Universidade de Aveiro 2012
Departamento de
Electrónica, Telecomunicações e Informática,

Pedro António Figueiredo Dias

Técnicas de Processamento com Múltiplas Antenas Para o Sistema LTE

Processing Techniques with Multiple Antennas for the LTE System

Universidade de Aveiro 2012
Departamento de Electrónica, Telecomunicações e Informática,

Pedro António Figueiredo Dias

Técnicas de Processamento com Múltiplas Antenas Para o Sistema LTE

Processing Techniques with Multiple Antennas for the LTE System

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

o júri / the jury

presidente / president	**Prof. Doutor José Carlos da Silva Neves** Professor Catedrático do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro
orientador / adviser	**Prof. Doutor Adão Paulo Soares da Silva** Professor Auxiliar do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro
co-orientador / co-adviser	**Prof. Doutor Atilio Manuel da Silva Gameiro** Professor Associado do Departamento de Electrónica, Telecomunicações e Informática da Universidade de Aveiro
arguente / examiner committee	**Prof. Doutor Pedro Renato Tavares de Pinho** Professor Adjunto no Departamento de Engenharia de Electónica e Telecomunicações e de Computadores do Instituto Superior de Engenharia de Lisboa

agradecimentos / acknowledgements

Esta dissertação é um marco muito importante na minha vida profissional e pessoal, porque simboliza o fim do meu percurso académico e a transição para uma nova etapa. Representa o culminar de muitos anos de dedicação e empenho. No entanto, este resultado final só foi possível porque pude contar com o apoio e o incentivo de muitas pessoas, que foram o meu suporte durante esta caminhada. Sendo assim, aproveito esta oportunidade para agradecer a todos os principais intervenientes que estiveram presentes e contribuíram, de alguma forma, para a realização desta dissertação.

Gostaria de agradecer aos meus pais, à minha irmã e aos meus avós, pelo apoio, pela força e pelo exemplo de vida que sempre me transmitiram. Foram, de facto, as pessoas que possibilitaram a realização dos meus objectivos e que sempre acreditaram em mim e nunca me deixaram desistir dos meus sonhos.

À Universidade de Aveiro pela a oportunidade e excelência na formação dos seus alunos, assim como a todos os docentes do Departamento de Electrónica, Telecomunicações e Informática, que se cruzaram no meu percurso.

Ao Professor Doutor Adão Paulo Soares da Silva pela orientação, coordenação, paciência e disponibilidade contínua que ofereceu.

Por ultimo mas igualmente importante, agradeço a todos os meus colegas e amigos que fizeram parte da minha vida académica, pelo companheirismo, cumplicidade e amizade dedicada, assim como à minha namorada pelo apoio incondicional, nos melhores e piores momentos ao longo deste período.

Palavras-Chave 3G, LTE, OFDMA, SC-FDMA, MIMO, D-SFBC, PIC, SIC

Resumo

Performance, mobilidade e partilha podem ser consideras como as três palavras-chave nas comunicações móveis de hoje em dia. Uma das necessidades fundamentais do ser humano é a partilha de experiencias e informação. Com a evolução ao nível do hardware móvel, a crescente popularidade de smartphones, tablets e outros dispositivos moveis, fez com que a exigência em termos de capacidade e taxa de transferência por parte das redes móveis não parasse de crescer.

As limitações das redes 3G fizeram com que não conseguissem corresponder a tais exigências e como tal, a transição para uma tecnologia mais robusta e eficiente passou a ser inevitável. A resposta escolhida como solução a longo prazo é a rede designada por LTE, desenvolvida pela organização 3GPP é assumido que será a rede de telecomunicações predominante no futuro. As vantagens mais sonantes são, naturalmente, elevadas taxas de transmissão, maior eficiência espectral, redução da latência e de custos de operação. As principais tecnologias em que o LTE se baseia, são o OFDM e sua variante para múltiplo acesso, OFDMA, usado para o downlink e o SC-FDMA para o uplink. Além disso, usa sistemas com múltiplas antenas para impulsionar a eficiência espectral. Apesar de já implementado em alguns países por diversas operadoras, constantes pesquisas continuam a ser realizadas com o intuito de melhorar a sua performance.

Nesta dissertação é proposto um esquema duplo de codificação na frequência e no espaço (D-SFBC) para um cenário baseado em OFDM com 4 antenas de transmissão e duas antenas de recepção (4×2 D-SFBC) para o downlink. No cenário considerado, 4 símbolos de dados são transmitidos utilizando unicamente 2 sub-portadoras, fazendo com que, este sistema seja limitado pela interferência. Para de forma eficiente descodificar os símbolos de dados transmitidos, foi desenvolvido um equalizador iterativo no domínio da frequência. Duas abordagens são consideradas: cancelamento da interferência em paralelo (PIC) e sucessivo cancelamento de interferência (SIC). Uma vez que apenas 2 sub-portadoras são usadas para transmitir quatro símbolos de dados em paralelo, o esquema desenvolvido duplica a taxa de dados quando comparado com o esquema 2×2 SFBC, especificado no standard do LTE.

Os esquemas desenvolvidos foram avaliados sob as especificações para LTE e usando codificação de canal. Os resultados mostram que os esquemas implementados neste trabalho utilizando um equalizador iterativo supera os convencionais equalizadores lineares na eliminação da interferência adicional introduzida, em apenas 2 ou 3 iterações.

