EDGE	Enhanced Data rates for GSM Evolution.
EGC	Equal Gain Combining.
EPC	Evolved Packet Core.
EPS	Evolved Packet System.
ETU	Extended Typical Urban model.
E-UTRA	Evolved- Universal Terrestrial Radio Access.
E-UTRAN	Evolved- Universal Terrestrial Radio Access Network.
FDD	Frequency Division Duplex.
FDE	Frequency Domain Equalizer.
FDM	Frequency Division Multiplexing.
FDMA	Frequency Division Mulpitle Access.
FEC	Forward Error Correcting.
FFT	Fast Fourier Transform.
GP	Guard Period.
GPRS	General Packet Radio Service.
GSM	Global Systems for Mobile communications.
HSDPA	High Speed Downlink Packet Access.
HSPA+	High Speed Packet Access Evolution.
HSS	Home Subscriber Server.
HSUPA	High Speed Uplink Packet Access.
IB-DFE	Iterative Block- Decision Feedback Equalizer.
ICI	Inter Carrier Interference.
IDFT	Inverse Discrete Fourier Transform.
IEEE	Institute of Electrical and Electronics Engineers.
IFFT	Inverse Fast Fourier Transform.
IMS	Internet protocol Multimedia Subsystem.
IMT-2000	International Mobile Telecommunications-2000.
I-NNI	Interconnect- Network Network Interface.
IP	Internet Protocol.
IS-136	Interim Standard-136.
IS-54	Interim Standard-54.
IS-95	Interim Standard-95.
ISI	Inter Symbol Interference.
ITU	International Telecommunications Union.

LAN	Local Area Network.
LSTC	Layered Space-Time Codes.
LTE	Long Term Evolution.
MAI	Multiple Access Interference.
MAN	Metropolitan Area Network.
MFB	Matched Filter Bound.
MIMO	Multiple Input Multiple Output.
MISO	Multiple Input Single Output.
MME	Mobility Management Entity.
MMSE	Minimum Mean Square Error.
MRC	Maximal Ratio Combining.
MSE	Mean Square Error.
NAS	Non-Access Stratum.
NMT	Nordic Mobile Telephone.
NTT	Nippon Telegraph and Telephone.
OFDM	Orthogonal Frequency Division Multiplexing.
OFDMA	Orthogonal Frequency Division Multiple Access.
PAPR	Peak-to-Average Power Ratio.
PCEF	Policy Control Enforcement Function.
PCRF	Policy Charging and Rules Function.
PDC	Personal Digital Cellular.
PDN	Packet Data Network.
PDP	Power Delay Profile.
P-GW	Packet Data Network Gateway.
PLMN	Public Land Mobile Networks.
PMIP	Proxy Mobile Internet Protocol.
PS	Packet Switched.
QAM	Quadrant Amplitude Modulation.
QoS	Quality of Service.
QPSK	Quadrature Phase Shift Keying.
RAN	Radio Access Network.
RB	Resource blocks.
RF	Radio Frequency.
RNC	Radio Network Controller.
R-NNI	Roaming Network Network Interface.

SAE	System Architecture Evolution.
SC	Selection Combining.
SC-FDMA	Single Carrier- Frequency Division Multiple Access.
SFBC	Space Frequency Block Code.
S-GW	Serving Gateway .
SIC	Successive Interference Cancellation.
SIMO	Single Input Multiple Output.
SISO	Single Input Single Output.
SNR	Signal to Noise Ratio.
SRVCC	Single Radio Voice Call Continuity.
STBC	Space Time Block Code.
STC	Space Time Code.
STTC	Space-Time Trellis Code.
TACS	Total Access Communication System.
TDD	Time Division Duplex.
TDMA	Time Division Multiple Access.
TD-SCDMA	Time Division Synchronous Code Division Multiple Access.
UE	User Equipment.
UMB	Ultra-Mobile Broadband.
UMTS	Universal Mobile Telecommunication System.
UNI	User Network Interface.
UpPTS	Uplink Pilot Time Slot.
UT	User Terminal.
UTRA	Universal Terrestrial Radio Access.
UTRAN	Universal Terrestrial Radio Access Network.
VoIP	Voice over Internet Protocol.
VoLGA	Voice over LTE via Generic Access.
VoLTE	Voice over Long Term Evolution.
W-CDMA	Wideband Code Division Access.
WiMAX	Worldwide Interoperability for Microwave Access.
ZF	Zero Forcing.
ZMCSCG	Zero Mean Circularly Symmetric Complex Gaussian.

1. Introduction

1.1. Mobile Networks Evolution

The history of mobile networks began in 1973, with the accomplishment of the first call from a mobile phone to a fixed one. This achievement proved the functionality of the cell phone and the network developed for this technology, implemented in 1947 through the development of the cell concept by the Bell Labs (USA), turning mobile networks into one of the most promising technological areas of all times. The first attempts of cellular networks implementations were developed for small number of users since the equipments were expensive and battery-hungry, being only usable on a car.

The first mobile network available at a large scale growth was developed in the 1980s, and went by the name of first generation systems (1G). These systems were based on analogue speech communications, and were the first ones to allow a user in movement to maintain a phone call anywhere within the coverage area of his mobile network. This ability created the need of a mechanism that allowed the transfer of a call between coverage areas (cells) belonging to different base stations- the handover. The channel access method of these systems was Frequency Division Multiple Access (FDMA), and the only service available was voice. Furthermore, for this first generation there was no standardization, leading to the development of a series of independent systems worldwide like the Analogue Mobile Phone System (AMPS-USA), Total Access Communication System (TACS-United Kingdom), Nordic Mobile Telephone (NMT-Scandinavia), C450 (Germany) and Nippon Telegraph and Telephone (NTT- Japan) that worked only on their own countries. Due to the growing need of mobile services and the needs of standardization in Europe and a more efficient use the radio frequency spectrum (more users per MHz), these systems replaced by second generation ones (2G) in the 1990s [1].

The main characteristics that stood out on 2G were the use of digital voice codification and digital modulation techniques that allowed a substantial increase of spectral efficiency (3 times the one available in 1G) and the use of Time Division Multiple Access (TDMA) and narrowband Code Division Multiple Access (CDMA). Besides, it was defined as primary objective to offer international roaming (chance of performing and receiving calls with the same cell phone and number, when changing countries and their respective networks). The technological evolution of integrated circuits (which enabled the current use of digital transmissions) among others allowed mobile phones to become portable and cheaper, fact that transformed 2G into the most exponentially used mobile technology so far. The main systems available are GSM (Global Systems for Mobile communications-Europe), CT-2(Europe, Asia), DECT (Digital Enhanced Cordless Telecommunications- Europe), IS-54(Interim Standard-54, USA and uses TDMA), IS-136 (USA and uses TDMA), CDMA IS-95 (USA) and PDC (Personal Digital Cellular- Japan) [1].

Although 2G was developed with the idea of supporting only voice communications, later releases were created to implement a coexistent data transmission (data=add-on) standard that became known as 2.5G. GSM evolved then to GPRS (General Packet Radio Service), a service that uses, aside from the usual Circuit Switched (CS- dedicated communication channels established before the actual communication) from previous technologies, Packet Switched (PS) data transmissions which could offer data rates up to 114 Kbps.

With the rising need of mobile internet, PS transmissions gained increased influence, resulting on the standardization of an upgrade of GPRS by the Third Generation Partnership Project (3GPP) named EDGE (Enhanced Data rates for GSM Evolution) that uses better digital coding (8-Phase Shift Keying [8-PSK] instead of the Quadrature Phase Shift Keying [QPSK]) and would reach rates up to 384 kbps by coding 3 bits per symbol [3].

EDGE offered then a high data flow for its current users needs because voice was still the main need for traffic, but network developing was being made throughout the world, producing different standards. Due to this, the International Telecommunications Union (ITU) created the International Mobile Telecommunications-2000 (IMT-2000) initiative to create a network that would provide services independently of the technology platform, and a global standard for wireless data networks. One of the goals was also to achieve data rates up to 2000 Kbps, which led to the name of the initiative, and the idea of a third generation was then created [4].

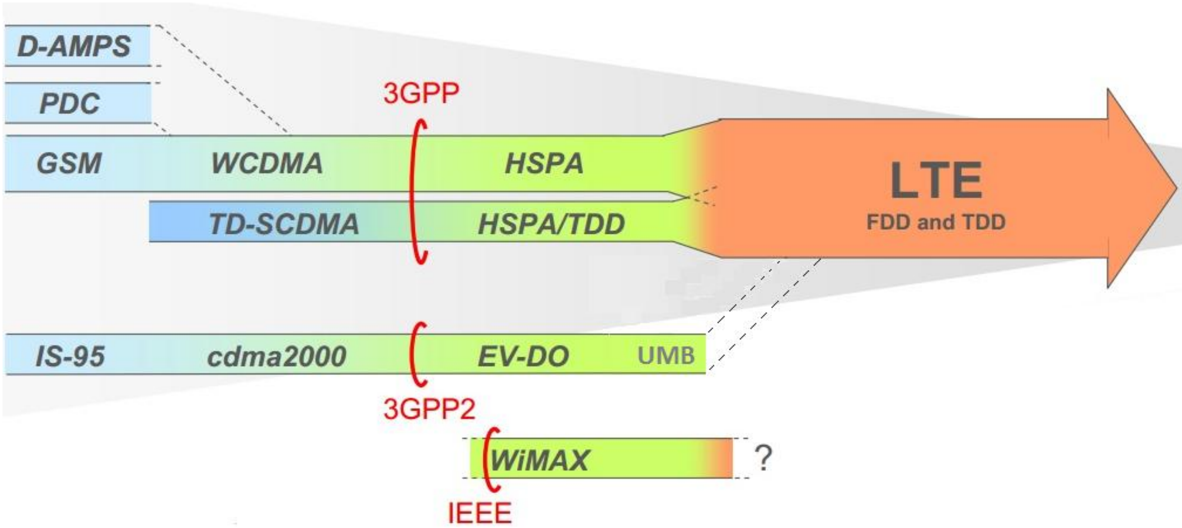

Figure 1 - Mobile Communications Standard evolution [5].

For this purpose, as we can see on Figure 1, three organizations developed their own beliefs about the ideal evolution for this third generation: the 3GPP, 3GPP2 and the Institute of Electrical and Electronics Engineers (IEEE).

The 3GPP chose UMTS (Universal Mobile Telecommunication System) with Wideband-CDMA (W-CDMA) as successor of GSM on Release 99, presenting theoretical data rates up to 2 Mbps based on different multiple accesses for Frequency Division Duplex (FDD) and Time Division Duplex (TDD) operation modes and 5 MHz bandwidth channels, making it not backwards compatible with its predecessor. 3GPP gave up then on their yearly release changing it since Release 4, which contained the new low chip rate version (TD-SCDMA: Time Division Synchronous Code Division Multiple Access) for the TDD mode of Universal Terrestrial Radio Access (UTRA). Release 5 presented High Speed Downlink Packet Access (HSDPA) with data rates from 7.2 to 14.4 Mbps, and then Release 6 came with the uplink version (High Speed Uplink Packet Access- HSUPA). Release 7 joined HSDPA and HSUPA enhancements and the use of Multiple Antenna systems (Multiple Input Multiple Output- MIMO), yielding High Speed Packet Access Evolution (HSPA+) that reached 42 Mbps. Extended enhancements of HSPA+ were introduced on Release 8 along with the first release of Long Term Evolution (LTE) that included the Evolved UTRA (E-UTRA) [6].

On the other hand, 3GPP2, which started with the American IS-95 standard (first one to use CDMA technology) and presented afterwards CDMA 2000, developed the One Carrier Evolved-

Data Optimized (1xEV-DO), a high rate wireless packet data system with substantial improvements in downlink capacity and coverage over the previous ones referred and shared the 1.25 MHz carriers bandwidth. The next step was then to cope with 3GPP LTE, through a system based on Orthogonal Frequency Division Multiplexing (OFDM) called Ultra Mobile Broadband (UMB). This approach was abandoned to converge with 3GPP LTE.

Another attempt was made by the IEEE 802 LAN/ MAN (Local Area Network/Metropolitan Area Network) standards committee, which created a new fully packet-oriented family globally known as WiMAX (Worldwide Interoperability for Microwave Access) or standard 802.16, promoted by the WiMAX Forum. Although the first version of this standard (802.16-2004) had fixed purposes, the following one (802.16e) left that restriction, going by the name of Mobile WiMAX. Still this family mobility and compatibility with operator’s core network can’t be compared to the ones of the previous organizations referred, that present core and radio access network evolutions [7].

With UMB dropped by 3GPP2 and Mobile WiMAX not close to the advantages of the usual mobile families, LTE became the righteous technology to earn the title of fourth generation (4G).

The definition of Generations (G’s) started in the 90’s when the cellular systems under research at the time were called third generation, but the word became a buzzword in the field leading to its use, but to represent a discontinuity or change in the paradigm of the cellular communications. Although such situation is not the case of LTE (since its purpose is to go further ahead than the objectives of 3G), in this case the population itself named it before any scientific opinion. This technology will be explained ahead on chapter 2, yet we can see below in Figure 2 and Figure 3 some information about its present and future presence in the telecommunications world. Figure 2 presents the impact of LTE on the matter of commitments made around the world till 2012, presenting relations with 285 operators over 93 countries, while Figure 3 shows the evolution of the number of LTE subscriptions in the next years, reaching more than 1 billion subscribers on 2018.

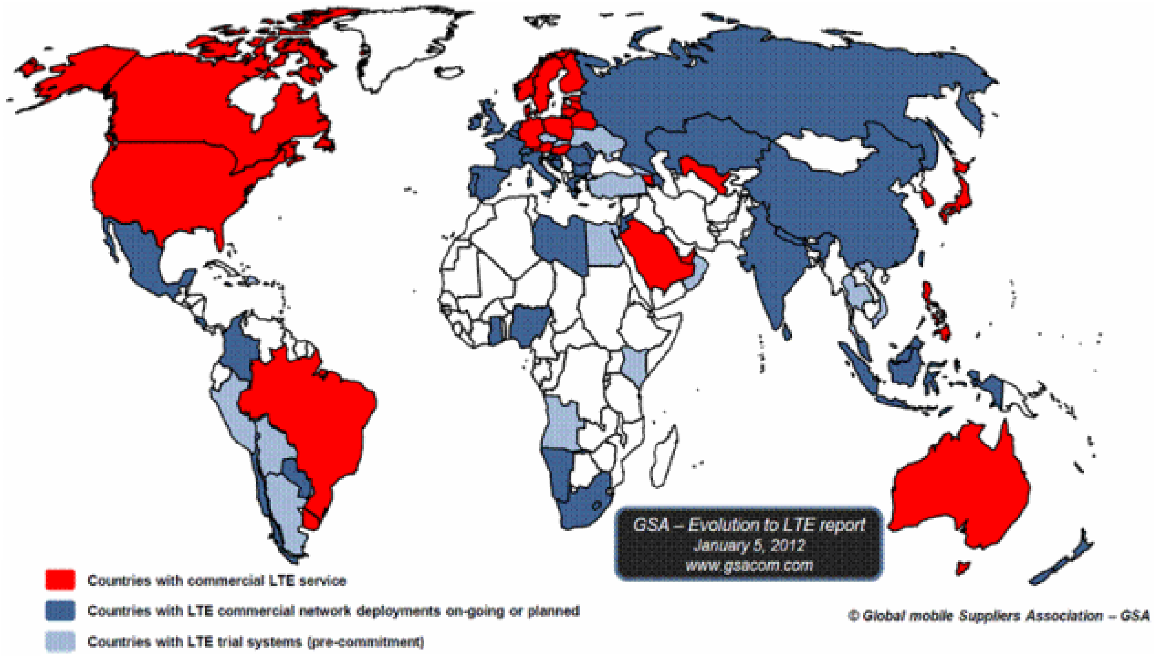

Figure 2 - LTE network commitments.

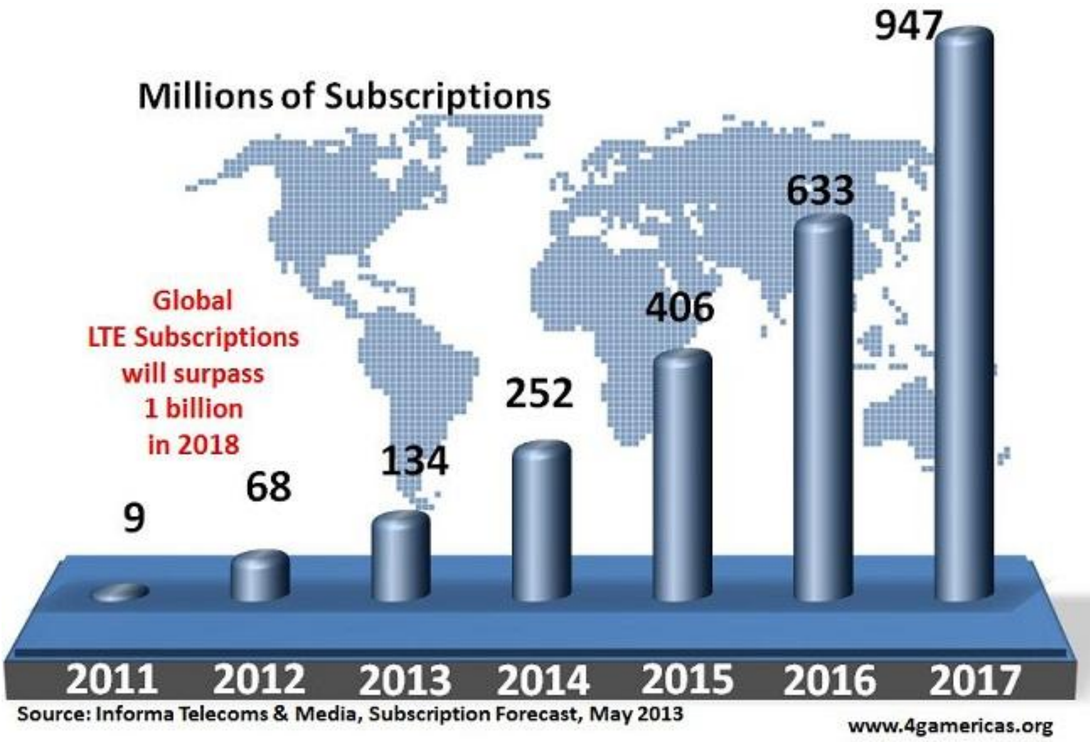

Figure 3 – Global LTE subscriptions evolution.

1.2. Motivation and objectives

As it is known, user requirements on mobile communications grew far beyond expectations on the last decade due to the appearance of Mobile TV among other multimedia contents directed to mobile use, exceeding the ones that served as targets for the 3G/UMTS technology, which is now almost 10 years old and struggles to cope with the needs of these data hungry users. Researchers were then forced to come up with more advanced and efficient technologies such as Mobile WiMAX and Long Term Evolution. LTE proved to be the best fitted to acquire the role of next step in mobile networks to replace 3G networks, the fourth Generation (4G).

This new technology presents a fully IP-based (Internet Protocol- based) integrated system (voice service included), presenting improvements in system performance such as peak transmission rates of 50 Mbps for uplink and from 100 Mbps to 1Gbps for downlink both indoor and outdoor, scalable bandwidth, interoperability and easy roaming, together with lower latency, the use of MIMO spatial multiplexing with all its advantages, and a simpler network architecture [8]. In the matters of multiple access techniques, 2 schemes are included. The Orthogonal Frequency Division Multiple Access (OFDMA) is used for the downlink as a multiuser form of the Orthogonal Frequency Division Multiplexing (OFDM), common already on previous systems. The highlight on this matter comes up on the uplink with the Single Carrier-Frequency Division Multiple Access (SC-FDMA), a modified form of OFDM with similar throughput performance, but presenting the low Peak-to-Average Power Ratio (PAPR) of single carrier schemes, solving the problem presented by OFDMA [9]. In the current version of the LTE standard and regarding the uplink SC-FDMA only closed form, frequency-domain linear equalization is considered. In scenarios with high level of interference, the performance of these schemes is poor and far from the optimum diversity gain. A Decision Feedback Equalizer (DFE) composed of a feedback and a feedforward filter designed for single user SC-FDMA was proposed in [10] to mitigate the Inter Carrier Interference (ICI). It was shown that this scheme increases the throughput in a power limited channel by up to 41% compared to linear equalization [10].

This thesis is then directed to the development of a multiuser Iterative Block- Decision Feedback Equalizer (IB-DFE) where both filters (feedback and feedforward) are designed in frequency domain, taking into account the interference between other users (Multiple Access Interference- MAI) and between carriers- ICI. Two IB-DFE schemes are implemented using both

Parallel Interference Cancellation (PIC) and Serial Interference Cancellation (SIC) based processing. We consider the uplink scenario where some users share the same physical channel to transmit its own information to the Base Station (BS). Also, we consider that the BS is equipped with multiple antennas and the User Terminals (UTs) with a single antenna. The aim of the studied iterative schemes is to efficiently remove both MAI and ICI, while allowing a close-to-optimum space-diversity gain with only a few iterations. The equalizers are assessed in a simulation platform based on the specifications of LTE

.

1.3. Outline

After the presentation of the evolution of mobile networks, the motivation and objectives of this thesis, 5 more chapters follow.

In chapter 2 the current standard of LTE is presented, from the reasons that led to it, the requirements made, until its specifications in the matters of bandwidth, spectrum, modulation schemes, data rates among others. The network architecture of this technology is also specified, together with its roaming and interworking abilities.