Keywords 3G, LTE, OFDMA, SC-FDMA, MIMO, D-SFBC, PIC, SIC

Abstract

Performance, mobility and sharing can be assumed as the three keywords in the mobile communications nowadays. One of the fundamental needs of human beings is to share experiences and information. With the evolution of mobile hardware level, the growing popularity of smartphones, tablets and other mobile devices, has made that the demand in terms of capacity and throughput by mobile networks did not stop growing.

Thus, the limitations of 3G stops it of being the answer of such demand, and a transition to a powerful technology has become unavoidable. The answer chosen is LTE, developed by the 3GPP organization is assumed to be the predominant telecommunications network in the future. The most relevant advantages are high transmission rates, higher spectral efficiency, reducing latency and operating costs. The key technologies in which LTE is based, are OFDM and its variant schemes for multiple access, OFDMA, used for downlink, and SC-FDMA for the uplink. It also uses multiple antennas systems in order to improve spectral efficiency. Although already implemented in some countries by several operators, continuous research is conducted in order to improve their performance.

In this dissertation it is proposed a double space-frequency block coding (D-SFBC) scheme for an OFDM based scenario with 4 transmit antennas and 2 receive antennas (4×2 D-SFBC) for the downlink. In the considered scenario, 4 data symbols are transmitted by using only 2 subcarriers and thus the system is interference limited. To efficiently decode the transmitted data symbols an iterative equalizer designed in frequency domain is developed. Two approaches are considered: parallel interference cancellation (PIC) and successive interference cancellation (SIC). Since only 2 subcarriers are used to transmit 4 data symbols in parallel the developed scheme achieve the double data rate when compared with the 2×2 SFBC, specified in the LTE standard.

The developed schemes were evaluated under the main LTE specifications and using channel coding. The results have show that the schemes implemented in this work using an interactive equalizer outperforms the conventional linear equalizers in the interference removal, just by using 2 or 3 iterations.

Contents

List of Figures

List of Tables

Acronyms

1G	First Generation.
2G	Second Generation.
3G	Third Generation.
3GPP	Third Generation Partnership Project.
3GPP2	Third Generation Partnership Project.
4G	Fourth Generation
AWGN	Additive White Gaussian Noise.
BER	Bit Error Rate.
BPSK	Binary Phase Shift Keying.
BS	Base Station.
CDD	Cyclic Delay Diversity.
CDMA	Code Division Multiple Access.
CDMAone	Code Division Multiple Access one.
CDMA2000	Code Division Multiple Access 2000.
CP	Cycle Prefix.
CPC	Continuous Packet Connectivity
CTC	Convolutional Turbo Code.
DFE	Decision Feedback Equalization.
D-SFBC	Double Space-Frequency Block Coding.
E-UTRA	Evolved UMTS Terrestrial Radio Access.
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network.
EAP	Extensible Authentication Protocol.
EDGE	Enhanced Data rates for GSM Evolution.
eNodeB	Evolved Node B.
EPC	Evolved Packet Core.
EPS	Evolved Packet System.
FDD	Frequency Division Duplexing.
FDE	Frequency Domain Equalizer.
FDM	Frequency Division Multiplexing.
FFT	Fast Fourier Transform.
FSTD	Frequency Shift Transmit Diversity.
GERAN	GSM EDGE Radio Access Network.
GPRS	General Packet Radio Service.
GSM	Global System for Mobile communication.
HSDPA	High Speed Downlink Packet Access.
HSPA	High Speed Packet Access.

HSPA+	HSPA Evolution.
HSS	Home Subscriber Server.
HSUPA	High Speed Uplink Packet Access.
ICI	Inter Carrier Interference.
IFFT	Inverse Fast Fourier Transform.
IMS	IP Multimedia Subsystem.
IMT-2000	International Mobile Telecommunications-2000.
IMT-Advanced	International Mobile Telecommunications-Advanced.
IP	Internet Protocol.
IS-95	Interim Standard 95.
ISI	Inter-Symbol Interference.
ITU	International Telecommunications Union.
LSTI	LTE/SAE Trial Initiative.
LTE	Long Term Evolution.
MBMS	Multimedia Broadcast Multicast Service.
MF	Matched Filter.
MIMO	Multiple Input Multiple Output.
MISO	Multiple Input Single Output.
MME	Mobility Management Entity.
MMSE	Minimum Mean Square Error.
OFDM	Orthogonal Frequency Division Multiplexing.
OFDMA	Orthogonal Frequency Division Multiple Access.
P-GW	Packet Data Network Gateway.
PAPR	Peak-to-Average Power Ratio.
PIC	Parallel Interference Cancelation.
PCRF	Policy Control and Charging Rules Function.
PDN	Packet Data Network.
PIC	Parallel Interference Cancelation.
PRB	Physical Resource Block.
QAM	Quadrature Amplitude Modulation.
QoS	Quality of Service.
QPSK	Quadrature Phase Shift Keying.
RAN	Radio Access Network.
RF	Radio Frequency.
RB	Resource Block.
RE	Resource Element.
RS	Resource Signal.
RRM	Radio resource management.
S-GW	Serving Gateway.
SAE	System Architecture Evolution.
SC-FDE	Single Carrier Frequency Domain Equalizer.
SC-FDMA	Single Carrier Frequency Division Multiple Access.
SFBC	Space-Frequency Block Code.
SFC	Space-Frequency Coding.
SIC	Successive Interference Cancelation.
SIMO	Single Input Multiple Output.
SINR	Signal to Interference-plus-Noise Ratio.