In chapter 3 the multiple access schemes of LTE are stated, along with its characteristics and modes of mapping the information on the subcarriers.

In chapter 4 it is explained one of the main properties of LTE, the use of MIMO systems and the concepts needed to understand its application.

Chapter 5 is the main chapter of this thesis and can be divided on three main components. At first, the two receivers with different base processing schemes are presented schematically, followed by the mathematical explanation step by step. Then, the simulation platform is presented, along with all the parameter manipulation possible, and finally the results of the application of both receivers on this simulation platform are showed (with the specification of the parameters chosen) over several scenarios, along with its analysis.

At last, in chapter 6 the conclusions of this thesis are stated, along with possible future research on this matter.

2. Long Term Evolution

2.1. Motivation and targets

In 2004, although the previous technology (HSDPA) wasn't finished yet, the path towards Long Term Evolution began with the start of the standardization through the creation of its targets by the 3rd Generation Partnership Project. This task takes around 5 years using interoperable standards, justifying its premature start. The key aspects taken into account during LTE development were the evolution of the wire line capability (needs to follow the one occurring in the meantime), the need for additional wireless capacity (to take maximum advantage from the available spectrum), lower cost wireless data delivery, and off course the competition of other wireless technologies like IEEE 802.16 WiMAX that promised similar achievements [6].

The key goals for LTE were completed in 2005 and are presented below, along with illustrations of some are then in Figure 4 [11] [12]:

- Increased user data rate and cell edge bit rate for uniformity of service provision.
- Reduced cost per bit by providing improved spectral efficiency.
- Greater flexibility in spectrum usage.
- Need for a packet switched optimization system- evolution to full IP.

- Simplified and cheaper network architecture, with element reduction if possible.
- Seamless mobility, even between different access technologies.
- Reasonable power consumption for the mobile terminal.
- Need for high quality services like the use of licensed frequencies, always on experience (reduced control plane latency) and small round trip delay.

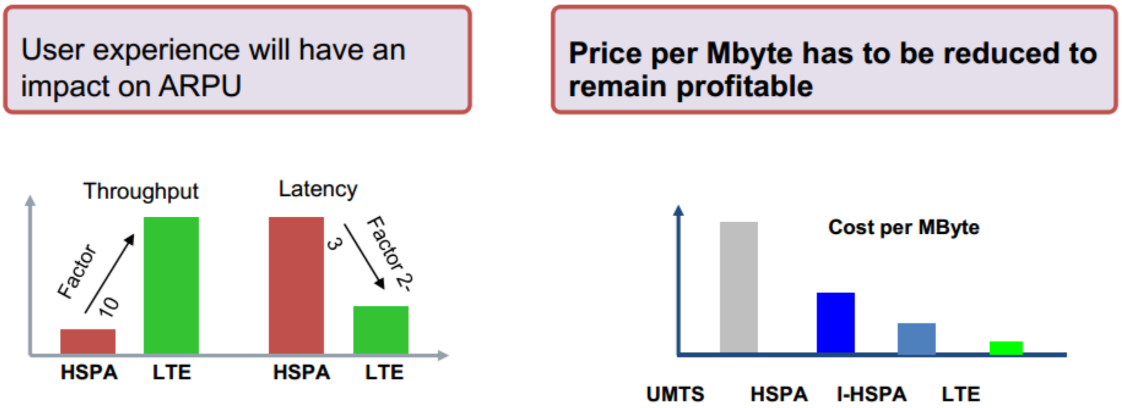

Figure 4 - LTE Improvements on throughput, latency and cost per MByte [11].

2.2. Overview

The main features of LTE Radio Access Network (RAN) stand divided in three groups, where the ones of bigger interest are [13]:

Deployment-related features:

- Deployment scenarios - there are 2 deployment scenarios to take into account, the standalone scenario where no interworking is available, and the one where its new RAN is integrated with the existing network already present.

- Spectrum flexibility - the spectrum allocation has, depending on the needs, adjusting sizes between 1.4, 3, 5, 10, 15 and 20 MHz in both downlink and uplink instead of UMTS (where fixed 5 MHz channels are used with any number of subcarriers used for transmission) to achieve high flexibility in channelization. This flexibility is applied also on the broadcast transmission mode, where LTE separates downlink from uplink through Time Division Duplexing (TDD), Frequency Division Duplexing (FDD) or both at the same time (operation in paired and unpaired spectrum is supported). These characteristics are illustrated on Figure 5.

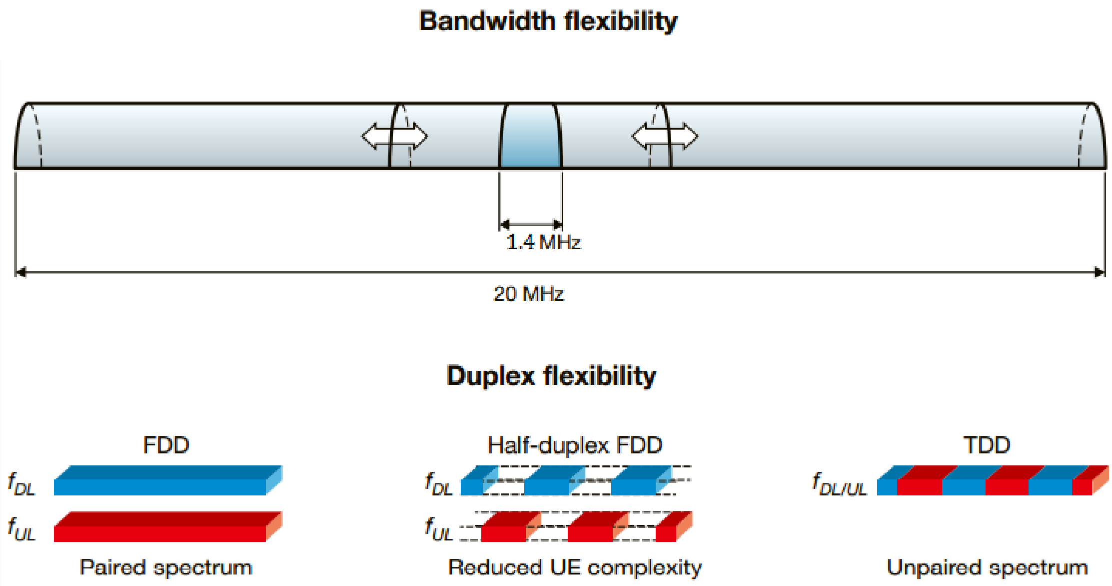

Figure 5 - LTE spectrum (bandwidth and duplex) flexibility [14].

Capability-related features:

- Peak data rates - the system is able to support an instantaneous peak data rate of 100 Mbps for downlink (with 2 receive antennas at the User Equipment [UE]) and 50 Mbps for uplink (with 1 transmit antenna at the UE) presenting, with the maximum spectrum allocation (20MHz), 5bps/Hz and 2.5bps/Hz respectively.

- Latency - on this topic 2 different situations are presented, User plane (U-plane) and Control plane(C-plane). U-plane latency is the one way transit time between a packet being available at the IP layer on the RAN edge node and its availability at the IP layer on the UE edge node, or contrariwise, and it has a latency of less than 5 ms in unload condition (single user with single data stream). C-plane latency is the time required to transit from the camped state (Release 6 IDLE Mode) to an active state (Release 6 CELL_DCH) in such a way that the user plane is established. In this case a delay of less than 100ms is offered. It is expected also to support at least 200 users per cell in active state for a spectrum allocation of 5 MHz, and at least 400 for higher spectrum allocation.

System performance features:

- User throughput – LTE offers an average user throughput/MHz 3 to 4 times higher than Release 6 HSDPA on downlink, and 2 to 3 times higher on uplink.

- Spectrum efficiency - for downlink, in a loaded network, LTE offers 3 to 4 times the spectrum efficiency (bits/sec/Hz/site) of Release 6 HSDPA, assuming Release 6 reference performance based on a single Tx antenna at the NodeB (name for base station on this release) with enhanced performance type 1 receiver in UE while the E-UTRA may use a maximum of 2 Tx antennas at the Node B and 2 Rx antennas at the UE. For uplink, in a loaded network, LTE offers 2 to 3 times the spectrum efficiency (bits/sec/Hz/site) of Release 6 Enhanced Uplink (deployed with a single Tx antenna at the UE and 2 Rx antennas at the Node B). This should be achievable by the E-UTRA using a maximum of a single Tx antenna at the UE and 2Rx antennas at the Node B.

- Mobility: the E-UTRAN (LTE access network, explained ahead on section 2.5.2) is optimized for mobile speeds up to 15 km/h, handle high performance till 120 km/h and maintain the connection up until 350 km/h (or even 500 km/h depending on the frequency band). The E-UTRAN shall also support techniques and mechanisms to optimize delay and packet loss during intra system handover.

- Coverage: assuming C/I limited scenarios, the E-UTRAN should present full performance up to 5 km, a slight degradation from 5 to 30 km, and should show acceptable operation up until 100km. For C/N scenarios such as deep indoor situations, the improvement over HSDPA/Enhanced Uplink Release 6 is not as clear. Also new modulation schemes with higher orders of modulation are used for data transmission to achieve higher data rates, with a consequent increase of the error chance and path loss. This fact states that the network will be adjustable to the distance between the base station (called eNodeB- evolved NodeB) and the UE, offering more complex modulation resulting on higher data rates, to users that are closer to the eNodeB. On the other hand, users that are further will have access to simpler modulation schemes that are more resistant o errors. The modulation schemes available are QPSK, 16-QAM (Quadrant Amplitude Modulation), and 64-QAM for downlink, while for the uplink 64-QAM is optional at the UE.

2.3. Frame structure

To present the structure of the LTE frame, we must first define the base time unit for this matter, T_s=1/(15000x2048)= 32.6 nanoseconds. This value depends on the maximum FFT size of 2048 and the spacing between subcarriers of 15 kHz.

The generic radio LTE frame lasts T_f=307200xT_s= 10 milliseconds, is composed of 10 subframes of 1 millisecond, and each subframe is further divided in 2 slots of 0.5 milliseconds. Each slot consists of 6 or 7 OFDM symbols, depending on the use of normal or extended Cyclic prefix (CP – explained ahead on section 3.1.4) respectively.

Since LTE can work in both FDD and TDD, two types of frame were defined. For FDD, the frame matches the generic one referred above, with 20 slots of 0.5 milliseconds. For TDD the same frame is divided on 2 half frames, and depending on the switch period between uplink and downlink being 10 or 5 milliseconds, one or both half frames respectively will contain (on the place of the second subframe) a special subframe that contains the switch information within the fields Downlink Pilot Time Slot (DwPTS), Guard Period (GP) and Uplink Pilot Time Slot (UpPTS). On one frame divided in such way, the first subframe and DwPTS of each half frame are reserved for downlink, UpPTS and the subframe that follows are reserved for uplink, while the remaining subframes can be used for either Uplink or Downlink. We can see on Figure 6 an illustration of both frame types for better understanding [15].

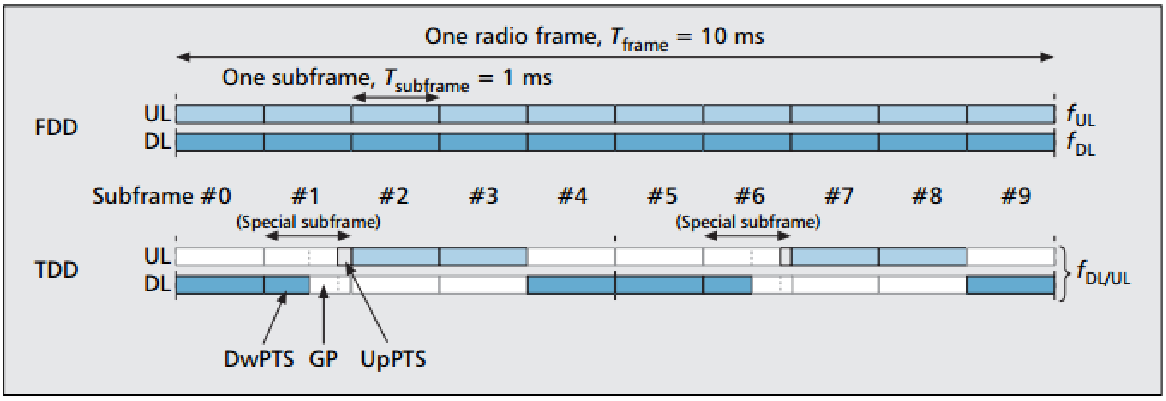

Figure 6 - LTE frame structure [16].

As said before, the slots of the LTE frame contain 6 or 7 symbols depending on the type of CP. Each of these symbols occupies a 15 kHz subcarrier called Resource Element. The Resource

Elements are organized on Resource Blocks (RB) of 6 or 7 symbols (1 slot) by 12 successive subcarriers (12 x 15 kHz = 180 kHz). The scheduler is then in charge of assigning RBs to physical channels from different users or for general system tasks. A single cell must have a minimum of 6 RBs (72 subcarriers) and a maximum of 110 (1320 subcarriers) [11]. This structure can be seen below on Figure 7.

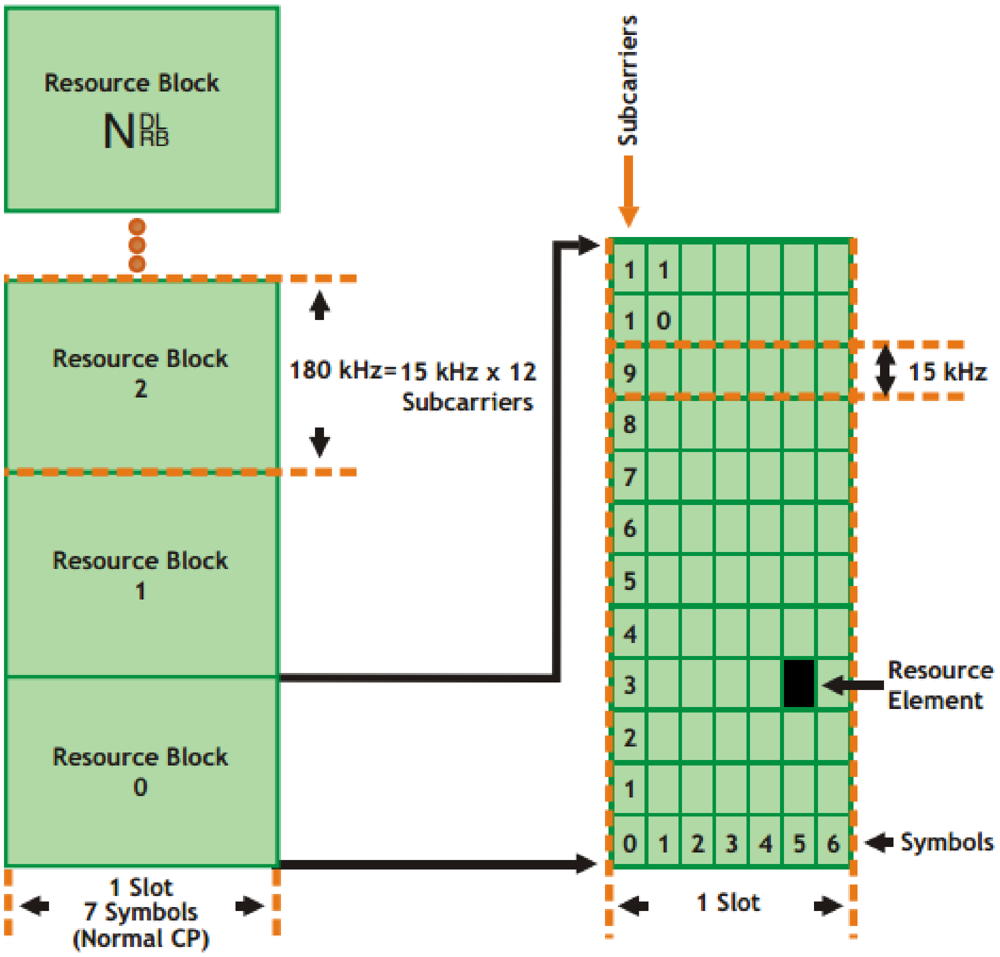

Figure 7 - Relationship between slots, symbols and Resource Blocks (using normal CP) [15].

2.4. Drawbacks

Although it presents a series of advantages, like all new developing technologies, LTE faces its obstacles. LTE presents itself as a very high speed technology, data-only (all-IP) oriented, but it also as very low latency which is critical for any kind of real time communications. Previous cellular communications (2G and 3G) were designed for this type of communication (voice), adding later data support through methods of tunneling inside voice connections.

Since it was designed for an all-IP purpose, LTE doesn't support the traditional voice service, so a new protocol is required to take advantage on the low latency and Quality of Service (QoS) of this technology to offer an even better voice service than the previous ones. Since 2000 the 3GPP have been working with IP Multimedia Subsystem (IMS), releasing many specifications regarding several functionalities, while the architecture was developed. This subsystem consists of an access-independent service control architecture based on the standard IP connectivity that provides various kinds of multimedia services to the final users.

With all components developed for the establishment of Voice over LTE (VoLTE), it was left for the service providers to choose which implementation to use, a mistake since without a more global standardization, the huge step of second generation would be lost. In the meanwhile, alternative implementations appeared, with 3GPP introducing switched fallback (CSFB) where the implementations for voice of the previous generations would be used instead, and the VOLGA Forum launched Voice over LTE via Generic Access (VoLGA).

A fierce competition followed, leaving doubts about when would VoLTE be definitely settled. This situation continued till the 4th November 2009, when the One Voice initiative was published by 12 major companies on the matter (such as Vodafone, Orange, Telefonica and Samsung) to define that the better approach would be 3GPP IMS based solution.

2.4.1. Voice over LTE

The LTE standard can in the end refer the voice service as a special data application with specific requirements in the matters of QoS, real time traffic and interworking with the existing voice CS core network infrastructure.

The LTE core network, called Evolved Packet Core network (EPC- explained ahead on section 2.5.1) was designed to handle all types of application and includes great support for the voice service, leaving then unneeded the previous voice core networks. On the other side, LTE RAN does not support direct connectivity to CS core and services, but it is connected to the EPC which provides IP connectivity for the user services and interworking towards existing CS networks [17].

To provide the VoLTE service, three interfaces are required: a User Network Interface (UNI) between the user's equipment and the operator's network, a Roaming Network Network Interface (R-NNI) between the home and visited network used by a user that is not attached to their home network (roaming), and a Interconnect Network Network Interface (I-NNI) located between the networks of the two sides of the call.

The final settlement of the VoLTE service is still being defined, and it will comprise many elements to ensure, per example, the continuity of voice calls when a user moves from an LTE coverage area to another where a fallback to another technology is required for the handover (solution can come from the use of Single Radio Voice Call Continuity- SRVCC), and the capacity to provide optimal routing of bearers for voice calls when a user is roaming [18].

2.5. LTE Network Architecture

As referred previously on this chapter, LTE can be defined as a system that accomplishes the objective of offering an all-IP multiservice air interface beyond voice calls. This is only achievable through the evolution of the RAN through the Evolved- UTRAN (E-UTRAN), but also the evolution of the non-radio aspects of the system, named System Architecture Evolution (SAE), that comprises the EPC.

The Evolved Packet System (EPS), which includes LTE and SAE, aims to provide seamless IP connectivity for a user with the Packet Data Network (PDN) to access the Internet and run the VoLTE service without any interruption to end users applications while moving, with high higher data rate, lower latency, and great QoS. The use of only one PDN through a fully PS core and access network allows operators to save resources and more than anything, the investment of having parallel networks [19] [20].

The EPS architecture with the interfaces applied and its main aspects, from the core network (EPC) to the access network (E-UTRAN), are presented below on Figure 8.

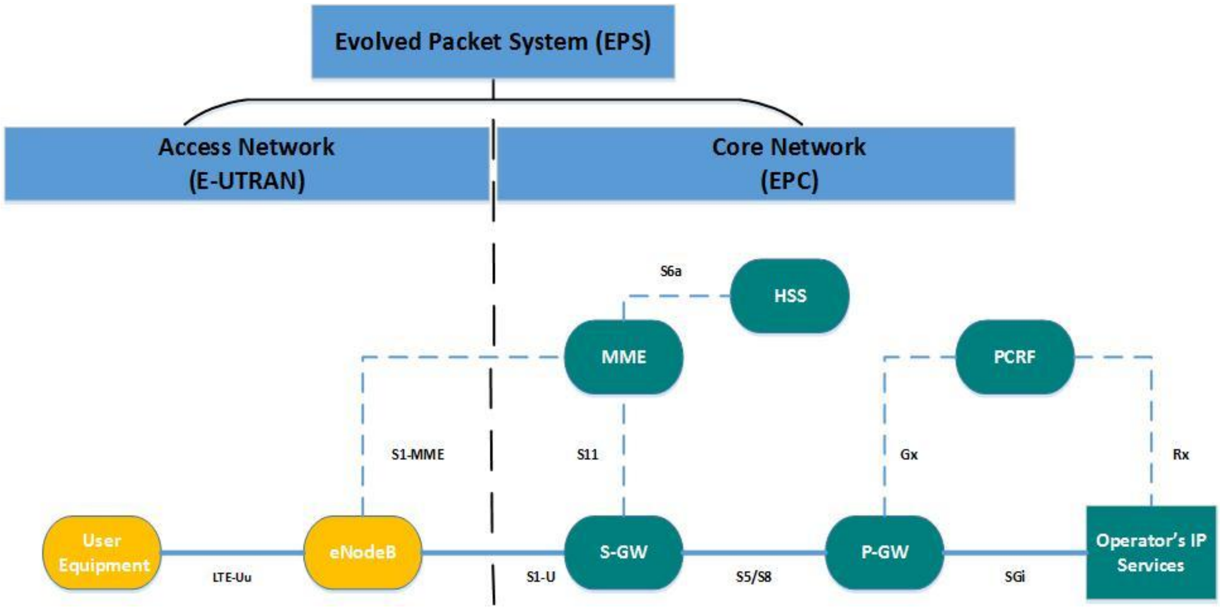

Figure 8 - LTE core and access network architecture.