SISO	Single Input Multiple Output.
SNR	Signal Noise Ratio.
STBC	Space Time Block Coding.
STC	Space Time Coding.
TD-DFE	Time-Domain Decision Feedback Equalizer.
TDD	Time Division Duplexing.
TDMA	Time Division Multiple Access.
TSTD	Time Shift Transmit Diversity.
UE	User Equipment.
UMB	Ultra Mobile Broadband.
UMTS	Universal Mobile Telecommunications System.
UTRA	UMTS Terrestrial Radio Access.
VoIP	Voice over Internet Protocol.
UTRAN	UMTS Terrestrial Radio Access Network.
W-CDMA	Wideband Code Division Multiple Access.
WiMAX	Worldwide Interoperability for Microwave Access.
ZF	Zero Forcing.
SM	Spatial Multiplexing

Chapter 1

Introduction

1.1 Overview

We are witnessing a transition in the paradigm of mobile communications. A new "G" generation is now taking over, besides all, essentially, marketing connotation this designation it is quite useful to distinguish some important changes in mobile communications. The predominant systems nowadays are still based on 2G-GSM and 3G-WCDMA technologies, and there are approximately 6 thousand millions mobile subscribers [1], but as it happened before, in the transition from 1G to 2G, and posteriorly to 3G, some disruptive changes in the technologies used are taking place. The rising number of subscriptions translates directly into the need of improvements in network capacity and also in higher peak data rates as also better spectral efficiency.

In the beginning of 3G development the dream was to make true the concept of "Anytime Anywhere", however, due to the immaturity of the technology, some system limitations and also economic reasons, the penetration in the market of mobile communications was considered a deception. However it had an critical importance in the widespread of data traffic usage. As we can see in Figure 1.1 mobile data traffic is rising exponentially and have already surpassed voice traffic in 2009 and doubled it in 2011. One explanation of the rising data usage, is the development, and great expansion in the market, of mobile devices like smartphones, tablets as also mobile pens to laptops and netbooks [2]. With increasing processor capacities, equipped with powerful cameras, and big storage capacity, they are authentic multimedia terminals. The incredibly human instinct to share information and personal data completes the theory.

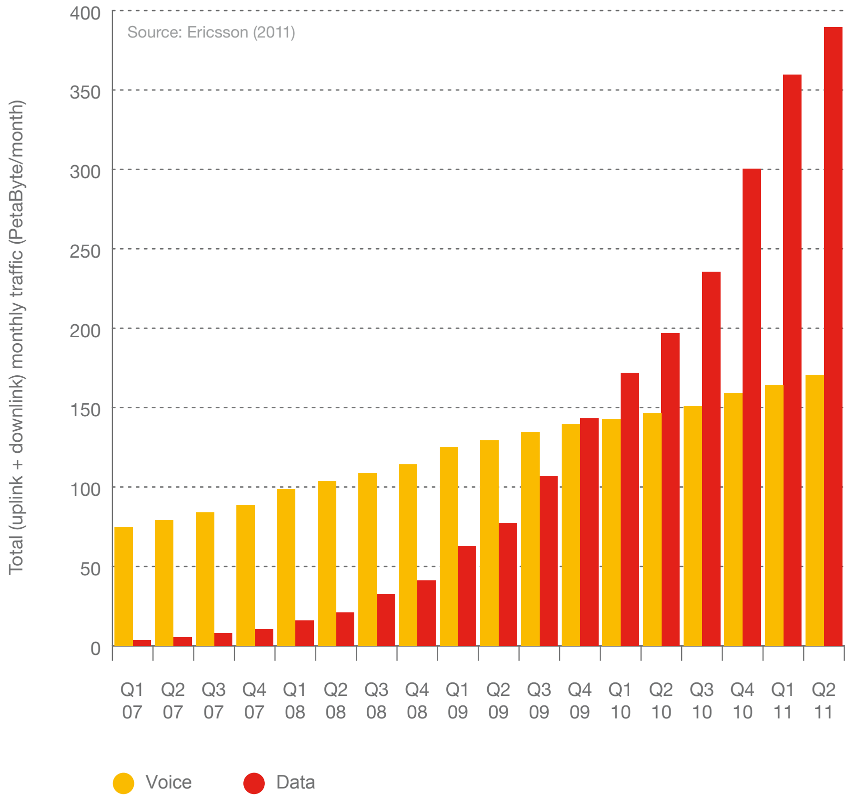


Figure 1.1: Global total traffic in mobile networks, 2007-2011 [3].

The evolutionary path of mobile communications has been long, with an history of big fragmentation over the years, which will better described in following section. Nevertheless thinking that all started just over hundred years, and see what we have achieved already accomplish, is quite amazing.

1.2 Wireless Technology Evolution

Everything started in 1901 with Guglielmo Marconi, that using Maxwell theory was capable to make the first wireless transmission of an telegraph signal. In 1915, analog radio communications, had begun, and for the first time, it was possible to make wireless voice communications between New York and San Francisco, Its usefulness was so obvious that have become indispensable. In 80's first analogical systems (1G) were implemented, solely directed to voice service. At this point the main characteristics were high power usage, poor spectral efficiency, poor quality of service and very low capacity.

The first transition paradigm in cellular technologies, arrives in the 90's with the introduction of the digital systems (2G), however, it continued to be targeted for the voice communications only. War of standards had begun, with three main competing 2G technologies being developed simultaneously. While Europe releases the Global System for Mobile communication (GSM) supported by Time Division Multiple Access (TDMA) techniques, U.S.A releases the Interim Standard 95 (IS-95) also referenced as CDMAone based on Code Division Multiple Access (CDMA), also JAPAN have their one system, the Japanese Digital Cellular (PDC), however the GSM success allowed, and continues nowadays, to be the predominant system [4]. Technologic changes by 2G consequently bringed better quality of service and great capacity, other important development was the introduction of roaming, which wasn't possible in 1G. In later releases to the voice service was added data transmission services. Referenced as 2.5G, added General Packet Radio Service (GPRS) that could achieve transmission rates up to 115 Kbps. More recently GSM/GPRS evolved to Enhanced Data Rates for GSM Evolution (EDGE), also referenced as a 2.75G technology.

In pursuing for better performance and the possibility of having a platform that could support multiple multimedia services, International Telecommunications Union (ITU) defined the Third Generation (3G) systems, in 1999. A set of requirements was specified by the ITU, where minimum peak user data rates in different environments were provided, through what is known as the International Mobile Telecommunications 2000 project (IMT-2000). The requirements included 2048 kbps for an indoor office, 384 kbps for outdoor to indoor pedestrian environments and 144 kbps for vehicular connections.

With the aim of forming a collaboration entity among different telecommunications associations, the 3rd Generation Partnership Project (3GPP) was established in 1998. The competing 3GPP2 standardization group for CDMA2000 was also formed. In 2000 3GPP Release-99 specifications was concluded, and Universal Mobile Telecommunication System (UMTS) was the term adopted to designate the 3G standards. It first introduced Wideband Code Division Multiple Access (W-CDMA) using a 5 MHz UMTS carrier. As expected 3GGP2 also standardized their system, the CDMA2000-1x and CDMA2000-3x using a 1.25 Mhz carrier bandwidth, both based on Code Division Multiple Access (CDMA). Initially these systems did not fulfill the IMT-2000 requirements in practical deployments. So 3GPP launched in 2002, Release 5 in which High Speed Downlink Packet Access (HSDPA) introduced packet switched data services to UMTS. Completing this upgrade, Release 6 was latter launched, adding High Speed Uplink Packet Access (HSUPA), both known collectively only as (HSPA). At this point of the evolutionary path, UMTS could achieve data rates of 14 Mbps in downlink and 5.8 Mbps uplink using 2 milliseconds Transmission Time Interval (TTI) [5]. 3GPP2 by is side standardized CDMA2000 One Carrier Evolved Optimized (1xEV-DO) providing peak theoretical downlink speeds of 3 Mbps in downlink and 1.8 Mbps for the uplink [6].

Motivated by increasing demand for higher data rates 3GPP launched another standard, Release 7. It contained further improvements for HSPA such as MIMO, 64-QAM on the downlink

and 16-QAM on the uplink, and is known as HSPA+. Release 7 also have the first studies on Long Term Evolution (LTE), it started working on the radio, core network, and service architecture of a globally applicable 4G technology specification.
In Release 8 HSPA continued to evolve with the addition of dual cell HSDPA, providing even higher data rates, however the main work was focus on LTE specifications.
The study of LTE began in 2004 with a project to define the Long Term Evolution of UMTS. The project efforts were developing a Evolved UMTS Terrestrial Radio Access (E-UTRA) and Evolved UMTS Terrestrial Radio Access Network (E-UTRAN), commonly referred by project name LTE. The first version of LTE specifications is documented in Release 8 of 3GPP launched in 2008. In summary, the 3GPP aims, were to develop a new network architecture that could improve capacity at the same time reducing operating costs. LTE is frequently referenced as a Fourth Generation (4G) network, but wrongly, since it not meet the predefined specifications on IMT-Advanced for 4G. Work in LTE enhancements remained in progress in following years with the Release 9 and 10, with LTE-Advanced designation trying to fulfill the ITU requirements for 4G.
The only reason, that we realized, it may consider LTE as a new generation of mobile communications, since there isn't any killer application, is the customer experience improvement by using a service with superior quality.

The following table summarizes the generations evolution [7].

Table 1.1: Generations evolutionary path.