2.5.1. Evolved Packet Core Network

The Core Network, named EPC network on LTE, is composed by the following main logical components that are noticeable on Figure 8 [12] [19] [20]:

- **Serving Gateway (S-GW):** acts as a mobility anchor for data bearers (service flow) forwarding and receiving packets to and from the eNodeB where the UE is being served, and retains info about the bearers when the UE is in IDLE mode. It works also as a mobility anchor that allows interoperability with other 3GPP technologies such as GSM and UMTS. Performs also its share of administrative functions in the visited network, like collecting information on the amount of data sent to or received from the user (for its charging), and legal interception.

- **PDN Gateway (P-GW):** interacts with the external PDNs (e.g. Internet, IMS) and has various responsibilities such as address allocation, QoS enforcement and flow-based charging according to PCRF (defined ahead) rules, and filtering downlink IP packets into different bearers according to its QoS level. It also serves as mobility anchor like the S-GW, but for non-3GPP technologies (e.g. WIMAX, CDMA 2000). Both P-GW and S-GW can be implemented as one physical network component, depending on the deployment scenarios an operators support.

- **Mobility Management Entity (MME):** is the control node responsible for the signal processing between UEs and the CN through Non-Access Stratum (NAS) protocols. Its main function is to manage the UEs mobility, and performs also authentication, authorization, security negotiations, idle-mode UE tracking and reachability. The MME is a signaling-only entity, so the user IP packets do not go through it.

- **Policy Charging and Rules Function (PCRF):** as the name states, is responsible for the policy control and decision making, along with the control of the flow-based charging functionalities in the Policy Control Enforcement Function (PCEF) which resides in the P-GW. Controls also the QoS authorization that defines how each data flow is treated in the PCEF.

- **Home Subscriber Server (HSS):** contains the subscriber profile (information on the QoS profile, access restrictions and roaming capabilities among others), information on the identity of the MME to which the UE is attached, and may also have an Authentication Center (AuC) that generates authentication vectors and security keys.

2.5.2. Access Network

The LTE access network, named Evolved-UTRAN, is nothing more than a simple network of eNodeBs that provides user plane and control plane protocol terminations towards the UEs. We can see on Figure 9 below a representation of UMTS UTRA and LTE E-UTRA for comparison.

As we can see, the E-UTRA architecture is simplified when compared to UMTS UTRA, since the RNC (Radio Network Controller) seizes to exist on the LTE architecture as a node (being embedded into the eNodeBs), reason why E-UTRAN is said to be a flat and cheaper architecture. Another distinction to be made is the separation of the Control and User planes for better scalability, being the C- plane directed to the Core Network MME, while the U- plane goes to the S-GW.

The eNobeBs are interconnected through an interface named X2, and each one is connected to the EPC through another interface called S1 (to the MME by means of S1-MME, and to the S-GW through the S1-U interface). This S1 interface has an important ability that links the access network to the core network, named S1-flex. This ability allows multiple Core Network nodes such as MMEs or S-GWs to serve a common area, being connected by a mesh network to the set of eNodeBs in the area. Between an eNodeB and the UEs, the protocols applied are known as Access Stratum (AS) protocols.

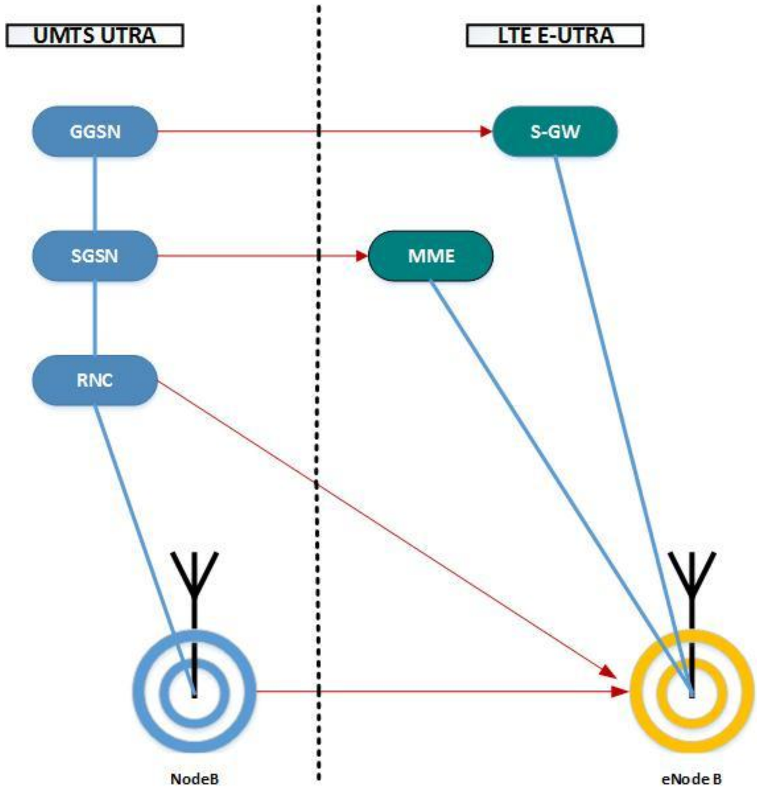

Figure 9 - Access Network comparison between LTE and UMTS.

The LTE access network is in charge of all radio-related functions, like [12] [19]:

- **Radio access Management:** all that is related with the bearers, such as bearer control, radio admission control, radio mobility control, dynamic allocation and scheduling of resources to the UEs;

- **Header Compression:** as the name refers, compresses the IP packet headers to avoid overheads, helping to ensure the efficient use of the radio interface;

- **Security:** through encryption of all the data to send;

- **Connectivity to the EPC:** signaling towards the MME and bearer path towards the S-GW.

By residing all radio control functions in the eNodeB, LTE allows tight interaction between the different protocol layers of the access network, leading to a raise of efficiency and reduction of latency.

Another change is that LTE does not support soft handover, seizing the need for a centralized data-combining function in the network. On the other side, as the UE moves, the network must transfer all the information regarding the UE and all the buffered data, to the eNodeB that controls the coverage area where the UE moved to [20] [21].

2.6. Roaming and interworking

Roaming consists on users being allowed to connect to other Public Land Mobile Networks (PLMN- network of one operator in one country) than the ones to which they are directly subscribed. On LTE, a roaming user is allowed to connect to the foreign country's E-UTRAN, MME and S-GW. On this situation, the P-GW of either the visited or the home network can be used, and while the home network P-GW allows the user access to his home operator's services, the visited network P-GW allows a "local breakout" to the visited network.

Inter-working is a different situation, where a user from operator A tries to call another user in the same country, but from operator B or previous technologies like GSM, CDMA 2000 or UMTS. On this case, the S-GW acts as a mobility anchor for inter-working with other 3GPP technologies, and the P-GW serves as an anchor allowing seamless mobility to the non-3GPP ones like WiMAX, and may also support a Proxy Mobile Internet Protocol (PMIP) based interface [20] [22].

3. Multiple Access Schemes of LTE

3G systems like UMTS are implemented through the use of Wideband Code Division Access (W-CDMA), used for both uplink and downlink by various users with different orthogonal Walsh codes multiplexed within the same 5MHz bandwidth.

For the LTE downlink, where data is sent from the eNodeB to the UE, it is required that transmissions on different Walsh codes are received as orthogonal (without multipath propagation). However, since we are applying it to cellular environments where multipath propagation exists, codes may interfere with each other destroying the orthogonality between them, leading to Inter-Symbol Interference (ISI) and Multiple Access Interference (MAI). A solution to this situation resides on the use of more complex receivers such as the linear Minimum Mean Square Error (MMSE), but this problem escalates with the increase of bandwidth, conflicting with one of LTE requirements on this matter (scalable bandwidth up to 20 MHz).

On the other side, the uplink transmission where data is sent from various UEs to an eNodeB, presents more challenging situation due to its many-to-one nature. The situation is worse than the downlink one since even without multipath propagation, the orthogonality is lost due to the non-synchronization between the codes received at the eNodeB. This happens because there is difference of propagation times of the data sent from several UEs located on different positions within the coverage area of the same cell. Aside from this, the number of Walsh codes used for a single user is limited, which by itself bounds the uplink signal Peak to Average Power Ratio (PAPR) to improve its efficiency.

Both scenarios present limitations that are not intended on LTE, leading to the search for new multiple access schemes.

A multi user version of OFDM, Orthogonal Frequency Division Multiple Access (OFDMA) appeared recently as a technology ready to provide high data rates, and it was already adopted in other wireless standards like WiMAX and IEEE 802.11a to increase their wireless communications. This solution fitted the needs of LTE, being selected for the downlink transmission. Although, the need for better efficiency and lower PAPR removed OFDM from the choices for the uplink communication in favor of Single Carrier- Frequency Division Multiple Access (SC-FDMA) [23] [24] [25].

On this chapter both approaches will be presented in detail, along with its main characteristics and block schemes.

3.1. Orthogonal Frequency Division Multiplexing

Leaving the analog/digital concern aside, the modulation systems began with the modulation of information onto one single carrier through the adjustment of its frequency, phase or amplitude. However, with the increase of bandwidth used, the duration of a bit becomes shorter, making the system vulnerable to interference and loss of the information due to impulse noise, signal reflections, and others that can deceive the capability to recover the information sent.

Frequency Division Multiplexing (FDM) is an extension of this single carrier concept, advancing to the use of multiple subcarriers within the same carrier (each with an equal share of the total bandwidth). This system requires guard bands to separate the subcarriers allowing individual demodulation, and it’s used on some television systems and FM stereo multiplexing [26].

Still, a better solution could avoid the use guard bands between the subcarriers, allowing higher spectral efficiencies: the use of orthogonal subcarriers that can overlap on the spectrum. This idea led to the creation of OFDM, a communication system that doesn’t rely on increased symbol (groups of bits) rates to reach high data rates, easing the control of the ISI. OFDM consists on dividing the given bandwidth into many narrowband orthogonal subcarriers for sending several data symbols in parallel (modulated in QPSK, QAM, 16QAM or 64QAM), resulting in better spectrum efficiency and requiring simpler equalization methods at the receiver [27]. Since the data is sent in parallel, OFDM symbols are longer than single carrier symbols on equivalent rate, and each of them is preceded by a CP that is used to mitigate the ICI [24].

This system brings advantages from working with a second dimension, the frequency domain, which brings additional winnings from the use of signal improvement techniques (like interleaving e error correcting codes) comparing to its use on the time domain. The use of both time and frequency domains comes from the use of the blocks Fast Fourier Transform (FFT) and its opposite Inverse Fast Fourier Transform (IFFT), which are mathematical equals to the Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT) operations that move the data between these two domains and can be viewed as mapping data into orthogonal subcarriers [26] [27].

There are many great characteristics serving OFDM, but the ones that deserve most attention are multicarrier modulation, the structure of the basic signal and the use of a cyclic prefix.

3.1.1. Multicarrier Modulation

Multicarrier modulation is a bandwidth efficient communication system in the presence of distortion which, as said before, divides the available bandwidth into several subcarriers with the same share of the total bandwidth ($K = W/\Delta f$, where K is the number of subcarriers, W is the bandwidth available and Δf if the subcarrier bandwidth). These subcarriers are so narrow that the frequency response characteristics are almost ideal, and different symbols can be transmitted simultaneously in the K subcarriers.

In the specific case of its application on OFDM, the symbol interval is $T=KT_s$ where T_s is the symbol interval of a single-carrier system. This way, K is chosen to be large enough to avoid ICI effects. There is still another option available with OFDM's multicarrier modulation, where as long as time synchronization between subcarriers is assured, we can transmit a different number of symbols on each subcarrier. Therefore, subcarriers that present lower attenuation can use higher orders or modulation (e.g. 64 QAM) to carry more symbols than subcarriers with higher attenuation [28].

3.1.2. Orthogonality

Orthogonality between two signals is verified if the dot product between them is equal to zero, allowing the transmission of multiple subcarriers at the same time in a short bandwidth without interference from each other. It can be defined by the equation:

$$\int_0^T Si(t).Sj(t)dt = \begin{cases} C & if\ i = j \\ 0 & if\ i \neq j \end{cases} \quad (4.1)$$

On the other hand, this property can be lost, resulting on degradation of the signal. The need for this property will be referred ahead on section 3.1.3.

3.1.3. Basic Signal Structure

The basic OFDM symbol consists of a group of Continuous Wave (CW) tones closely spaced in the frequency domain. Each of these CW tones can be seen as a pulse generated with QAM modulation (all other LTE supported modulation types fit the same representation), which presents itself as a traditional sinc function centered on the subcarrier frequency, as the one represented below.

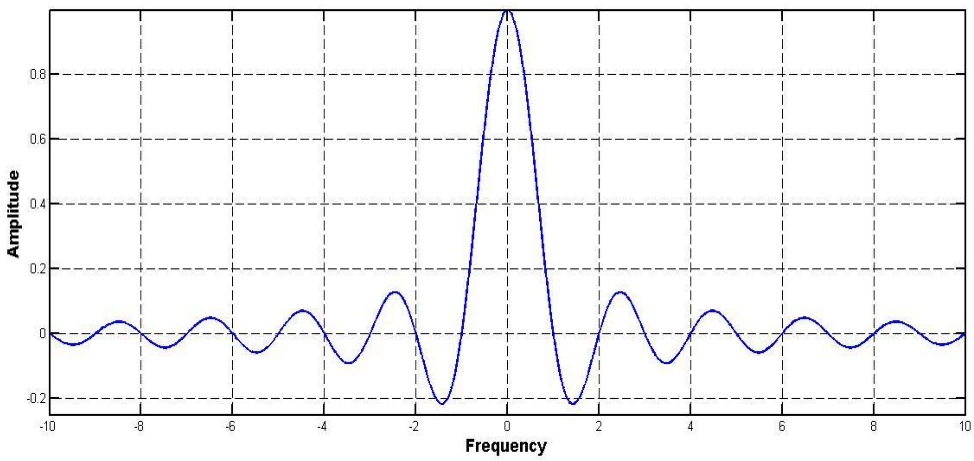

Figure 10 - QAM signal spectrum, frequency normalized to multiples of 1/T.

On the OFDM system, the spacing between subcarriers is selected so that each subcarrier is centered on the points where every other is at a zero, as we can see on Figure 11 [29].

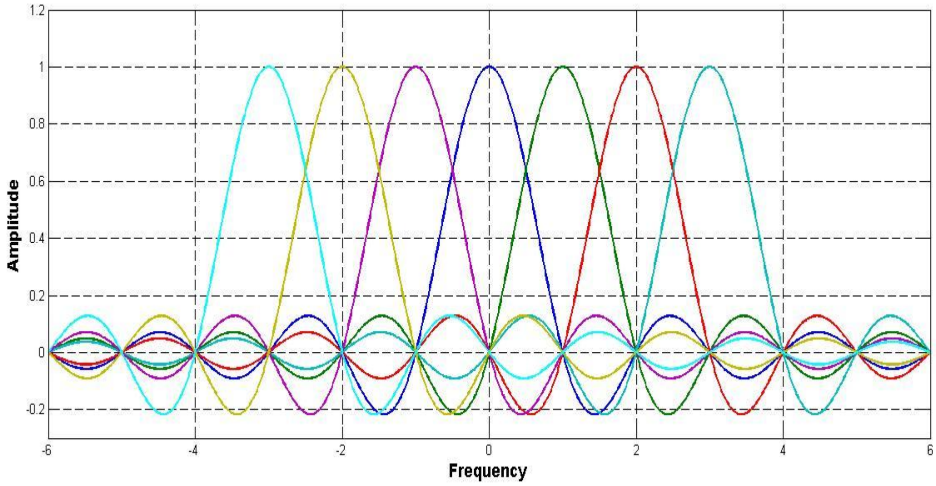

Figure 11 - QAM subcarriers of an OFDM signal, frequency normalized to multiples of 1/T.

These subcarriers indeed overlap, but since they are delayed by multiples of the symbol rate, they present the property of orthogonality that allows the recovery of the symbols contained on each subcarrier (assuming that the spacing between subcarriers is the same on reception). This overlapping of the subcarriers achieves a considerable reduction of the bandwidth used, reaching approximately 50%.

When compared to the LTE 15 ksps subcarrier symbol rate, UMTS 3.84 Msps is higher, but using the same bandwidth available for UMTS (5 MHz), LTE can transmit 300 subcarriers leading to a 4.5 Msps subcarrier symbol rate that surpasses its predecessor. On top of that, the bandwidth available for LTE can reach 20 MHz, which can assure an even bigger advantage when compared to UMTS [27] [29].

3.1.4. Cyclic prefix

The OFDM system is naturally resistant to ISI caused by multipath propagation due to its low subcarrier symbol rates, avoiding loss of orthogonality. Then, if an OFDM signal is received without being corrupted, each subcarrier can be demodulated and the correct data is recovered. On the other hand, there's a chance of partially or totally losing this orthogonality if the channel is time-dispersive, situation where the demodulator correlation interval for one path will overlap with a symbol from another path. This chance allows the existence of not only ISI, but ICI.

To prevent this from happening, a Cyclic Prefix (CP) is added on the beginning of each symbol, which consists on a copy of a portion of the end of the data symbol that works as a guard interval. At first look, some would say that it would be easier just to add zeros instead of this procedure. That solution is not available because if we use a “zero” guard band, the initial part of the OFDM symbol will not suffer the same type of interference as the remaining part, leading to a not direct appliance of the FFT algorithm. The CP increases then the size of the OFDM symbol to

$$T'_S = T_S + T_{CP}, \tag{4.2}$$

which implies a reduction of the symbol data rate.

To define the CP size, a trade-off is established between fully removing the ISI (CP must be bigger than the maximum path delay) and avoiding substantial spectral efficiency loss (due to the reduction of the transmission rate), ending up on the condition

$$T_G < \frac{T_S}{4} \tag{4.3}$$

The duration of CP is 4.69µs for the normal type and 16.67µs for extended one, and the symbol period has 66.67µs. The final size of the OFDM symbols is then 66.67µs + CP [24] [30]. An illustration of the CP addition procedure is presented below.

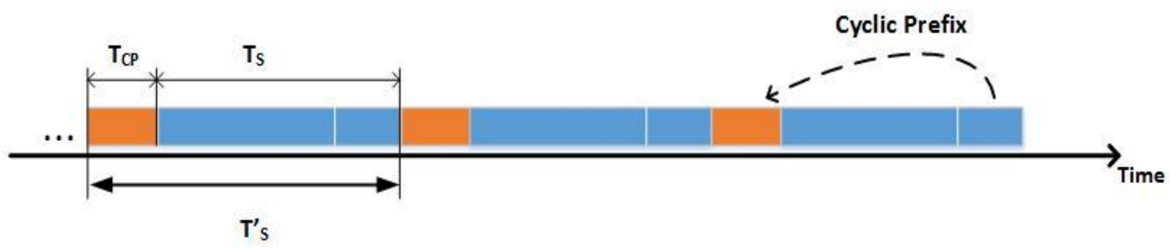

Figure 12 - Cyclic Prefix implementation.

3.2. Downlink: OFDMA

So far the OFDM system was defined and characterized, but LTE uses a multi user version of it for the downlink communication instead, the OFDMA. OFDM uses fixed allocation of the subcarriers to each user that may lead to interference and narrowband fading. To avoid this situation, OFDMA performs a dynamic allocation of the subcarriers between users through the use of components of Time Division Multiple Access (TDMA), resulting on a more robust system with increased capacity [29]. The OFDMA system depends, as the OFDM, on the use of FFT and IFFT to move the data between domains, and presents an easy implementation, high spectral efficiency, high resistance to multipath propagation and is compatible to MIMO technologies. Due to these characteristics, it was chosen not only by LTE, but also by technologies like WiMAX, WIFi, ADSL/ADSL2+ and DVB [30].

As for the implementation, the transmitter modulates the data to be sent onto one of the types supported by LTE (QPSK, QAM, 16QAM or 64QAM), then is sent to a serial to parallel converter and each output is mapped into the specific subcarrier and then goes through the IFFT block. It is important to notice that the data of each subcarrier can use different types of modulation. The next step is a parallel to serial converter, followed by the addition of the cyclic prefix, which as referred previously is done to avoid ISI and ICI, and is done using a copy of the end of the symbol at the beginning of the symbol (better than applying a break on the transmission to make the signal seem periodic and allow the use of FFT and IFFT). The size of this CP is greater than the delay spread of the environment where is applied to assure its purpose. A Digital to Analog Converter/Radio Frequency (DAC/RF) block follows, converting the signal to RF, amplifying it and getting it ready to be transmitted.

At the receiver, although threats of ISI and ICI are eliminated at the transmitter, the signal suffered the channel effects (frequency dependent phase and amplitude changes). This situation is solved through the insertion of pilot symbols on the time and frequency domains that are interpolated with a reference symbol grid. In the matters of the actual receiver, it starts with an Analog to Digital Converter/Radio Frequency (ADC/RF) block, followed by the removal of the CP, serial to parallel conversion, replacement on the frequency domain (FFT block), subcarrier de-mapping and equalization, parallel to serial conversion and finally, demodulation. The usual equalizer used is a Frequency Domain Equalizer (FDE) that uses the estimated channel frequency response (phase and amplitude changes forced by the channel) and multiplies it with each subcarrier, representing a simpler action than the one applied on W-CDMA, and does not depend on the length of the channel. A representation of the OFDMA transmitter and receiver is showed below on Figure 13.

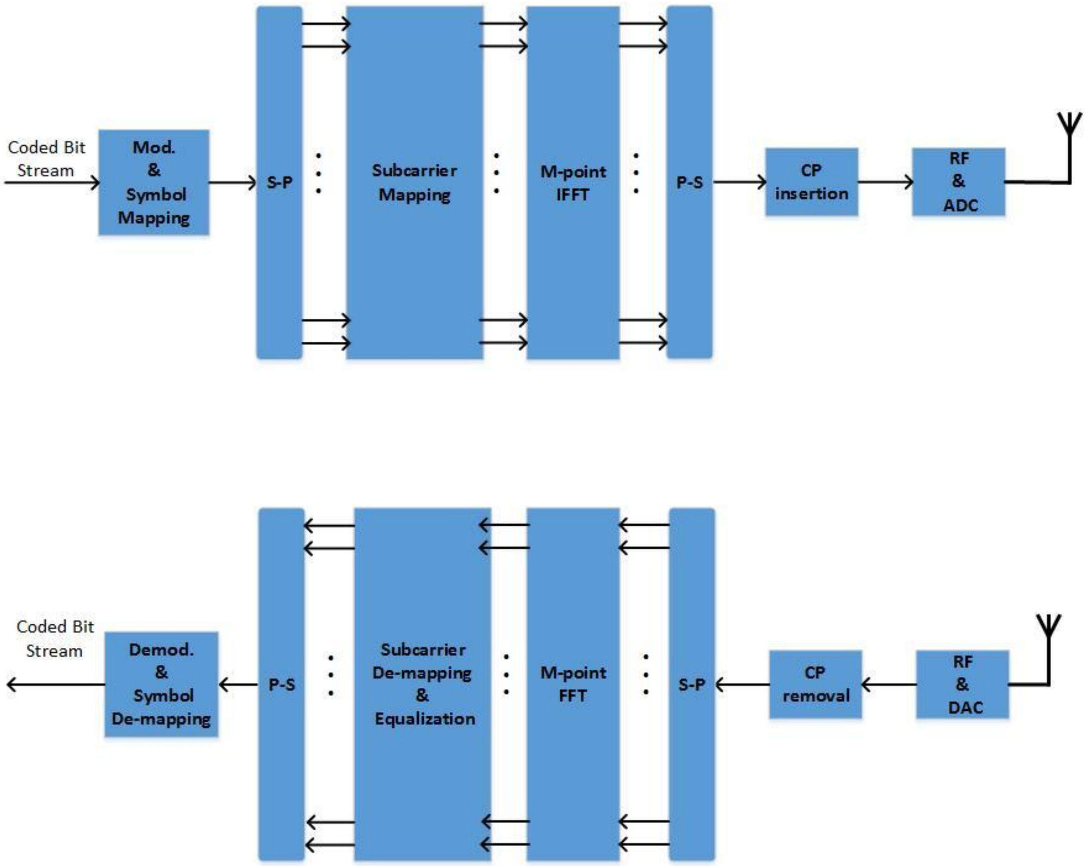

Figure 13 - OFDMA transmitter and Receiver.

The use of a cyclic prefix by OFDMA requires time and frequency synchronization in order to perform its correct removal. While time synchronization is assured through correlation between known data samples and the received data, frequency synchronization is obtained estimating the frequency offsets between each UE and the eNodeB. In this case, and since the eNodeB oscillator is more accurate, the UE locks to the frequency obtained from it.

Some interesting details of OFDMA are that the subcarrier spacing is fixed to 15 kHz no matter the bandwidth of the transmission, and that the eNodeB can allocate users to any subcarriers in the frequency bandwidth, where HSPDA could allocate in the time and code domain, but always with full bandwidth (no choice available).

If we look at the OFDMA transmission on the time domain, it consists of multiple sinusoidal waves with different frequencies with steps of 15 kHz, fact that leads to a strong variation of the signal envelope (the instant sum of the sinusoids results on a Gaussian distribution with various peak amplitudes)- high PAPR. This variation requires the use of additional back-off by the amplifier, resulting on a reduction of its power efficiency or a smaller output power [29].

3.3. Uplink: SC-FDMA

As it was mentioned on the previous section, OFDMA presents a high variation of the envelope signal that requires the use of back-off on the power amplifier. This fact raises no problems when applied to downlink since the source (eNodeB) is permanently connected to the fixed main power grid of that area, but when considered for the uplink that is not the case since the UEs are fed by batteries. Due to this fact, one of two consequences is felt: or the uplink range gets shorter, or there's a substantial increase on the power consumption of the UE battery.

It is obvious that power consumption and range are vital aspects on any uplink cellular communication, fact that led to the exclusion of OFDMA as option for LTE uplink.

SC-FDMA was then chosen for the uplink communication, due to a combination of low PAPR techniques of its single carrier system (like GSM and CDMA), and the strong points of OFDMA like multipath resistance, flexible frequency allocation, and the avoidance of the need to use guard bands between different users. Also, a cyclic prefix is periodically added, and most of OFDMA architecture is shared [6] [29]. The architecture of SC-FDMA transmitter and receiver are presented below in Figure 14, highlighting the difference when compared to OFDMA.

Beginning on the transmitter, firstly the data to be sent is modulated, and then goes through the serial-to-parallel converter. The modulated symbols are then divided into groups of *N* that are processed in an N-point DFTs (cause *N* may not be a power of 2, it is not an N-point FFT), being moved to the frequency domain. The outputs of these blocks are then mapped into *M* subcarriers (*M* is limited to 1320), and moved to the time domain again through the M-point IFFT. This block is followed by the parallel-to-serial converter, and the DAC/RF block that converts the signal to RF, amplifies it and gets it ready to be transmitted.

At the receiver, the opposite processes are performed: after the RF/ADC block, the CP is removed. Then the M-point FTT block moves the subcarriers to the frequency domain, allowing subcarrier de-mapping and frequency equalization (eg: Zero Forcing Equalizer or Minimum Mean Square Error Equalizer) to be applied for channel correction purposes. The equalized symbols are afterwards converted to time domain again through the N-point IDFT, converted to serial and then demodulated. Aside from these signal receiver elements, the receiver has also additional functionalities, such as channel estimation and Forward Error Correcting codes (FEC).

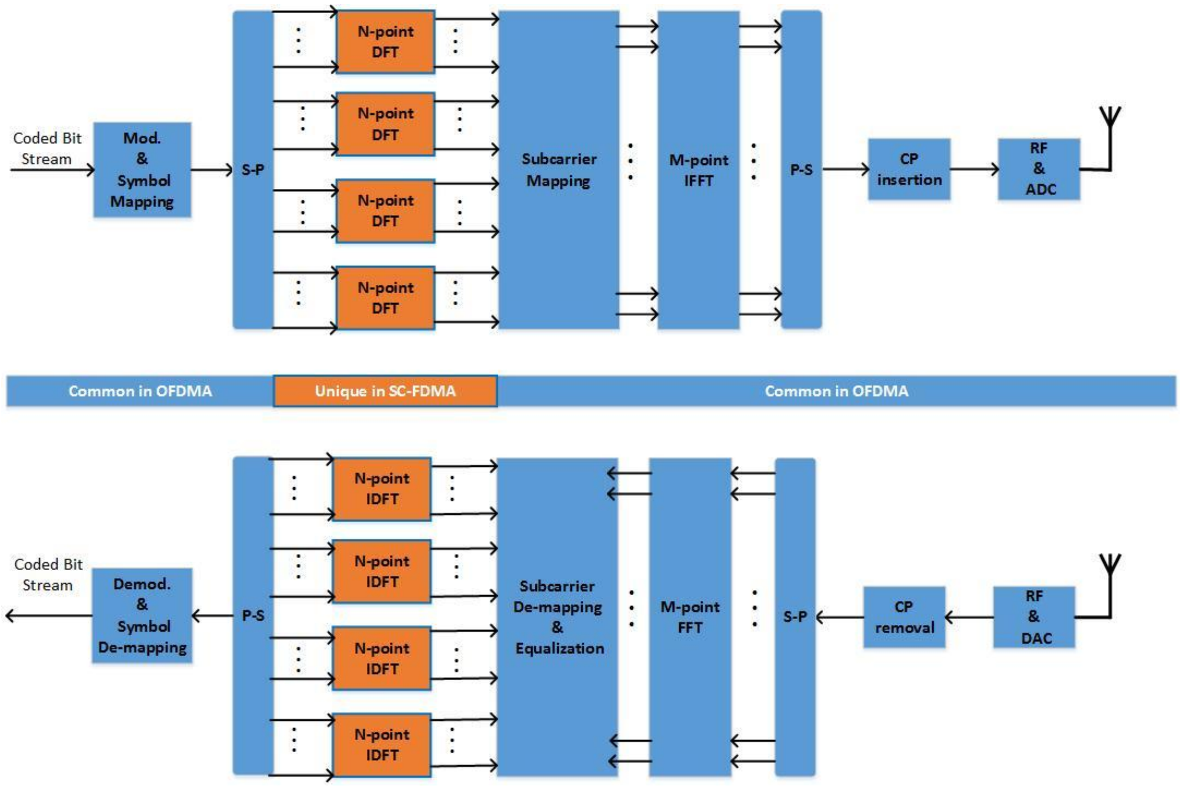

Figure 14 - SC-FDMA architecture and comparison to OFDMA.

As it is noticeable on the block diagram, the difference between both architectures is the existence, on the SC-FDMA, of the earlier move of the data to the frequency domain in groups of N symbols through the N-point DFT blocks, before the subcarrier mapping at the transmitter, and after the subcarrier de-mapping and equalization at the receiver through N-point IDFT blocks [9] [32].

In short, SC-FDMA is a multiple access scheme that fits best the needs of the uplink communication since it presents the main advantages of OFDMA, and offers a PAPR approximately 2 dB lower when compared to the OFDMA. It has still a disadvantage to the downlink solution, presenting a more complex scheme on the transmitter and receiver that although being negligible on the transmitter, become important on the receiver because of the requirement to support multiple users in parallel.

For a better understanding of the actual difference between OFDMA and SC-FDMA transmissions, an illustration is presented In Figure 15, where a sequence of data symbols mapped over QPSK modulation are to be transmitted on both multiple access techniques over 4 subcarriers. It is noticeable that on the OFDMA case, each frequency component carries a unique data symbol, while on SC-FDMA the data symbols are spread over the 4 subcarriers for a short period of time.

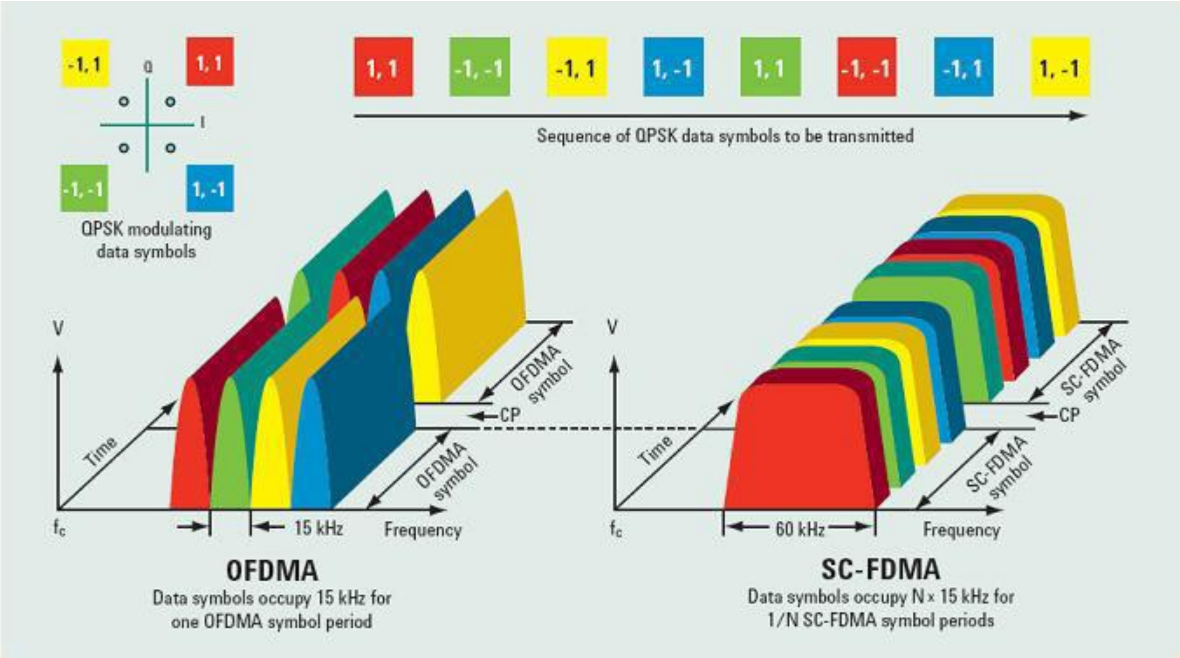

Figure 15 - OFDMA/SC-FDMA comparison: spectrum allocation for transmission [11].

To conclude, a comparison between LTE uplink and downlink is presented below on Table 1 to highlight the main similarities and differences.

Parameters	Uplink (UL)	Downlink (DL)
Peak Data Rate	50 Mbps	100 Mbps
Duplexing Mode	FDD, TDD or half duplex FDD	
Channel Bandwidth	scalable between 1.4, 3, 5, 10, 15 and 20 MHz	
Constellation Schemes	QPSK, 16QAM, 64QAM (optional)	QPSK, 16QAM, 64QAM
Multiple Access Schemes	SC-FDMA	OFDMA
MIMO Schemes	1x2, 1x4	2x2, 4x2, 4x4

Table 1 - LTE Uplink/ Downlink comparison.

3.4. Subcarrier Mapping

In both uplink and downlink communication, an operation called subcarrier mapping is done to organize the data to send on the supposed subcarriers. Although the inputs on the OFDMA and SC-FDMA schemes to this operation are differently organized (as groups of symbols from each user, or groups of symbols as outputs of the N-point DFT blocks, respectively), they both can be organized through localized or distributed mapping. On the first case, each group is mapped on a portion of the total bandwidth, in consecutive subcarriers. On the distributed option, the symbols of each group are attributed to subcarriers along the total bandwidth, leaving the ones between them with zero amplitude. There's a special option for the distributed case where the spacing between the subcarriers used is the same, named interleaved SC-FDMA [32]. On Figure 16 we can see the application of both situations.

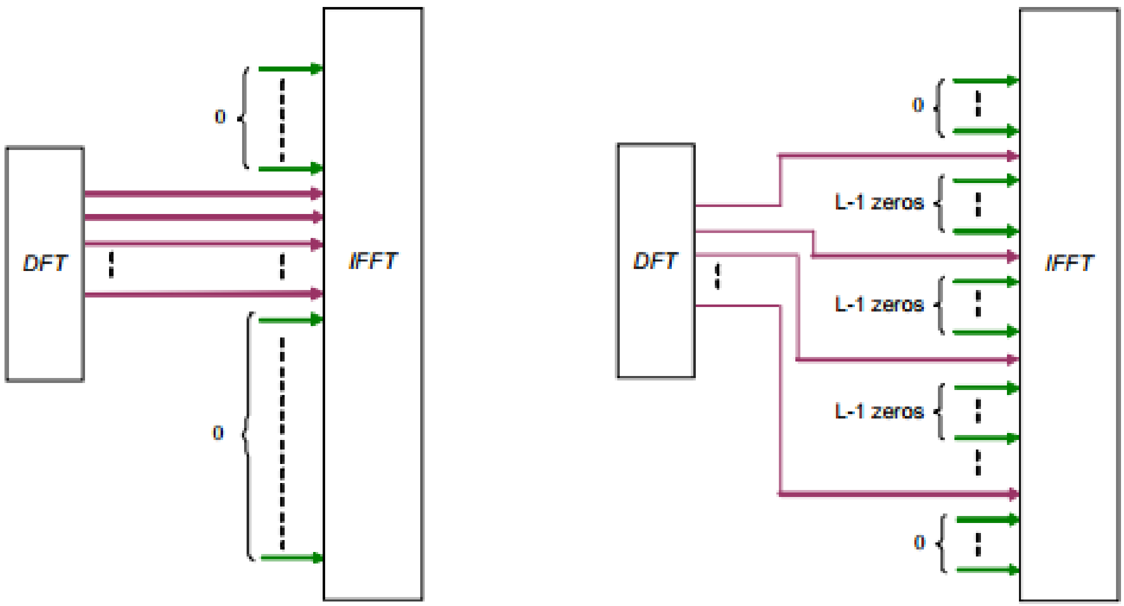

Figure 16 - Subcarrier Mapping: Localized (left) and interleaved (right) [32].

4. Multiple Antenna Diversity

As it is known, the world demands on wireless technologies have grown much over the past few years on the matters of network capacity, QoS and most importantly data rate and effective usage of the spectrum. LTE gave a big step on improving these targets by being the first mobile cellular technology to include MIMO systems as a key element.

Previous technologies were based on the traditional Single-Input Single-Output (SISO) systems taking advantage on time and frequency domains, but MIMO uses additional antennas on both ends (transmitter and receiver) to make use of the spatial domain, along with signal precoding and detection. This dimension is used through spatial multiplexing that consists on sending different data streams on different antennas, and signal processing that separates these data streams at the receiver. With these abilities, this dimension allows either an increase the data rate, or an improvement of QoS references like the Bit Error Rate (BER) through the addition of diversity, being also able to act on both fronts [20] [33].

According to the number of antennas available on the transmitter and receiver, four multiple antenna configurations can be applied. The different types are displayed in Figure 17, and each case will be resumed ahead:

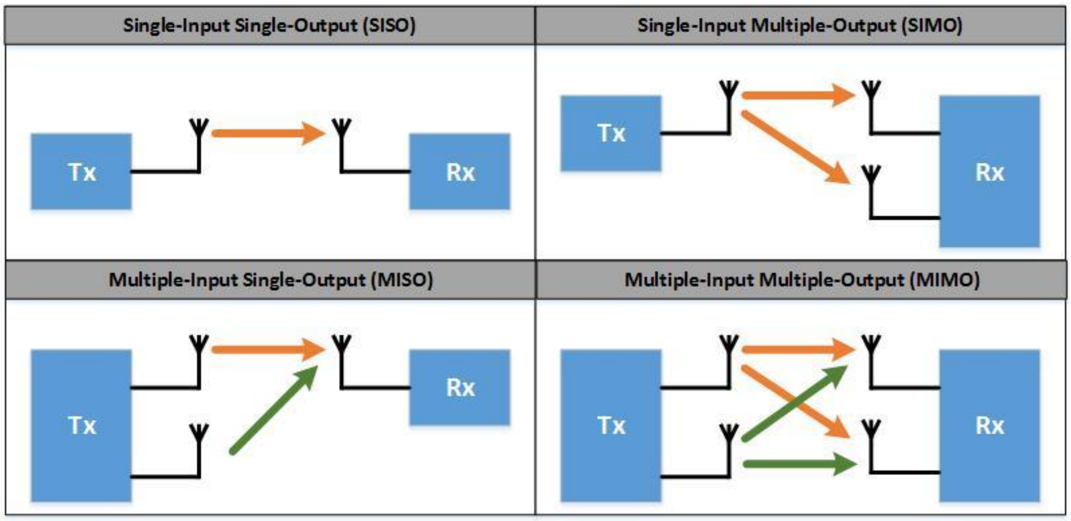

Figure 17 - Multiple Antenna configurations.

Most of these schemes attempt to use diversity that consists on sending the same information over different paths through time, frequency, space, receive and transmit diversity. On LTE, time diversity is hard to apply since very high UE speeds are required for its use on the subframes (1ms). Frequency diversity can be included by scheduling transmissions at the slot level (0.5 ms) transmitting at 2 different frequencies within a subframe.

There are also other types of diversity, like polarization diversity (signals are polarized horizontally or vertically by two transmit antennas, and received by antennas with the same polarization) where it is assured that no correlation exists between the data streams, and angle diversity where the carrier frequencies are above 10 GHz (signals sent are highly scattered in space), allowing the use of two highly directional antennas in opposite directions to obtain two copies of the same signal that are absolutely independent.

Focusing ourselves now at the antenna configurations, the SISO implementation is the one applied commonly to previous systems, and gives the baseline information on performance for improvements on other configurations.

In the SIMO case, multiple antennas at the receiver are used to achieve receive diversity that offers diversity gain and array gain, and show better performance on low Signal to Noise Ratio (SNR) conditions like cell edge or strong fading environments. The data rate is not improved, but there's a decrease of the data lost on the transmission.

On the other hand, MISO and its multiple antennas on the transmitter obtain transmit diversity through open loop techniques like space-time/frequency coding or closed loop techniques like beamforming or precoding, to achieve better performance on fading channel conditions, maintaining the default data rates like the SIMO situation.

As referred previously on this chapter, the MIMO configuration is defined by multiple antennas on both transmitter and receiver and uses spatial multiplexing, although this situation can also be only a mixing of MISO and SIMO where only one stream of data is sent [29].