Generation	Requirements	Observations
1G	No requirements pre-defined	Deployed in the 1980s; Analog technology; poor efficiency and quality
2G	No requirements pre-defined	Deployed in the 1990s; Digital technology; voice oriented; Low data rates; GSM
3G	ITU- IMT-2000: 144kbps	Deployed in the 2000; W-CDMA ; HSPA; HSPA+
4G	ITU- IMT-Advanced: 1Gbps downlink; 500Mbps uplink Spectrum Allocation up to 40 MHz	high-data-rate; low-latency; packet-optimized; OFDM; MIMO; SAE

1.3 Motivation and Objectives

The expected increase in demand for broadband services, which require high transmission rates, can not be satisfied in the future with the existing systems of 3G. Thus the Third Generation Partner-Ship Project (3GPP-www.3gpp.org) undertook a research and specification of a new standard, called LTE. This mobile communications system is based on a completely different technology, the Orthogonal Frequency-Division Multiple Access (OFDMA) for the downlink. A major objective of this system is to provide future transmission rates of around 100Mbps and 50Mbps for downlink to uplink, respectively, values well above the current 3G systems.

The use of spatial diversity will be a key to effective use of the diversity inherent in wireless channels and the consequent reach of broadband capabilities. The spatial diversity can be obtained using antenna arrays. A system in which both terminals (base station and handset) are equipped with multiple antennas is called multiple input multiple output (MIMO). Unlike the 3G system, the LTE has already specified processing techniques with multiple antennas. One of this techniques is the Space-Time Block Coding (STBC) proposed by Alamouti [8] for 2 transmit antennas. This scheme can be also applied on frequency domain referred as Space-Frequency Block Coding (SFBC). Note that there isn't an orthogonal SFBC or STBC scheme, with code rate 1, for more than 2 transmit antennas. In the LTE, and for 4 transmit antennas the Alamouti code is performed in pairs of 2 antennas. Considering 4 data symbols, the first 2 are coded over the first 2 antennas and 2 subcarriers; the third and fourth are coded over the last 2 antennas and other 2 subcarriers. In this scheme 2 different set of 2 subcarriers are used for each pair of 2 antennas. The transmission from one set of 2 antennas (e.g. antenna 0 and antenna 1) happens as a normal SFBC for 2 transmit antennas. The SFBC scheme for four antennas adopted in the LTE standard is not the most efficient since it requires four subcarriers to transmit four data symbols over the four antennas. The main objective of this thesis is to develop and asses a more efficient SBFC scheme for the LTE. In the considered scheme, 4 data symbols are transmitted over 4 antennas but using only 2 subcarriers. This scheme is usually referred as Double Space-Frequency Block Coding(D-SFBC). The advantage is that the spectral efficiency increase by a factor 2, i.e., with this scheme the system can transmit the double of the data symbols than the one considered in the current release of the LTE. However, since the 4 data symbols are transmitted over only 2 subcarriers they interfere each other at the receiver and thus employing linear equalizer is not the most efficient. Therefore, we propose an iterative equalizer designed in frequency domain to efficiently remove the interference and achieve spatial diversity. The results were obtained using typical LTE specifications and for several scenarios.

1.4 Outline

This thesis it's divided into six chapters. Chapter 1 provides a general introduction to the thesis work scope and outlines the contents of the thesis report. In Chapter 2 are described the theoretical fundamentals of LTE and it includes some of the key technologies in LTE, which gives background knowledge for further discussion on this thesis. Chapter 3 presents the multi-carrier system OFDM and describes the physical layer of LTE. The basic concepts of the multiple access techniques (i.e. OFDMA and SC-FDMA) are also discussed. In Chapter 4 it's introduced the MIMO systems, with different antenna configurations, and the diversity concept. It's also presented the linear frequency domain equalizers, Zero Forcing (ZF) and Minimum Mean Square Error (MMSE). Chapter 5 contains the work developed in the ambit of this thesis and analysis the results obtained, namely the iterative equalizer in the frequency domain. Chapter 6 concludes the thesis work, and gives some ideas to future work that could be developed.

Chapter 2

LTE Overview

When 3GPP began studying the 3GPP LTE, in 2004, and discussed the requirements for this new technology, one of the main objective was to develop a solution that can meet the massive data growth forecast at the time, and that eventually confirm. The key goals can be summarized as follows:

- reduced delays, in terms of both connection establishment and transmission latency;
- increased user data rates;
- increased cell-edge bit-rate, for uniformity of service provision;
- increased service provisioning - more services at lower cost with better user experience;
- reduced cost per bit, implying improved spectral efficiency;
- greater flexibility of spectrum usage, in both new and pre-existing bands;
- simplified network architecture, open interfaces;
- reasonable power consumption for the mobile terminal.

To accomplish these objectives, a disruption with current technologies was needed, 3G have reached a saturation point in his development and can not anymore fulfill future demands for mobile broadband services. So new modulation and digital processing techniques need to be adopted with the specific aim of enhance the 3GPP radio access and the radio network.
LTE is based on three fundamental technologies that will be followed in detail in the next chapters: OFDM modulation, multiple antenna techniques and the application of packet-switching to the radio interface.
OFDM in resume, provides high performance in frequency selective channels and high spectrum efficiency, also allows a smooth transition from the existing radio access technologies.