The main concepts on the matters of Transmit and Receive diversity will be specified along this chapter.

4.1. Transmit Diversity

Transmit diversity is based on signal processing techniques at the receiver that take advantage on the introduction of controlled redundancies at the transmitter. This kind of diversity is possible in two ways, depending on the knowledge at the transmitter of the Channel State Information (CSI).

The most common is the one where the CSI is available at the transmitter, situation where closed loop techniques, such as beamforming and precoding, are applied. FDD obtains the CSI through feedback from the users to the base station, while TDD makes use of channel reciprocity to train on reverse link and obtain an estimate of the channel at the base-station. There are also situations where the CSI is not available at the transmitter, requiring a different treatment - open loop techniques like space time/frequency coding [34] [35] [36].

The first attempts to present an answer to the non availability of the CSI at the transmitter were made taking as test subject a MISO configuration with M_T=2 and M_R=1 over a flat fading environment, trying to send the same signal simultaneously on both antennas. Assuming h_1 and h_2 as the channels that the signals from transmit antennas 1 and 2 experience, the received signal r is given by

$$r = \sqrt{\frac{E_S}{2}}(h_1 + h_2)s + n \tag{5.1}$$

where E_s is the average energy over a symbol period at the transmitter (half of it to each antenna) and n is the additive Gaussian noise at the receiver (Zero Mean Circularly Symmetric Complex Gaussian - ZMCSCG). Since the addition of two complex Gaussian random variables is also a complex Gaussian, $\frac{1}{\sqrt{2}}(h_1 + h_2)$ is also ZMCSCG with unit variance. This means that in practice, this procedure is the same as sending the signal over the channel h=$h_1 + h_2$ resulting on

$$r = \sqrt{E_s}\, hs + n \tag{5.2}$$

fact that proves that diversity is not being applied. Later, the delay diversity scheme appeared to solve the problem of this approach by transmitting the same signal over the two antennas, but with a delay of one symbol interval between the transmissions. At this point, the receiver sees two channels with independent path fading and equal average energy, represented as

$$h[i] = h_1\delta[i] + h_2\delta[i-1], i = 0,1,2 \ldots \tag{5.3}$$

achieving then the use of diversity. Consequently, the probability of losing information decreases with the number of antennas transmitting. On the other hand, this scheme introduced interference between symbols and added an exponential growth of the detectors complexity with the increase of the transmit antennas. Other options were then searched to avoid these disadvantages, leading to the creation of Space Time Codes (STC) [34].

4.1.1. Space-Time Coding

In this form of coding (STC), the data streams are encoded jointly over the transmitter antennas to improve the link reliability by providing diversity gain, or throughput by providing multiplexing gain [37]. The STCs can be divided in two groups. The first one maximizes the spatial diversity with the objective of obtaining better power efficiency and includes Space Time/Frequency Block Codes (STBC/SFBC) and Space Time Trellis Code (STTC), while the second increases the capacity using a layered approach, like the Layered Space Time Codes (LSTC).

STBC are codes created to assure orthogonal characteristics between the signals sent, obtaining then full diversity gain with simple decoding. These abilities are the ones most desired for the situation of CSI not available at the transmitter, reason why this technique is the one to be commonly used. SFBC is nothing more than an STBC, but with time reinterpreted as frequency. The choice between STBC and SFBC relies on the selectivity of both time and frequency domains. Basically, STBC is used if the channel varies slowly in the time domain when the UE moves slowly, no matter the delay spread of the channel. On the opposite situation, SFBC is applied if the channel varies slowly on the frequency domain when the delay spread of the channel is small, no matter the UE movement speed [38]. An example of an STBC will be presented on section 4.1.2, the Alamouti coding.

As it was mentioned above, STBC offers maximum diversity using low complexity decoding, but no coding gain. STTC appeared then as a coding scheme that offers both diversity and coding gain, together with error control and ability to face the fading effects. The disadvantage of this scheme is that the decoding complexity increases with the code length and modulation constellations.

Both STBC and STTC are used to achieve diversity gain, but there are cases where the objective is to achieve multiplexing gain instead (like on LTE MIMO schemes). Foschini proposed then to exploit the delay spreads existing in a wideband channel, looking at them as independent highways on the channel between the antennas on both ends. LSTC were based on this idea, resulting on the creation of a new class of Space Time Codes designed to improve the multiplexing gain through the transmission of different information on each antenna [34].

4.1.2. Alamouti Coding

The Alamouti scheme was the first STBC/SFBC to be presented, and it is still a valuable asset since it was chosen to be applied on LTE [38]. This is a very simple scheme that has no bandwidth expansion (code rate=1 → ratio between number of symbols transmitted on each antenna and the number of symbols that enter the encoder) since 2 symbols are transmitted every 2 time intervals, and creates orthogonal codes from 2 transmit antennas to Mr receive antennas, achieving a maximum diversity of 2Mr [39]. Also, the need to redesign existing systems to incorporate this diversity scheme does not exist. As an STBC/SFBC, no CSI is required from the receiver to the transmitter to achieve full diversity and no coding gain is provided.

This form of coding is pretty much simple and works based on the code matrix

$$\mathbf{S} = \begin{bmatrix} S_n & -S_{n+1}^* \\ S_{n+1} & S_n^* \end{bmatrix} \tag{5.4}$$

where S_n and S_{n+1} are two modulated symbols to transmit, (.)* represents the hermitian operation, the first and second columns represent the first and second transmission periods/frequencies and the first and second rows represent the symbols to be sent on each transmitter antenna (these rows are orthogonal to each other). Taking this into account, an example of the Alamouti transmitter-receiver communication for a MISO scheme is presented on Figure 18 to better understand the application of the code matrix.

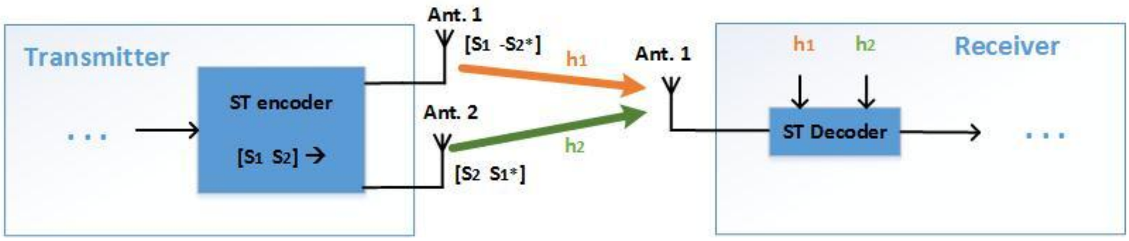

Figure 18 - Alamouti MISO 2x1 scheme.

With the application of the coding, the received signal is given by

$$\begin{cases} y_n = \dfrac{1}{\sqrt{2}} h_{1,n} s_n + \dfrac{1}{\sqrt{2}} h_{2,n} s_{n+1} + n_n \\ y_{n+1} = -\dfrac{1}{\sqrt{2}} h_{1,n+1}\, s_{n+1}^* + \dfrac{1}{\sqrt{2}} h_{2,n+1} s_n^* + n_{n+1} \end{cases} \tag{5.5}$$

where $\frac{1}{\sqrt{2}}$ performs power normalization, the channels from the transmitter antennas on both moments/ frequencies are represented as $h_{1,n}$, $h_{1,n+1}$, $h_{2,n}$ and $h_{2,n+1}$, and the noise at the receiver on the two moments/frequencies are n_n and n_{n+1}. The Alamouti decoding scheme is

$$\begin{cases} \hat{s}_n = \dfrac{1}{\sqrt{2}} h_{1,n+1}^* y_n + \dfrac{1}{\sqrt{2}} h_{2,n} y_{n+1}^* \\ \hat{s}_{n+1} = \dfrac{1}{\sqrt{2}} h_{2,n+1}^* y_n - \dfrac{1}{\sqrt{2}} h_{1,n} y_{n+1}^* \end{cases} \tag{5.6}$$

Replacing (5.5) on (5.6), the soft estimate for both symbols is

$$\begin{cases} \hat{s}_{n=\frac{1}{2}} \left(h_{1,n+1}^* h_{1,n} + h_{2,n} h_{2,n+1}^* \right) s_n + \dfrac{1}{\sqrt{2}} h_{1,n+1}^* n_n + \dfrac{1}{\sqrt{2}} h_{2,n} n_{n+1}^* \\ \hat{s}_{n+1=\frac{1}{2}} \left(h_{2,n+1}^* h_{2,n} + h_{1,n} h_{1,n+1}^* \right) s_{n+1} + \dfrac{1}{\sqrt{2}} h_{2,n+1}^* n_n - \dfrac{1}{\sqrt{2}} h_{1,n} n_{n+1}^* \end{cases} \tag{5.7}$$

where the interference of the second symbol on the estimation of the first and the one of the first symbol on the estimation of the second cease to exist. Furthermore, channels between two adjacent frequencies or moments are highly correlated, allowing the assumption that the channel from each antenna is kept the same on both moments/frequencies ($h_{1,n} = h_{1,n+1};\ h_{2,n} = h_{2,n+1}$), obtaining

$$\begin{cases} \hat{s}_{n=\frac{1}{2}}\left(\left|h_{1,n}\right|^2 + \left|h_{2,n}\right|^2\right)s_n + \frac{1}{\sqrt{2}}h_{1,n+1}^* n_n + \frac{1}{\sqrt{2}}h_{2,n}n_{n+1}^* \\ \hat{s}_{n+1=\frac{1}{2}}\left(\left|h_{2,n}\right|^2 + \left|h_{1,n}\right|^2\right)s_{n+1} + \frac{1}{\sqrt{2}}h_{2,n+1}^* n_n - \frac{1}{\sqrt{2}}h_{1,n}n_{n+1}^* \end{cases} \tag{5.8}$$

Only the target symbol and the noise of both antennas remain (to be handled after), proving that the Alamouti coding creates indeed orthogonal codes for both antennas.

The limitation of the Alamouti coding is that only 2 antennas can be used on the transmitter to obtain orthogonal codes for both. Solutions for this situation are offered through Quasi-Orthogonal Block codes or Tarockh codes trough bandwidth expansion (code rate < 1) [23].

4.2. Receive Diversity

As the name states, the receive diversity consists on applying diversity schemes to improve the signal quality through diversity gain and array gain.

The diversity gain emerged as a solution for the effect of multipath fading, which consists of the fluctuation of the signal strength experienced on the transmissions, leading to high BERs. The diversity gain mitigates this phenomenon by transmitting or receiving (reception on this case) the signal over various antennas, aiming for the decorrelation of the fading on each antenna. This diversity is commonly measured as the number of effective diversity branches, called “order”.

Array gain comes from the fact that the noise terms of the transmitted signals received on each receiving antenna are uncorrelated. This allows the receiver to combine the data received on several antennas with different weights to enhance the signal as much as possible (increase of the average SNR) [20] [34].

There are many diversity combining techniques that explore these two characteristics, like the ones referred below [41] [41]:

- **Maximal Ratio Combining (MRC) -** also known as Matched Filter (MF), obtains the maximum output SNR by co-phasing all the receiving branches and summing them with optimal weighting, giving bigger influence on the outcome to the branches that have higher received power.
- **Equal Gain Combining (EGC) -** it's a reduced complexity version of MRC where equal weight is attributed to every branch, performing only phase rotation and then combining them. Lower array gain is obtained since the channel amplitudes are ignored, but the same diversity gain as MRC is offered, achieving similar performance to MRC.
- **Selection Combining (SC) -** this technique is cheap and simple, and differs from MRC and EGC because it uses only one branch for the output. Basically the receiver chooses the branch that presents higher instantaneous SNR and uses it for detection. It obtains the same diversity gain as MRC and EGC, but much lower array gain leading to a lower performance than these two.
- **Scanning Combining -** each antenna is scanned till the moment a signal that exceeds a predefined threshold is found, and if the signal falls below this threshold afterwards, new scanning is done. This approach uses only one receiver since only one signal is used at a time, but still uses multiples antennas.

There is also another solution for this situation that converts the problem of a joint decoder into single decoding of the data streams called linear sub-optimal receiver equalizers. Some examples of this kind of architecture are listed below [41] [42]:

- **Zero Forcing (ZF) Equalizer -** applies the inverse of the channel frequency response to the received signal. This algorithm eliminates completely the ICI on noiseless channels, but in practical situations (where noise exists commonly) it doesn't work so well since the inverse of the channel is applied to the received signal, amplifying also the experienced noise at the receiver.

- **Minimum Mean Squared Error (MMSE) equalizer -** consists on an algorithm that works better on noisy conditions than ZF, substantially reducing the mean square error between the transmitted symbol and the estimation of the same symbol at the receiver. Although the ICI is not totally mitigated, the noise power at the receiver is considerably reduced.
- **Successive Interference Cancellation (SIC) -** as the name states, it's an interference cancellation technique that uses banks of MMSE or ZF equalizers to decode the received data streams sequentially. Basically, once the signal is equalized and the first estimated symbol is decoded, this information is subtracted to the signal before the equalization and decoding of the second symbol, reducing the amount of symbols that are seen at that receiver as interference (every other than the one been targeted for estimation). This strategy is applied continuously until the last equalization, where only one symbol remains. The problem of this strategy is that if an error occurs on the decoding of one symbol, the subtraction on the received signal to decode the next symbol will not have "zero" interference from the previous one, and this error will propagate through every following symbol. Cancelling the symbols according to its average power (from the strongest to the weakest) is the most reliable way to use this technique. An illustration of the SIC application is presented following on the Figure 19.

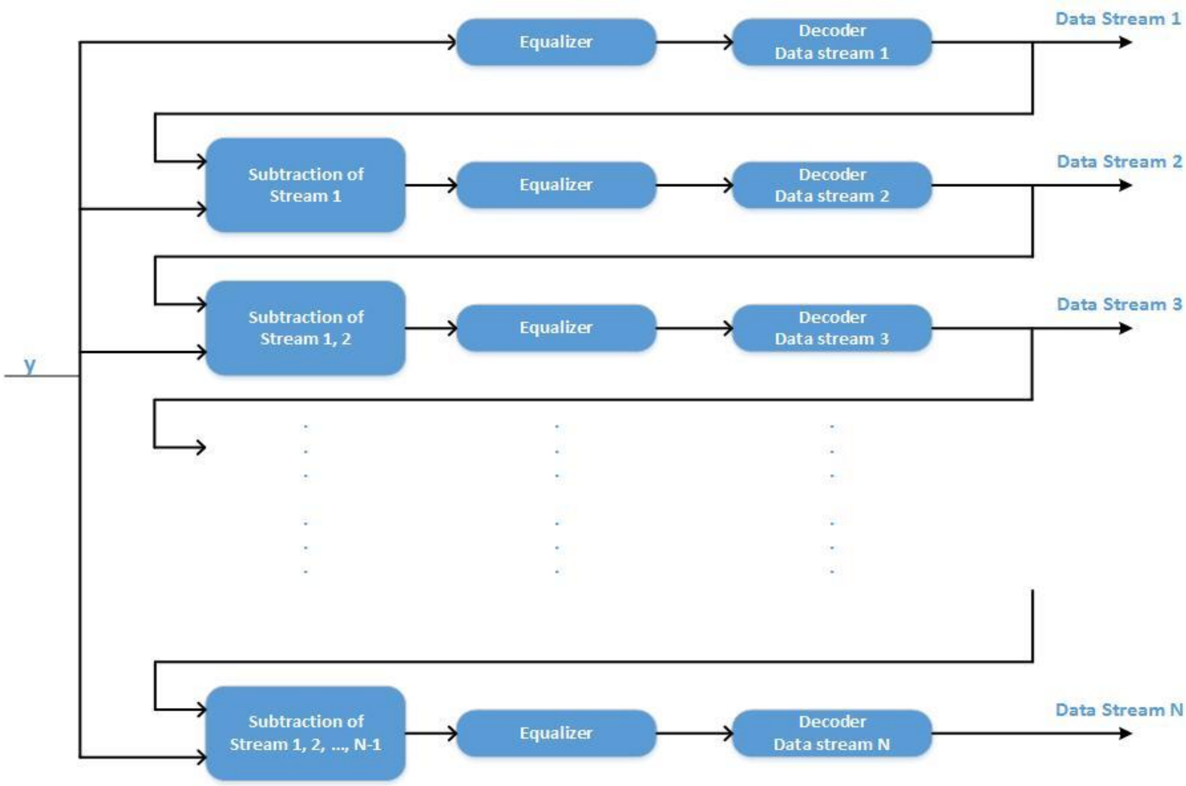

Figure 19 - Successive Interference Cancellation configuration.

5. Iterative Frequency-Domain Equalizers for LTE

Although conventional linear equalizers like ZF and MMSE have been considered in wireless systems, there are better solutions that can improve LTE performance over frequency-selective radio channels at the cost of a small complexity increase, like the Frequency Domain Equalizers (FDEs). These equalizers were first designed in time domain (TD-FDE), and consist on the use of both a feedforward and a feedback filter that partially mitigate the ICI. The complexity of these schemes comes from the design of these two filters and from the signal processing. The complexity issue, although small, was an obstacle to the success of these schemes, reason why a series of attempts were made to solve it.

The first one was the application of a block base to this technique, followed by the creation of a hybrid structure where the feedforward filter would work on the frequency domain through a block DFT acting on groups on receiving signals, but neither one actually solved it. Only after that was proposed a FDE named Iterative Block-Decision Feedback Equalizer (IB-DFE) where both filters were implemented on the frequency domain [43].

The support of MIMO systems in LTE allows the visualization of the uplink communication as a *virtual* multi-user MIMO scheme where single antenna UEs communicate with a multi antenna Base Station (the single antenna UEs are processed jointly at the multi-antenna BS, reason why the MIMO scheme is sometimes referred as *virtual*). The cell maximum data rate can be increased by allocating some UEs to the same frequencies, i.e., sharing the same physical channel. These MIMO multi-user scenarios are supported by the LTE standard for the uplink communication. In this case, the information sent from several users, affected by different channel conditions, requires separation through efficient equalization at the receiver.

For the SC-FDMA multiple access scheme, multiuser linear equalizers are not efficient to remove the ICI and MAI. Thus, in this thesis we extent the IB-DFE based equalizers designed for single carrier modulations like SC-FDMA to efficiently mitigate both ICI and MAI, while allowing a close-to-optimum space-diversity diversity gain with only a few iterations. Two IB-DFE schemes are implemented using both PIC and SIC based processing.

Notation: Throughout this chapter, we will use the following notations. Lowercase letters, uppercase letters, are used for scalars in time, scalars in frequency, and boldface uppercase letters are used for both vectors and matrices. The index (*n*) is used in time while the index (*k*) is for frequency. $(.)^H$, $(.)^T$ and $(.)^*$ represents the complex conjugate transpose, transpose, and complex conjugate operators, $\mathrm{E}[.]$ represents the expectation operator, $\mathbf{I}_N$ is the identity matrix of size $N \times N$ vector and $\mathbf{e}_p$ is an appropriate column vector with 0 in all positions except the *k*th position that is 1.

5.1. System Characterization

As referred before, the scenario in question here is a MIMO system established between several single antenna UEs {*p*= 1, 2, …, *P*} sharing the same frequency resources, and a BS with R receiving antennas, as shown in Figure 20. Each UE sends data blocks, called symbols, with equal size {$s_{k,p}$:*k*= 0, 1, …, *N*-1} mapped using QPSK or 16-QAM modulation. Each block sent, after being processed by a DFT operation, is represented by {$S_{k,p}$:*k*= 0, 1, …, *N*-1}, where *k* represents each subcarrier.

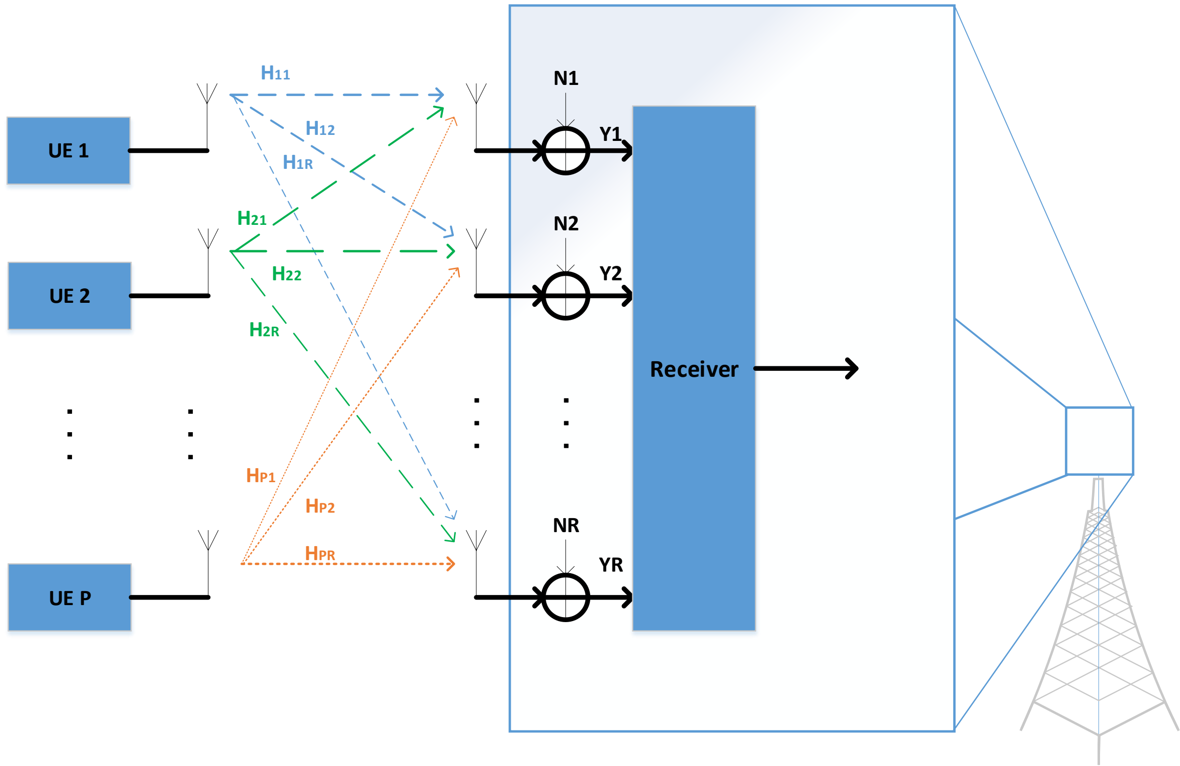

Figure 20 - System Characterization.

Then a conventional OFDM modulation (IFFT operation) is performed and the CP is inserted, as shown in Figure 21.

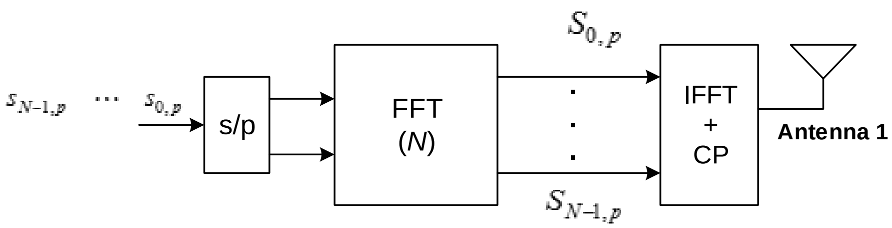

Figure 21 - SC-FDMA transmitter for a generic user *p*.

The signal received on each BS antenna, according to the correct action of the CP, is given by

$$Y_k^{(r)} = \sum_{p=1}^{P} S_{k,p} H_{k,p}^{eq(r)} + N_k^{(r)} \tag{6.1}$$

where $H_{k,p}^{eq(r)} = \sqrt{\beta_p H_{k,p}^{(r)}}$ represents the overall channel frequency response between the *p*th UE and the *r*th antenna of the BS at the *k*th subcarrier and β_p is the long-term channel power gain between the user *p* and the BS. Using the notation of Figure 21, the equation 6.1 can be written, considering the matrix notation, as

$$\mathbf{Y}_k = \mathbf{H}_k^T \mathbf{S}_k + \mathbf{N}_k \tag{6.2}$$

The signals to be send, received and the noise on equation 6.2 can be organised as the column vectors:

$$\mathbf{Y}_k = \begin{bmatrix} Y_k^{(1)} \\ Y_k^{(2)} \\ \cdot \\ \cdot \\ \cdot \\ Y_k^{(R)} \end{bmatrix}, \tag{6.3}$$

$$\mathbf{S}_k = \begin{bmatrix} S_k^{(1)} \\ S_k^{(2)} \\ \cdot \\ \cdot \\ \cdot \\ S_k^{(P)} \end{bmatrix}, \tag{6.4}$$

$$\mathbf{N}_k = \begin{bmatrix} N_k^{(1)} \\ N_k^{(2)} \\ \cdot \\ \cdot \\ \cdot \\ N_k^{(R)} \end{bmatrix}, \tag{6.5}$$

and $\mathbf{H}_\mathrm{k}$ is a matrix with dimensions *P*x*R* that contains the channel frequency response between each antenna at the receiver and each UE, being represented as

$$\mathbf{H}_k = \begin{bmatrix} H_{k,1}^{eq(1)} & \cdots & H_{k,1}^{eq(R)} \\ \vdots & \ddots & \vdots \\ H_{k,P}^{eq(1)} & \cdots & H_{k,P}^{eq(R)} \end{bmatrix}. \tag{6.6}$$

5.2. IB-DFE based Equalizers

In this section we present the two IB-DFE approaches implemented: PIC and SIC based processing. As shown in

Figure 22, this receiver consists of a feedforward and feedback equalizer coefficients both designed in frequency domain. The feedback filter $\{B_{k,p}^{p'}: p' = 0, 1, \dots, P\}$ tries to remove the ICI and the interference, and the feedforward filter $\{F_{k,p}: k = 0, 1, \dots, N-1\}$ completes the task of the feedback filter in case of its failure due to decision errors on previous decision steps. The estimate of the transmitted block from the pth user $\{\hat{s}_{n,p}: n = 0, 1, \dots, N-1\}$ is obtained through a translation of the symbols received for the time domain after the IDFT $\{\tilde{s}_{n,p}: n = 0, 1, \dots, N-1\}$, followed by a hard decision device.

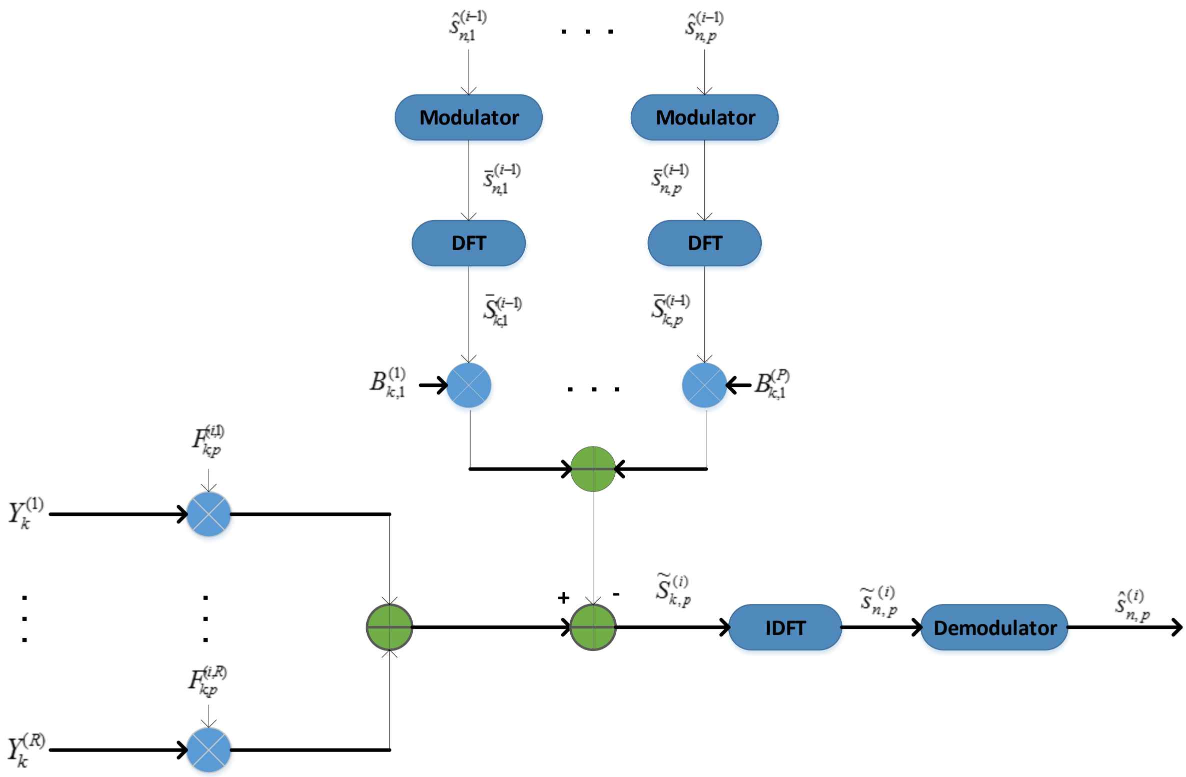

Figure 22 - IB-DFE structure for each user.

5.3.1. PIC Approach

In this topology, for each iteration we detect all P users on kth subcarrier, in a parallel way as shown in Figure 23, using updated estimates of the transmit data symbols to cancel the interferences. Thus, our receiver can be regarded as an iterative PIC base processing. However, as with conventional IB-DFE based receivers, we take into account the reliability of the block data estimates for each detection procedure.

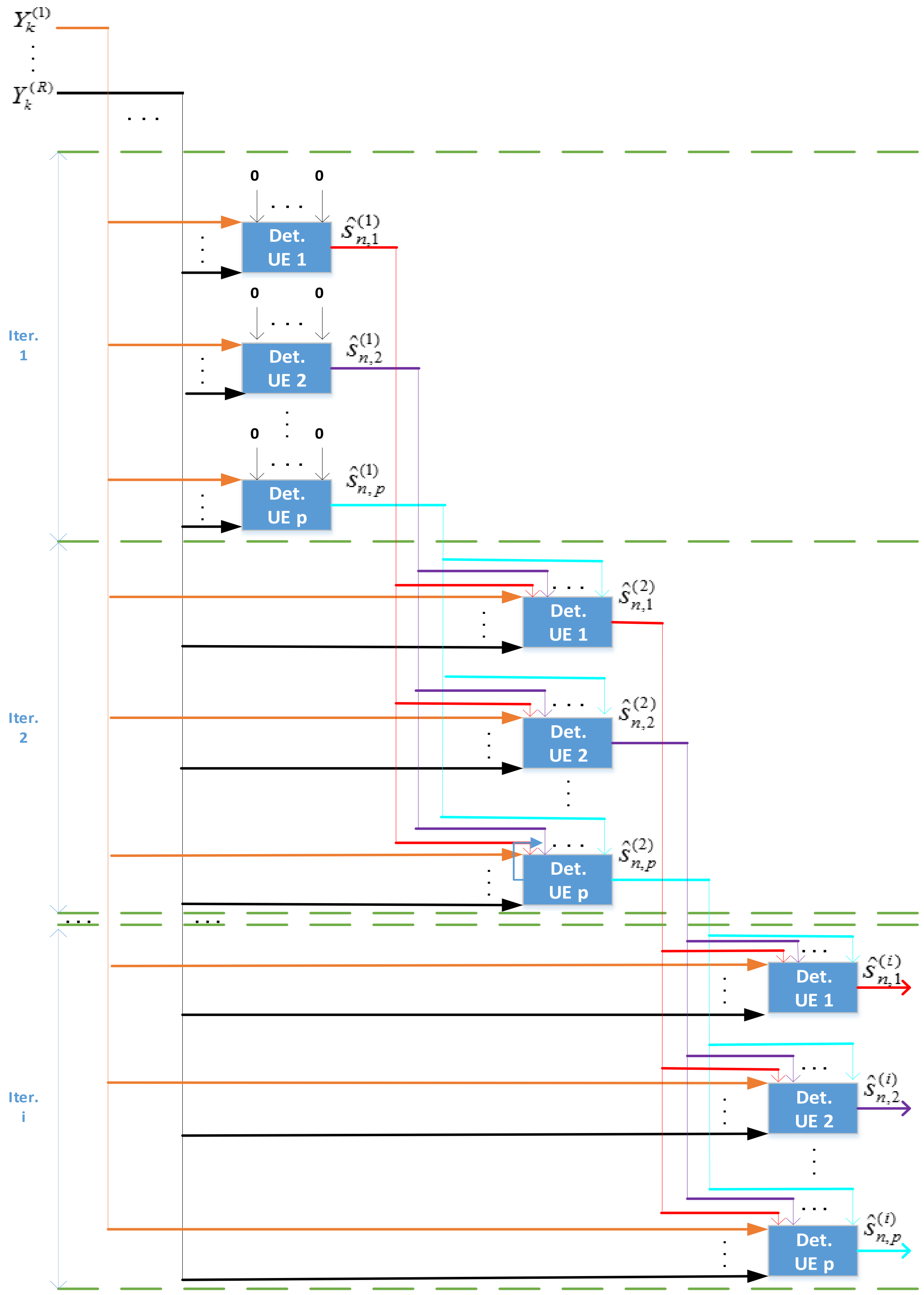

Figure 23 - PIC IB-DFE receiver topology.

From Figure 22 and 22, it is understandable that the samples $\tilde{\mathbf{S}}_k$ for the *i*th iteration are obtained as

$$\tilde{\mathbf{S}}_k^{(i)} = \mathbf{F}_k^{(i)T}\mathbf{Y}_k - \mathbf{B}_k^{(i)T}\bar{\mathbf{S}}_k^{(i-1)} \tag{6.7}$$

where $\bar{\mathbf{S}}_k$ is the vector of the soft decisions of S_k from the previous iteration, $\mathbf{F}_k^{(i)}$ is a matrix of dimensions *R*x*P* that contains the forwarding coefficients, and $\mathbf{B}_k^{(i)}$ which is a matrix of dimensions *P*x*P*. Both matrixes are presented below:

$$\mathbf{F}_k^{(i)} = \begin{bmatrix} F_{k,1}^{(i,1)} & \cdots & F_{k,p}^{(i,1)} \\ \vdots & \ddots & \vdots \\ F_{k,1}^{(i,R)} & \cdots & F_{k,p}^{(i,R)} \end{bmatrix}, \tag{6.8}$$

$$\mathbf{B}_k^{(i)} = \begin{bmatrix} B_{k,1}^{(i,1)} & \cdots & B_{k,p}^{(i,1)} \\ \vdots & \ddots & \vdots \\ B_{k,1}^{(i,P)} & \cdots & B_{k,p}^{(i,P)} \end{bmatrix}. \tag{6.9}$$

Decision errors can still occur, obtaining an $\bar{s}_{n,p}$ that may not correspond to $s_{n,p}$, leading to $\bar{S}_{k,p} \neq S_{k,p}$. To simplify the receiver coefficients computation, it is assumed that [44]

$$\bar{\mathbf{S}}_k^{(i-1)} \approx \mathbf{P}^{(i-1)}\mathbf{S}_k + \Delta_k = diag(\rho_1, \rho_2, \dots, \rho_p)\mathbf{S}_k + \Delta_k \tag{6.10}$$

where $\mathbf{P}^{(i-1)}$ is the feedback noise, Δ_k is a mean zero error vector uncorrelated with $\mathbf{P}^{(i-1)}$, and ρ_p is the correlation coefficient of the pth user, given by

$$\rho_p = \frac{E[\bar{s}_{n,p}s_{n,p}^*]}{E[|s_{n,p}|^2]} = \frac{E[\bar{\bar{S}}_{k,p}S_{k,p}^*]}{E[|S_{k,p}|^2]} \ , \tag{6.11}$$

which represents a measure of reliability of the estimates associated to the *i*th iteration and can be estimated as described on [44].

The feedforward and feedback matrices are computed by minimizing the Mean Square Error (MSE) between $\mathbf{S}_k$ and $\tilde{\mathbf{S}}_k^{(i)}$, the optimization problem can be formulated as,

$$\Im_{MSE} = \mathrm{E}\left\{\left\|\tilde{\mathbf{S}}_k^{(i)} - \mathbf{S}_k\right\|^2\right\} \text{ s.t } \frac{1}{N}\sum_{K=0}^{N-1}\sum_{r=1}^{R} F_{k,p}^{(r,i)} H_{k,p}^{eq(r)} = 1 \forall p \tag{6.12}$$

By employing the Lagrange multiplier's method, and after some straightforward but lengthy mathematical manipulations, we obtain the solution for both the feedforward and feedback matrices (specified by LTE), given by

$$\mathbf{F}_k^{(i)} = [\mathbf{H}_k^H(\mathbf{I}_p - \mathbf{P}^{(i-1)^2})\mathbf{H}_k + \sigma^2\mathbf{I}_R]^{-1}\mathbf{H}_k^H\mathbf{Q}\,, \tag{6.13}$$

$$\mathbf{B}_k^{(i)} = \mathbf{H}_k\mathbf{F}_k^{(i)} - \mathbf{I}_p\,, \tag{6.14}$$

where $\mathbf{H}_k^H$ is the transposed of the frequency response matrix, $\mathbf{I}_p$ represents a eye matrix, σ^2 is the noise variance and $\mathbf{Q} = diag(Q_1, \dots, Q_p)$ is a diagonal normalization matrix of dimensions *P*x*P* that ensures the following condition:

$$\frac{Q_p}{N}\sum_{k=0}^{N-1}\sum_{r=1}^{R} F_{k,p}^{(r,i)} H_{k,p}^{eq(r)} = 1 \tag{6.15}$$

Applying the equations (6.2) and (6.10) on (6.7), it is obtained

$$\tilde{\mathbf{S}}_k^{(i)} = \mathbf{F}_k^{(i)T}\mathbf{H}_k^T\mathbf{S}_k - \mathbf{B}_k^{(i)T}\mathbf{P}^{(i-1)}\mathbf{S}_k - \mathbf{B}_k^{(i)T}\Delta_k + \mathbf{F}_k^{(i)T}\mathbf{N}_k \tag{6.16}$$

and replacing (6.14) on (6.16) we end up with

$$\tilde{\mathbf{S}}_k^{(i)} = \mathbf{I}_p\mathbf{S}_k + \left(\mathbf{F}_k^{(i)T}\mathbf{H}_k^T - \mathbf{I}_p - \left(\mathbf{F}_k^{(i)T}\mathbf{H}_k^T - \mathbf{I}_p\right)\mathbf{P}^{(i-1)}\right)\mathbf{S}_k - \left(\mathbf{F}_k^{(i)T}\mathbf{H}_k^T - \mathbf{I}_p\right)\Delta_k + \mathbf{F}_k^{(i)T}\mathbf{N}_k \tag{6.17}$$

which consists of the sum of the DS and ICI+MAI, subtracting then the feedback noise, and finally adding the channel noise, respectively. It is important to highlight that on the first iteration, since there are no estimated symbols, $\mathbf{B}_k = 0$ and $\mathbf{P}_k = 0$, reducing the system to a multi user MMSE FDE, and that with the increase of the iterations, the matrix $\mathbf{P}^{(i-1)}$ tends to an identity matrix, converting the interference member of the last equation (ICI+MAI) into zero.

5.3.2. SIC Approach

Contrary to the PIC approach, in this approach each UE's received signals are detected separated. For each iteration, the UEs are detected in a successive way, as shown in Figure 24, using the most updated estimates of the transmitted data symbols associated to each UE to cancel the corresponding residual interference. Thus, this receiver can be regarded as an iterative SIC scheme. However, as with conventional IB-DFE based receivers, it is taken into account the reliability of the block data estimates associated to UEs for each detection and interference cancellation procedure.

From Figure 24, it is understandable that the samples $\tilde{S}_{k,p}$ of the *p*th users and of the *i*th iteration are obtained as

$$\tilde{S}_{k,p}^{(i)} = \sum_{r=1}^{R} F_k^{(i,r)} Y_k^{(r)} - \sum_{p=1}^{P} B_k^{(i,p)} \bar{S}_{k,p}^{(i-1)} \quad (6.18)$$

Similar to the PIC approach, the feedforward and feedback equalizer coficientes are computed by minimizing the mean square error (MSE) between $S_{k,p}$ and $\tilde{S}_{k,p}^{(i)}$ for each user, now given by

$$\mathbf{F}_{k,p}^{(i)} = \mathbf{Q}_p [\mathbf{H}_k^H (\mathbf{I}_p - \mathbf{P}^{(i-1)^2}) \mathbf{H}_k + \sigma^2 \mathbf{I}_R]^{-1} \mathbf{H}_k^H \mathbf{\Gamma}_p \quad (6.19)$$

$$\mathbf{B}_{k,p}^{(i)} = \mathbf{H}_k \mathbf{F}_{k,p}^{(i)} - \mathbf{\Gamma}_p \quad (6.20)$$

Where $\mathbf{\Gamma}_p$ is a column vector with 0 in all positions except the *p*th position that is 1. Basically these vectors are used to select the equalizer vectors of the *p*th user.