LTE for downlink direction uses a variant of OFDM, the Orthogonal Frequency Division Multiplexing Access (OFDMA) which supports flexible bandwidths and allows high peak data rates. Besides that, a crucial characteristic of OFDM is the robustness to time dispersion on the radio channel, this allows lower complex receivers for equalization. In the uplink direction it uses Single Carrier Frequency Division Multiple Access (SC-FDMA) because OFDMA have high Peak to Average Power Ratio (PAPR) what leads to a less power-efficient transmission, which is one of the most important factors in order to reduce terminals power consumption and complexity.
Other important function of LTE standard is the Adaptive Modulation and Coding (AMC), in mobile communications channel conditions are normally variable, in order to handle these variations to minimize their effects, it is possible to adapt the modulation scheme or the coding rate. Low-order modulation like QPSK, is more robust and can tolerate higher levels of interference but penalizes the transmission bit rate, high-order modulations like 64-QAM, provides the complete opposite effects. In resume this function improves the throughput increasing the system capacity and reducing the probability of signal errors, adjusting the parameters to channel conditions. For the code rate, for a given modulation, the code rate can be chosen depending on the radio link conditions: a lower code rate can be used in poor channel conditions and a higher code rate in the case of high Signal Interference Noise Ratio (SINR) [9].
LTE also have the advantage of allowing flexibility in spectrum allocation since can operate in wide range of frequencies: 1,25; 2,5; 5; 10; 15; and 20 MHz. The frequency allocation schemes that LTE can operate are Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) modes, to separate downlink and uplink traffic, for operation in paired as well as unpaired spectrum. In addition to FDD and TDD, half-duplex FDD is also allowed, which facilitates implementation of multi-mode terminals and allows roaming. Unlike FDD, in half-duplex FDD operation a User Equipment (UE) is not required to transmit and receive at the same time avoiding a costly duplexer in the UE.
The system is primarily optimized for low speeds up to 15 km/h, however, the system specifications allow mobility support in excess of 350 km/h with some performance degradation.
In parallel with LTE 3GPP also defined a new network, the System architecture Evolution (SAE) which defines the split between LTE and a new Evolved Packet Core (EPC), with the goal to support packet-switched traffic, deliver higher throughput, quality of service, minimal latency and lower costs. The EPC is also designed to provide seamless interworking with existing 3GPP and non-3GPP access technologies.
The first commercial implementation was in 2009 by TeliaSonera, since then the number of operators that adopted LTE has risen significantly.
HSPA and EDGE technologies are also continuing to be developed to offer higher spectral efficiencies. Enhancement of UMTS continues in 3GPP with new releases of specifications ensuring backward compatibility with earlier releases, as mentioned before Release 7 HSPA+

introduced higher order modulations and MIMO, in parallel with LTE, HSPA+ improvements were released in Release 8. These backward-compatible enhancements will enable network operators who have invested heavily in the W-CDMA technology of UMTS to generate new revenues from new features while still providing service to their existing subscribers using previous systems. However, LTE is the expected predominant system in the future, it is a new system designed from the beginning with the benefit of being compatible with previous technologies [10].

2.0.1 Requirements

The enhancements in performance compared to the existing systems is the key goal of the mobile operators, in order to guarantee competitiveness of LTE system and ensure his successful penetration in the market. Table 2.1 give us a resume of the LTE specifications.

Table 2.1: LTE system specifications [11].

	Downlink	Uplink
Peak data rate (20 MHz)	100 Mbps (1×1)	50 Mbps (1×1)
	173 Mbps (2×2))	86 Mbps (1×2)
	326 Mbps (4×4)	
MIMO	(1×1), (2×2), (4×2),(4×4)	(1×1), (1×2), (1×4)
Multiple access	OFDMA	SC-FDMA
Scalable Bandwidth	1.25-20 MHz	
Adaptive Modulation	QPSK, 16-QAM and 64-QAM	BPSK, QPSK and 16-QAM
Channel coding	Turbo code	
Duplexing	FDD, TDD, half-duplex FDD	
Mobility	350 km/h	
Latency	$<$ 10 ms	
Other techniques	Channel sensitive scheduling	
	Link adaptation	
	Power control	
	ICIC	
	Hybrid ARQ	

2.1 System Architecture

As already mentioned, a parallel 3GPP project named SAE, defined a new all-IP, packet-only Core Network (CN) known as the EPC. In Release 8 specifications LTE term corresponds to the evolution of the radio access through the E-UTRAN, and it is accompanied by an evolution of the non-radio functions provided in the CN under the term EPC. The combination of both the EPC/SAE and the LTE/E-UTRAN terms, corresponds to the whole system architecture referenced as the Evolved Packet System (EPS) [12]. Figure 2.1 shows a simplified view of EPS and his network elements. As is noticeable there are present all logical nodes and standardized interfaces. It also shown the specific connections that make possible the integration of existing networks architectures like GSM/GPRS/EDGE or 3G UTRAN in EPS. [13] [14]