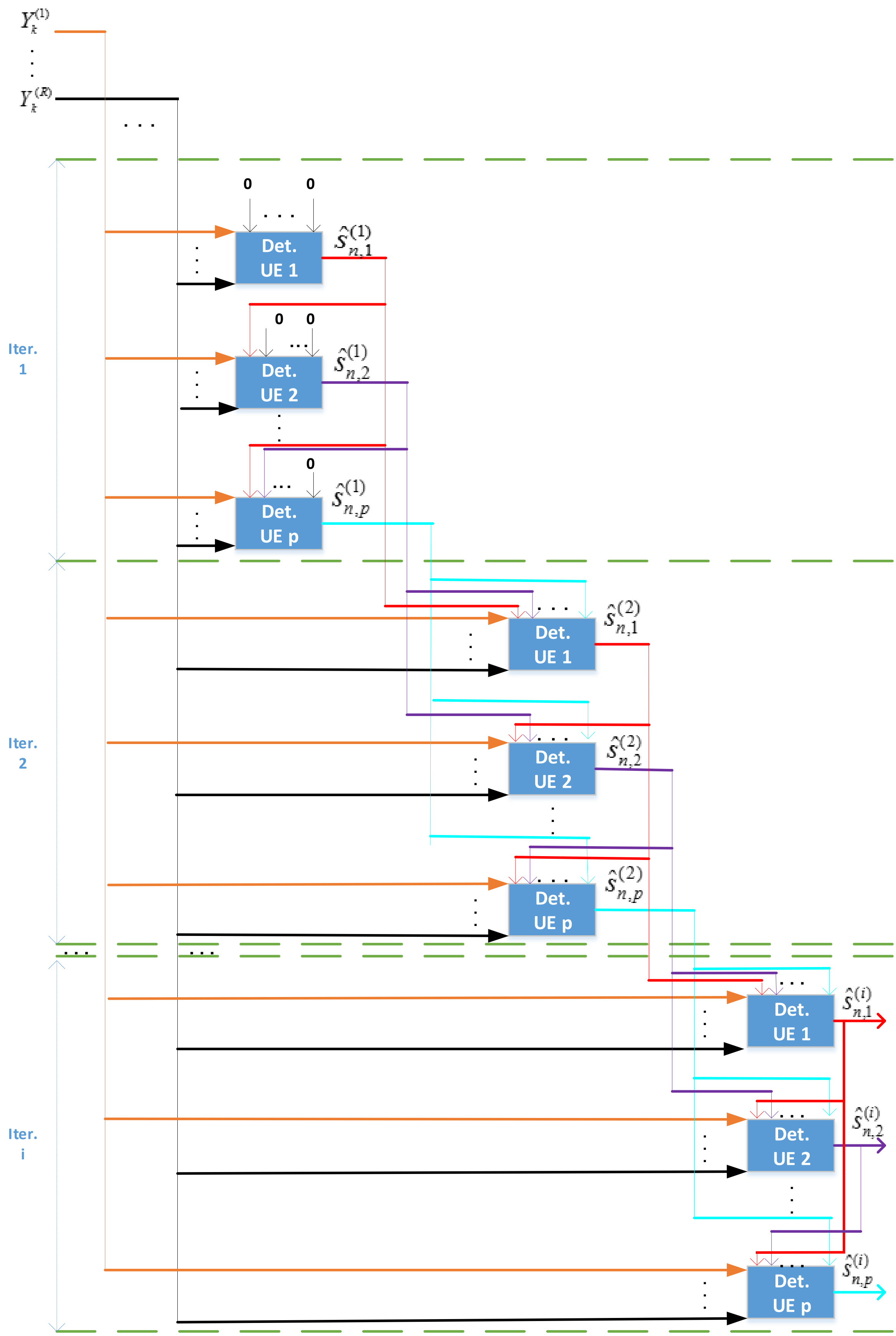

Figure 24 - SIC IB-DFE receiver topology.

5.4. Simulation Platform

The simulation platform was implemented so that the set of parameters presented on Table 2 can be controlled as wished to apply several different sets of conditions.

Parameter	Variable	Options
Modulation type	*m*	Q-PSK, 16-QAm or 64-QAM
No. UEs	*P*	1 to 4
No. Receiving Antennas	*R*	1 to 4
Coder type	Coder	Off or $\frac{1}{2}$ CTC
N_FFT size	*N*	16, 32, 64 or 128
Interleaver	Interleaver_on_of f	On or Off
Equalizer Topology	Topology	PIC or SIC

Table 2 - Simulation platform variable parameters.

The structure of the simulation transmitter and receiver are presented next, along with a brief explanation of each block operation.

5.4.1. Transmitter Structure

The transmitter block structure can be seen below on Figure 25, and it consists mainly of:

- Data Generator – creates a vector of random binary data with size according to N_Codeword = 1536.
- Channel Coder – performs, if required, the channel coding type Convolutional Turbo Code (CTC).

- Data Modulation – modulates the random data vector according to the chosen constellation type (QPSK, 16-QAM or 64-QAM).
- N-FFT – according to the chosen N (FFT size), splits the data into T groups of size N, followed by the separate FFT operation of each block.
- SC-FDMA Framming – performs the mapping of the outputs of the N-FFT blocks into subcarriers, which are consequently organized into SC-FDMA frames. This allocation into SC-FDMA frames is done according to the activation or not of the interleaver, allowing then adjacent mapping or interleaved one, respectively. More detailed information on this matter is available on section 3.4.

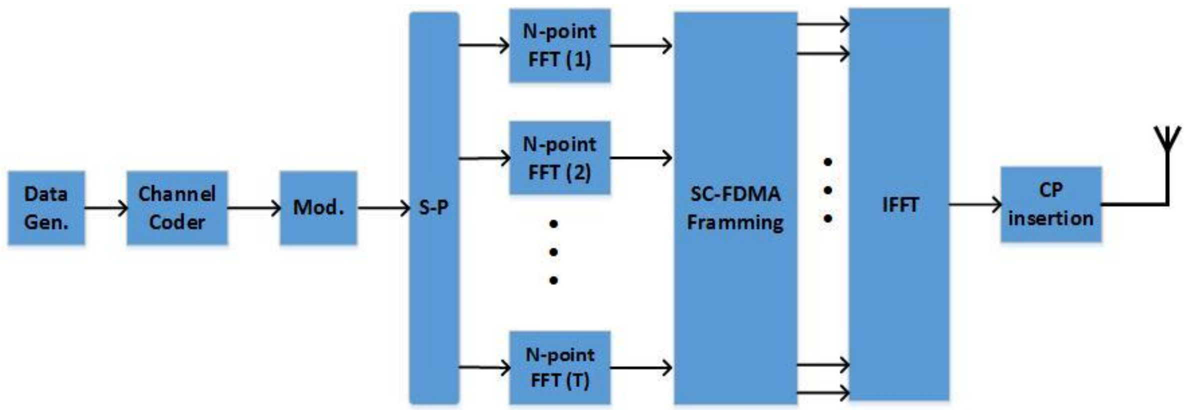

Figure 25 - Transmitter Block Structure for each UE.

5.4.2. Receiver Structure

The receiver block structure can be seen below on Figure 26, and it consists mainly of:

- Multi-user Equalizer – implements the IB-DFE receiver referred before on section 6.1 according to the topology selected (PIC or SIC);
- SC-FDMA De-framming – performs the de-mapping of the subcarriers and undoes the interleaving, if applied on the transmitter;
- IFFT – separates the vector at the output of the SC-FDMA De-framming block into bocks of size N and moves them back to the time domain through the IFFT operation on each block;
- Data Demodulator – converts the modulated symbols again into a stream of bits;
- Channel Decoder – nullifies the affects of the CTC coding, if applied.

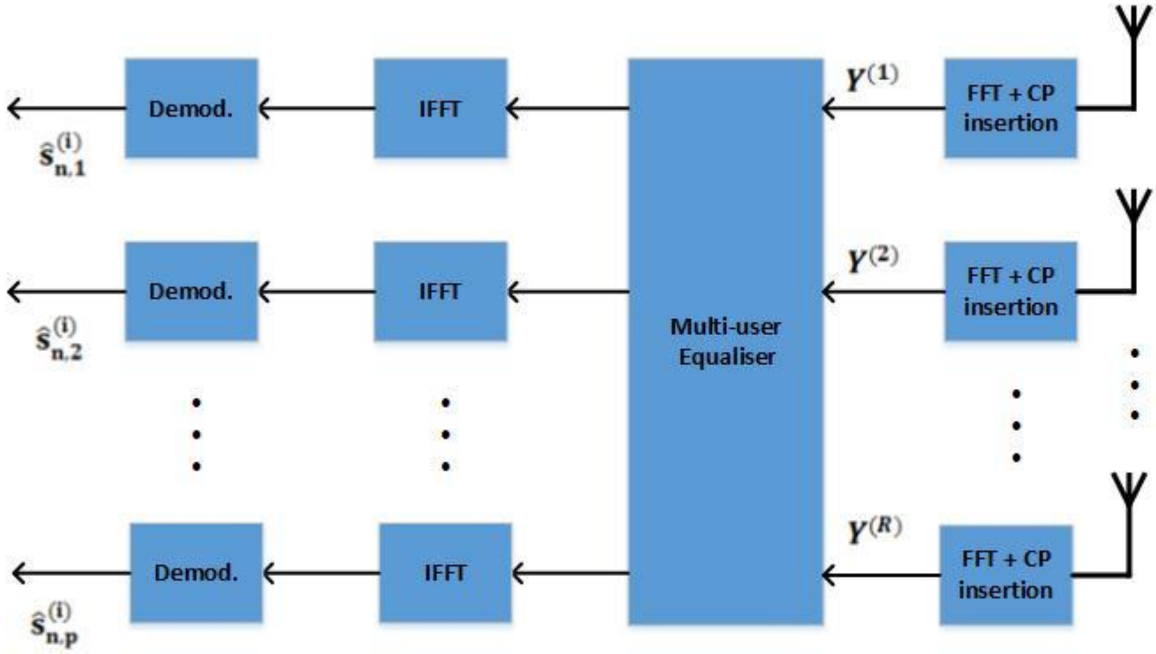

Figure 26 - Receiver block Structure at the Base Station.

6. Numerical Results

In this section the performance results of the implemented multi-user Iterative Block Frequency Domain Equalizer are presented and discussed. The key parameters used in the simulation are according to the LTE standard and presented on the table below.

Variable	Value
OFDM FFT size	1024
N_FFT size	64
Sampling frequency	15.36 MHz
Useful symbol duration	66.67 µs
Cyclic Prefix duration	5.21 µs
Total symbol duration	71.88 µs
Subcarrier separation	15 kHz
Frame size	12 OFDM symbols
Modulation	QPSK
Channel coder	CTC / UNCODED

Code rate	1 /2 – (1536/3072)
Channel type	Uncorrelated (U) or LTE extended
No. transmitting antennas pre UE	1
No. receiving antennas	2 or 4

Table 3 - Parameters selected for the simulation.

In the matters of channel model, both an uncorrelated Rayleigh fading channel and a channel specified for the LTE, which is based on the Power Delay Profile (PDP) presented on Table 1, were considered. For the decoder, a Max Log MAP algorithm with 8 iterations was used (performing optimization), and it is assumed perfect synchronization and channel estimation. The results are presented in terms of average BER as function of Eb/N0. The scenarios considered are presented next.

Delay (ns)	Average Power (Db)
0	-1
50	-1
120	-1
200	0
230	0
500	0
1600	-3
2300	-5
5000	-7

Table 4 - LTE Extended Typical Urban channel model (ETU).

All scenarios presented in the following sections show MIMO situations with the application of both PIC and SIC topologies of the developed receiver with 1, 2 and 3 iterations. It is important to note that the first iteration of the PIC topology matches the linear frequency domain MMSE equalizer, and on the SIC topology this equalizer is also applied for comparison. As performance reference for its analysis, the linear frequency equalizer Zero Forcing (ZF) and the Matched Filter Bound (MFB) are used.

6.1. MIMO 2x2 U Channel

For the first scenario, 2 single antenna UEs transmit to a BS with 2 antennas, representing a virtual MIMO 2x2 scheme, and a uncorrelated Rayleigh fading channel (U channel) is used. Focusing on the PIC topology results on Figure 27, it is possible to note that the linear MMSE (PIC IB-DFE 1st iteration) outperforms the linear ZF (8 dB penalty for BER=$1.0e^{-2}$). With the use of the IB-DFE with two iterations the previous approaches are outperformed, and it is visible a penalty of only approximately 3 dB for BER=$1.0e^{-3}$, and the third iteration shows a performance with 1.5 dB penalty when compared to the MFB at the same BER.

Looking now to the SIC performance in Figure 28, it is noticeable an improvement of approximately 1 dB on the first iteration and second iterations when compared to the MMSE and second iteration of the PIC topology (for BER=$1.0e^{-3}$). From the second iteration on, the improvement is negligible.

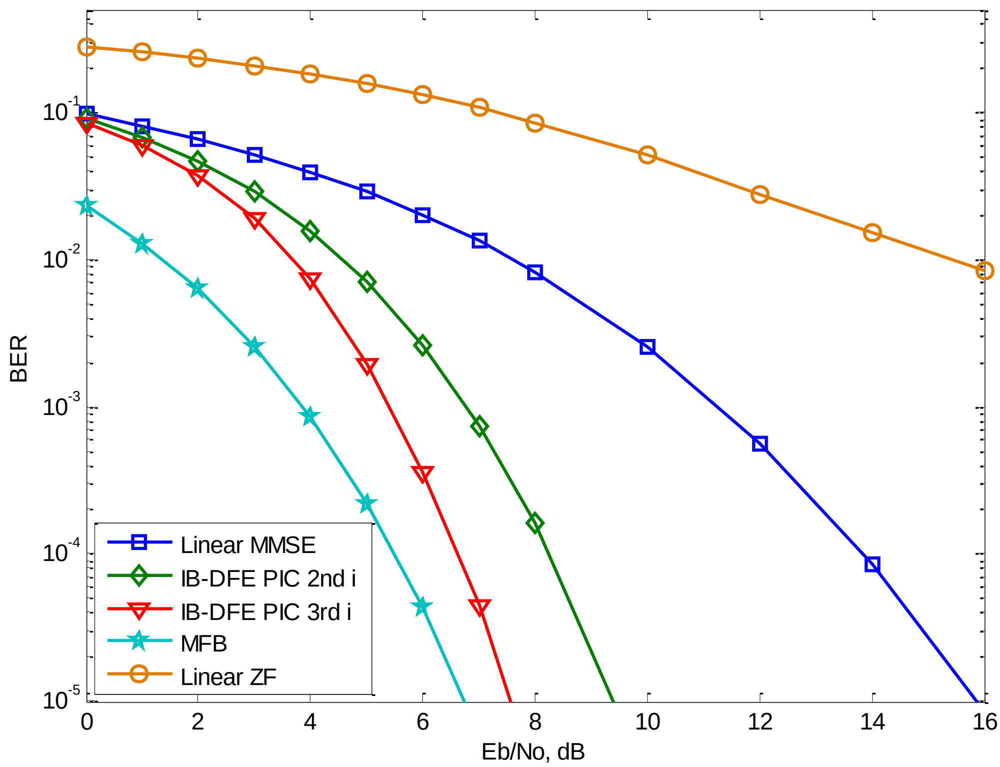

Figure 27 - MIMO 2x2 PIC U channel performance.

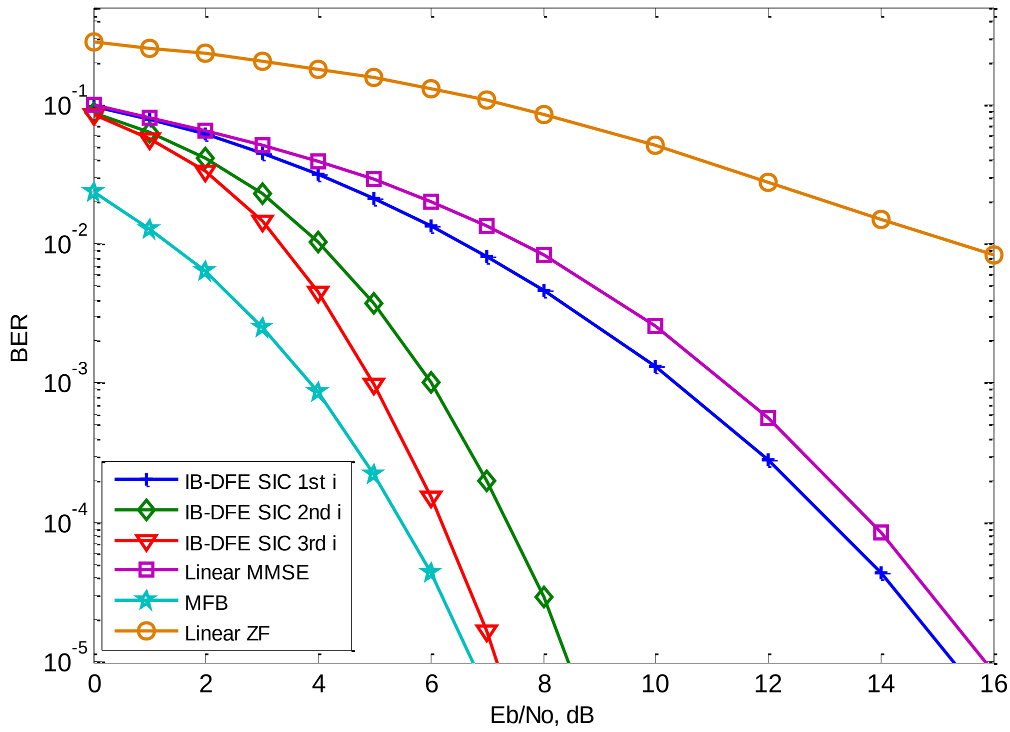

Figure 28 - MIMO 2x2 SIC U channel performance.

6.2. MIMO 2x2 LTE Channel

Now we consider the same previous scenario, but the channel used is the one specified for LTE, representing a more realistic simulation. Beginning with the PIC results on Figure 29, the linear MMSE (PIC IB-DFE with one iteration) outperforms the linear ZF with an 8 dB penalty for BER=$1.0e^{-2}$ as in the previous section. With the increase of the number of iterations, the implemented algorithm tends to MFB performance, presenting penalties of 3 and 2 dB for the second and third iterations, respectively (for BER=$1.0e^{-3}$). Comparing these results with the PIC ones of the previous section, an extra penalty is noticeable, but the improvements maintain themselves visible. This extra penalty is due to the lower diversity order of the LTE channel, when compared to the uncorrelated one.

As for the SIC results (Figure 30) in comparison to the PIC ones, improvements similar to the ones on the U channel are visible, of approximately 1 dB on the first two iterations, and negligible for the third one (for BER=$1.0e^{-3}$).

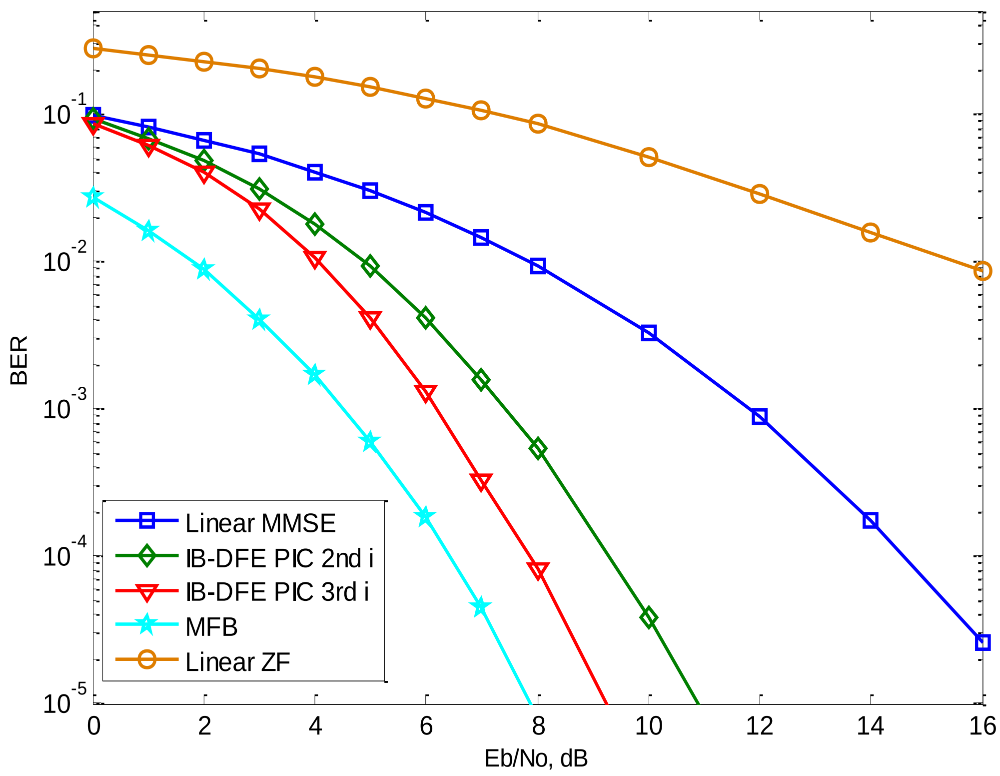

Figure 29 - MIMO 2x2 PIC LTE channel performance.

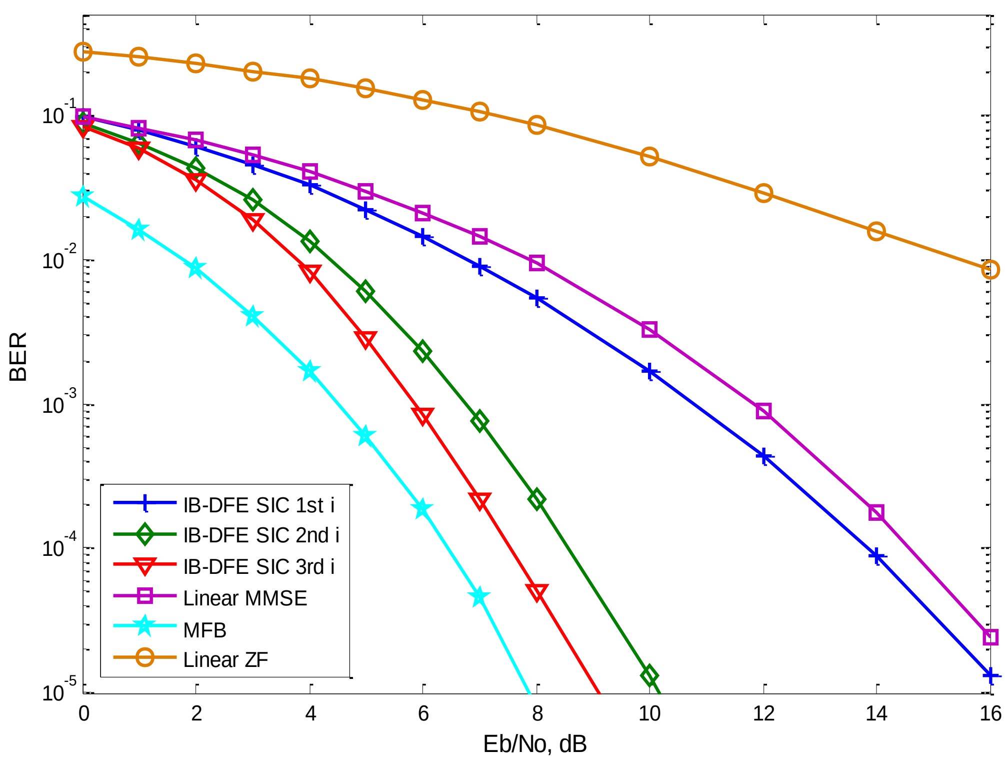

Figure 30 - MIMO 2x2 SIC LTE channel performance.