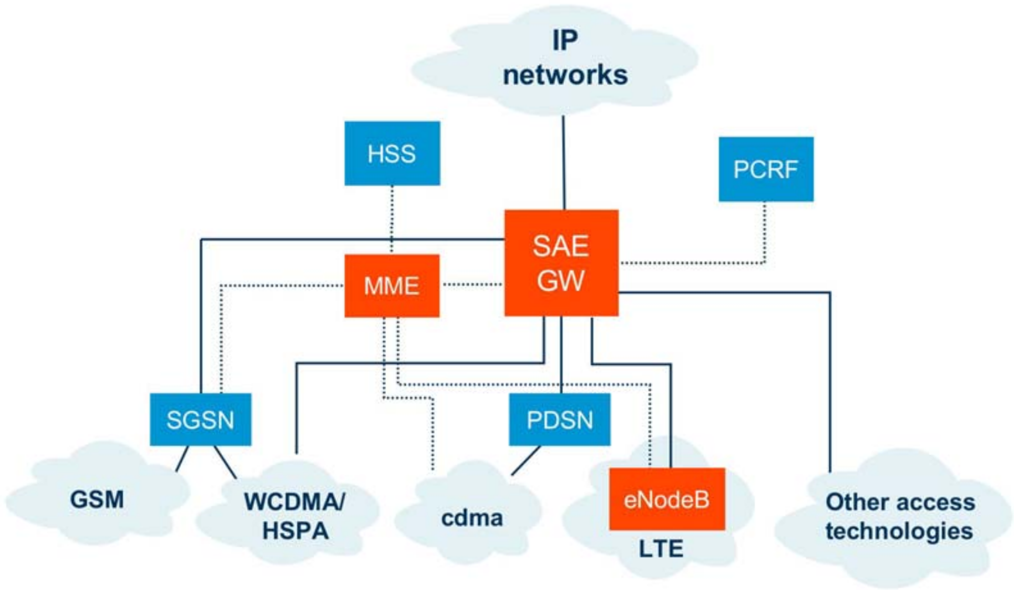


Figure 2.1: Evolved Packet System [15].

It is clear that LTE network architecture could be divided in two high level domains: Radio Access network (E-UTRAN) and CN. While CN have many logical network nodes, E-UTRAN is only constituted by one, the evolved NodeB (eNodeB or eNB).
The LTE network architecture main goal is to provide IP connectivity between UE and the Packet Data Network (PDN) with seamless mobility, quality of service (QoS) and minimal latency. EPS uses the concept of EPS bearers to route IP traffic from a gateway in the PDN to the UE. A bearer is an IP packet flow with a defined Quality of Service (QoS) between the gateway and the UE. The E-UTRAN and EPC together set up and release bearers as required by applications. The network should also ensure effective security and privacy for users.
Both CN and E-UTRAN network elements have different roles and functions which will be more detailed in the following subsections.

2.1.1 Core Network

In the core level domain EPC is a flat all-IP-based and circuit-switched free CN, but his functionality is the same of the previous 3GPP networks. However this architecture is significatively different, in order to simplify the path between UE and PDN for accessing multiple services like Voice over IP (VoIP) and Internet, with different QoS streams. EPC improves network performance by the separation of control and data planes, through a flattened IP architecture, which reduces the hierarchy between mobile data elements. EPC is represented in Figure 2.2.

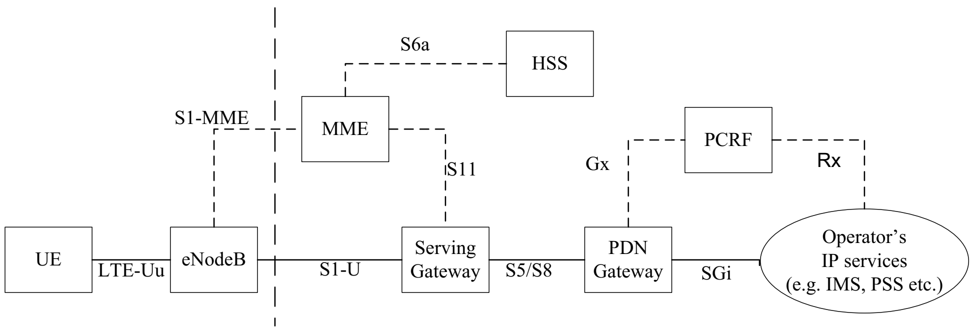


Figure 2.2: Evolved Packet Core.

The main entities of the EPC an their functionalities are shortly summarized bellow:

- Mobility Management Entity (MME)- MME is a signaling entity and is in charge of all the control plane functions related to subscriber and session management. These functions are: managing security functions (authentication, authorization, NAS signalling), terminal session handling and idle state mobility, roaming, and handovers.

- Packet Data Network Gateway (P-GW)- is the termination point of the packet data interface towards the Packet Data Network. Acts as an anchor point for sessions towards the external Packet Data Networks, the PDN-GW also supports Policy Enforcement features and provides security connection between UEs connected from an non-3GPP access network with the EPC.

- Serving Gateway (S-GW)- as the P-GW, the S-GW acts as an anchor, it's the mobility anchor point for both intra E-UTRAN handover and mobility with other 3GPP technologies, such as 2G/GSM and 3G/UMTS. Is the termination point of the packet data interface towards E-UTRAN. It also performs packet routing and forwarding as well inter-operator charging.

In addition to these nodes, EPC also includes other nodes and functions, such as:

- Policy Control and Charging Rules Function (PCRF)- The PCRF server manages the service policy and controls QoS configuration for each user session and accounting rule information. Is the network entity where the policy decisions are made. Provide operator-defined charging rules applicable to each service data flow.

- Home Subscriber Server (HSS)- supports the database containing all the user subscription information. Is the concatenation of the HLR (Home Location Register) and the AuC (Authentication Center) two functions being already present in pre-IMS 2G/GSM and 3G/UMTS networks. The HLR part of the HSS is in charge of storing and updating when necessary the database containing all the user subscription information.