6.3. MIMO 4x4 U Channel

In this scenario, 4 single antenna UEs transmit to a BS with 4 antennas, and a U channel is used. Since we have a higher diversity order than the virtual MIMO 2x2 scheme used on the precious sections, the signal at the receiver suffers a more effective influence from MAI, fact that allows a better response from the MFB and our IB-DFE. On Figure 31 we can see the performance results for the PIC topology, where again the linear ZF presents high penalty when compared to the linear MMSE (10 dB for BER=$1.0e^{-2}$). With the second and third iterations the IB-DFE performance is better, showing penalties of 3 dB and 1.5 dB respectively, when compared to the MFB.

Taking now the SIC performance into account (Figure 32) the improvements when compared to the ones on the previous sections are more noticeable, presenting on the first iteration a 2dB better performance when compared to the linear MMSE. With two iterations, the SIC IB-DFE presents a 2 dB penalty when compared to the MFB and 1 dB penalty with the third iteration (for BER=$1.0e^{-3}$). The improvement at the third iteration is also visible, showing when compared to the PIC with 3 iterations for BER=$1.0e^{-3}$ a 1 dB better performance, and presenting practically the same performance as the MF from BER=$1.0e^{-4}$ on.

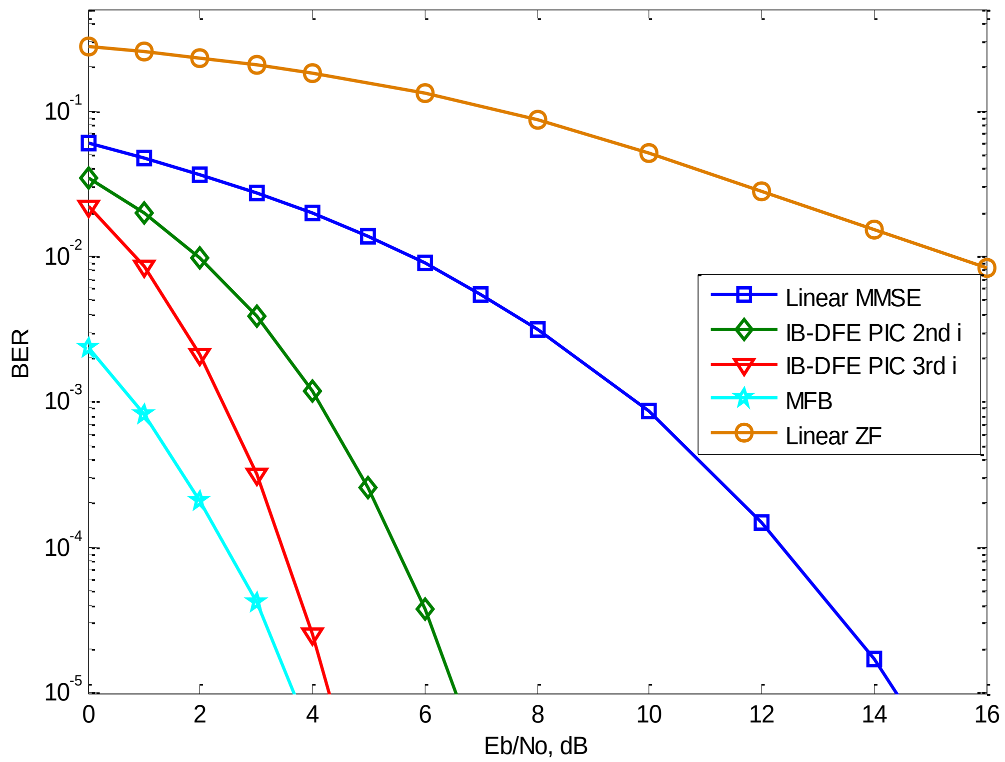

Figure 31 - MIMO 4x4 PIC U channel performance.

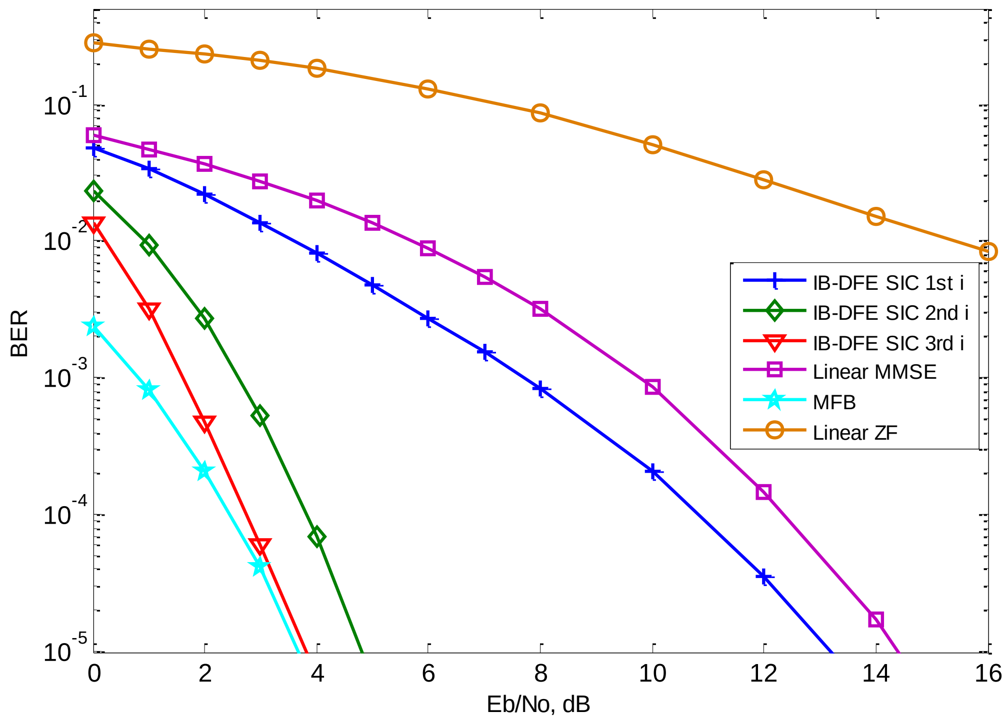

Figure 32 - MIMO 4x4 SIC U channel performance.

6.4. MIMO 4x4 LTE Channel

Now the same scenario as the previous section is applied, but using the LTE specified channel. Starting with the PIC topology presented on Figure 33, it is once again clearly visible the outperformance of the linear MMSE equalizer when compared to the linear ZF, rounding the 10 dB for BER=$1.0\mathrm{e}^{-2}$. As for the IB-DFE, the second iteration presents a penalty of 3.5 dB when compared to MFB, while the third iteration has a 1.5 dB penalty (for BER=$1.0\mathrm{e}^{-3}$).

Focusing now on the SIC performance (Figure 34), the linear MMSE has a 2dB penalty when compared to the SIC first iteration. For the use of 2 or 3iterations, the PIC version presents a 1 dB penalty with the same number of iterations (for BER=$1.0\mathrm{e}^{-3}$). Once again the third iteration of the SIC topology presents practically the same performance as the MF from BER=$1.0\mathrm{e}^{-4}$ on.

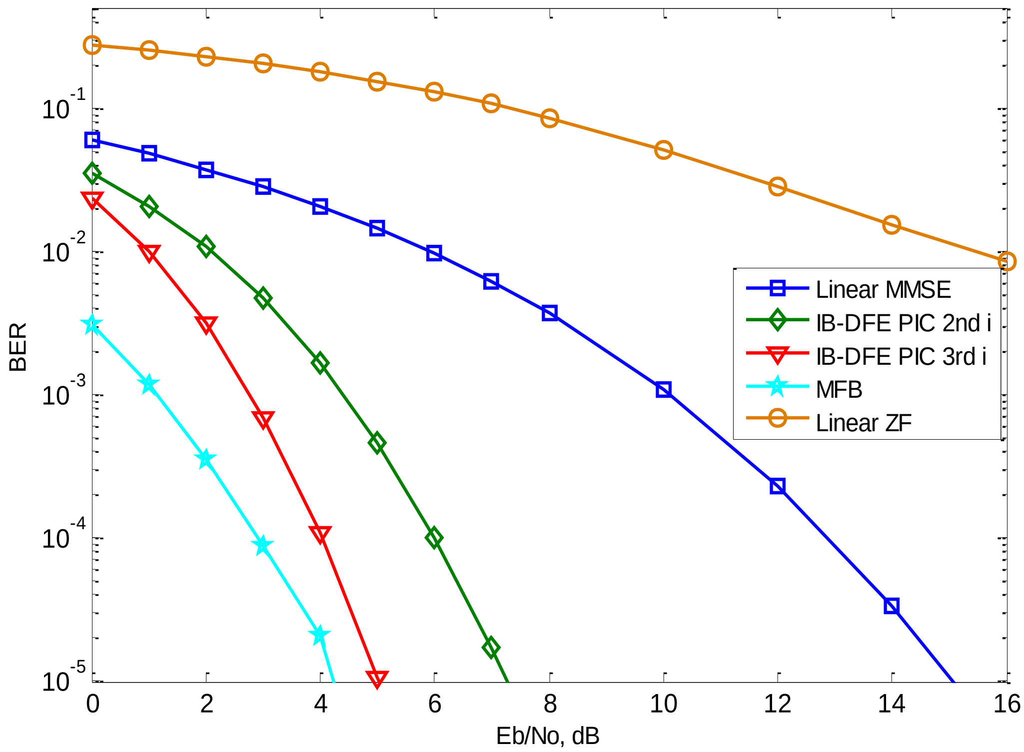

Figure 33 - MIMO 4x4 PIC LTE channel performance.

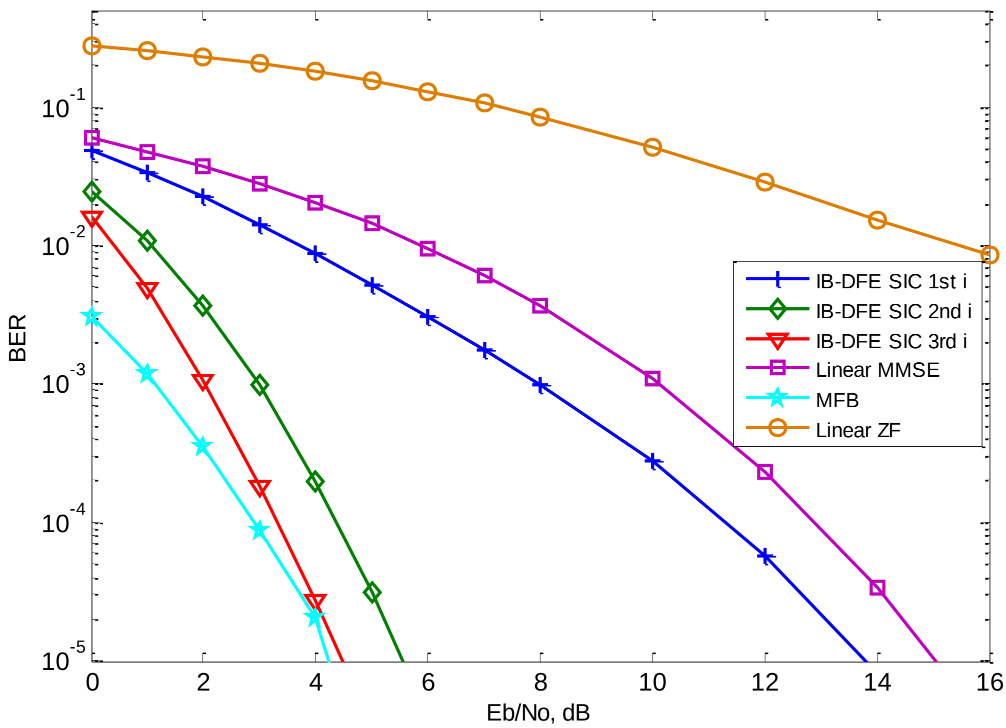

Figure 34 - MIMO 4x4 SIC LTE channel performance.

6.5. MIMO 2x2 LTE channel with Channel Coding

Finally, this last scenario is similar to the 2x2 MIMO scheme of section 5.5.2, being distinguished by the codification of the channel through a Convolutional Turbo Code. Figure 35 and Figure 36 show the performance results obtained on this scenario with both PIC and SIC base processing. Comparing this results with each other, it is noticeable a better performance on the SIC implementation with 2 and 3 iterations of about 0.5 dB (for BER=$1.0e^{-3}$). It is also useful to compare these results with the ones obtained in section 5.5.2 where channel coding is not applied. It is visible that without channel coding, both implementations present a penalty of 3.5 dB for 2 and 3 iterations.

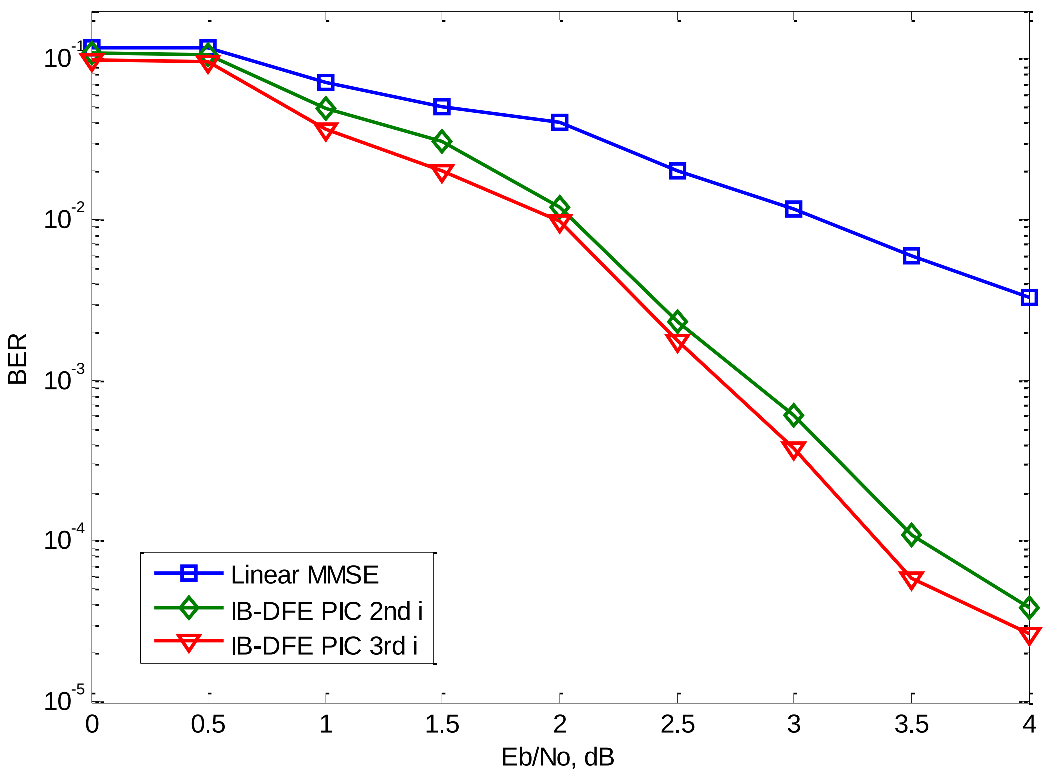

Figure 35 - MIMO 2x2 PIC LTE channel performance with CTC channel coding.

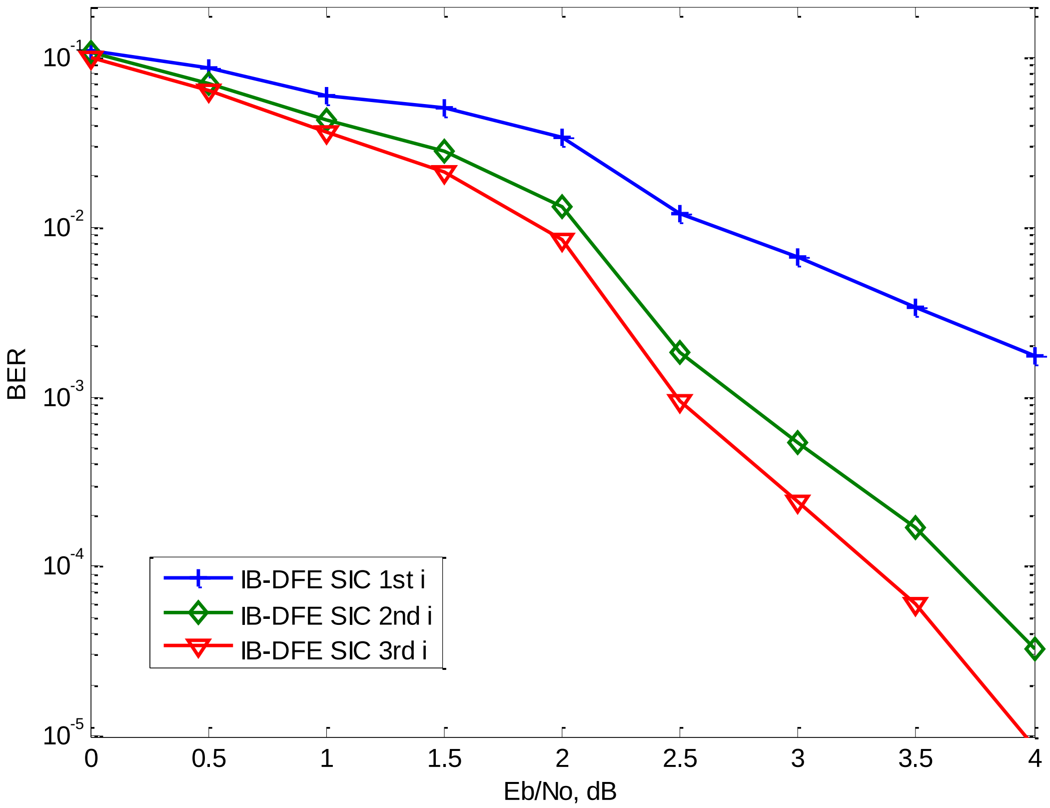

Figure 36 - MIMO 2x2 SIC LTE channel performance with CTC channel coding.

7. Conclusion and Future Work

For the past thirty years, the evolution of mobile networks was unbelievable, and with it the number of users and their needs grew incredibly also. In the last years, we reached a situation where again the mobile communication requirements exceeded the boundaries of the current technology applied, the 3G UMTS in this case. A series of technologies were then developed to be the answer to the increasing user requirements for a decade time window ahead of us, and Long Term Evolution was then chosen from these technologies to be the next step on mobile communications evolution. This fourth generation consists of a full IP-based integrated system that offers much higher data rates on uplink as well as downlink, scalable bandwidth according to the strength of the signal to provide a better service, lower latency, the availability of MIMO systems, together with simpler network architecture.

The main objective of this thesis is the study and development of an iterative frequency domain equalizer to improve the performance of the LTE uplink communication, to ease the task of responding to the growing needs of the world population on the matters of mobile communications.

To begin with, in chapter 1 a short overview of the mobile communications evolution so far was made to see the path that led to LTE. Afterwards, a proper description of this standard, including all the requirements and specifications is presented in chapter 2, along with an analysis of the system architecture network highlighting the changes when compared to its predecessor's one (UMTS). After this the attention is turned to chapter 3 where the multiple access schemes applied on LTE are defined for both downlink and uplink, taking into account its similarities. On chapter 4 are presented the multiple antenna systems, new concept included on the LTE standard that allow the use of MIMO schemes to increase spatial diversity and data rates, referring some diversity techniques at the transmission through space time/frequency coding, and at the receiver through combining techniques or equalization of the received signals.

In chapter 5, IB-DFE equalizers are obtained for the MIMO uplink (using SC-FDMA), and several performance simulations are done using a simulation platform developed to use the schemes 2x2 and 4xx4 using independent channels, or LTE standard channels. There's also the chance of using Channel Turbo Coding.

With a careful analysis of the simulation results and considering the first 4 scenarios, using the MIMO configurations 2x2 and 4x4, with the uncorrelated Rayleigh fading channel or the channel specified for LTE, both IB-DFE receivers outperformed the linear equalizers ZF and MMSE. Comparing the base processing modes applied, it is obvious in all four scenarios that the SIC choice presents better performance than the PIC one for the first and second iterations. As for the third iteration, the performances are similar, although it should be noted that they are pretty close to the MFB performance, presenting a penalty rounding the 0,5 dB. On the matters of channel coding, it is proved that its existence show better performances, although the distinction between the 2 implementations is not as noticeable.

To sum up, it was proved that the IB-DFE equalizer with SIC based processing offers substantial improvements on LTE uplink communication for the first 2 iterations.

7.1. Future Work

Taking into account to work developed so far, there are a few ideas that could be further developed on future work, like

- In all scenarios implemented, all the UEs considered were using a single antenna, turning interesting the case where multiple antenna UEs are applied.
- In this thesis only one type of channel coding was applied (CTC), making interesting the implementation of other channel coders.
- All simulations performed were made under the assumption of perfect channel information. There would be interest then to try and implement this same algorithm under imperfect channel information.

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