2.1.2 Radio Access Network

Like EPC, E-UTRAN uses an simplified network architecture at the access level interface, and is constituted only by one node element, the the evolved Node B (eNodeB), see Figure 2.3 [16]. E-UTRAN network is a mesh of eNodeBs and all the radio related protocols are held at this point. X2 interface is responsible to inter-connect the neighboring eNodeBs, forming the network.

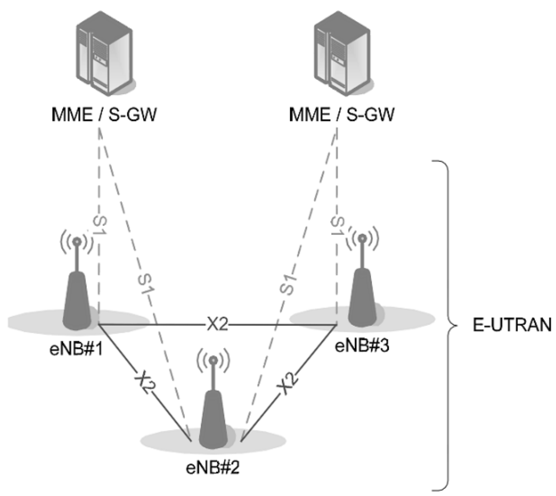


Figure 2.3: Evolved-User Transport Radio Access Network.

The main difference to 2G and 3G radio access is that there is no centralized intelligent controller, and there is no soft handovers, eNodeB's can now inter-operate between them

reducing latency and being more cost-efficient. This brings the advantage of making the network architecture simpler and improves the performance over the radio interface.
Another advantage with the distributed solution is that the MAC protocol layer, which is responsible for scheduling, is represented only in the UE and in the base station leading to fast communication decisions between the eNodeB and the UE. The connection with core network is assured by the S1 interface. More precisely S1-MME interface connects eNodeBs with the MME and the S1-U interface with S-GW making the separation between the user plane and control plane.
From a functional perspective, E-UTRAN is responsible for all radio-related functions, which are summarized as:

- **RRM-Radio Resource Management**- Controls the allocation of radio resources, based on requests and schedules traffic according to required Quality of Service(QOS), and monitories resources usage. This relates to the allocation, modification and release of resources for the transmission over the radio interface between the user terminal and the eNodeB.

- **MM-Mobility Management**- Makes continuous measurements and analysis and control UE measurements, and then make decisions to handover UE between cells. This function relates to terminal mobility handling while the terminal is in an active state.

- **Connectivity to the EPC**- This consists of the signalling towards the MME and the bearer path towards the S-GW.

- **Header Compression**- This helps to ensure efficient use of the radio interface by compressing the IP packet headers which could otherwise represent a significant overhead, especially for small packets such as VoIP. Also answers to the requirements to maintain privavy over the radio interface.

- **Securing and optimizing radio interface delivery**- In the OSI Data Link way, the layer 2 purpose is to ensure transfer of data between network entities. This implies detection and possibly correction of errors that may occur in the physical layer.

All these functions are responsibility of the eNodeBs, and each one can handle multiple cells. The eNodeB is defined by the 3GPP using the traditional OSI model, and the functions above are handled by different layers of the eNodeB, like the physical layer, the RLC/MAC data link layer, or the Radio Resource Control signalling layer.

2.2 Summary

Below on the following Table 2.2 is listed the key features from LTE [5] [17] [18].

Table 2.2: LTE Key Features.

Latency	User-plane	Less than 5 ms latency for small internet protocol (IP) packets
	Control-plane	Transition time of less than 100 ms from a camped state, such as Release 6 Idle Mode, to an active state such as Release 6 CELL-DCH; Transition time of less than 50 ms between a dormant state such as Release 6 CELL-PCH and an active state such as Release 6 CELL-DCH
User throughput	Downlink	average user throughput per MHz, 3 to 4 times Release 6 HSDPA
	Uplink	average user throughput per MHz, 2 to 3 times Release 6 Enhanced Uplink
Co-existence and Interworking with other technologies	Co-existence in the same geographical area with legacy standards and collocation with GERAN/UTRAN on adjacent channels.	
	E-UTRAN terminals supporting also UTRAN and/or GERAN operation should be able to support measurement of, and handover from and to, both 3GPP UTRAN and 3GPP GERAN.	
	The interruption time during a handover of real-time services between E-UTRAN and UTRAN (or GERAN) should be less than 300 ms.	
	Inter-working with others radio access technologies (e.g. cdma2000).	
	Compatibility and inter-working with earlier 3GPP radio access technologies (e.g. GSM and HSPA).	
Radio Resource Management	Enhanced support for end to end QoS	
	Efficient support for transmission of higher layers	
	Support of load sharing and policy management across different Radio Access Technologies	
Mobility	E-UTRAN should be optimized for low mobile speed from 0 to 15 km/h.	
	Higher mobile speed between 15 and 120 km/h should be supported with high performance.	
	Supported up to 350 km/h or even up to 500 km/h.	
Complexity	Minimize the number of options.	
	No redundant mandatory features.	

Peak data rate	Downlink	100Mbps within 20Mhz spectrum allocation (5 bps/Hz)
	Uplink	50Mbps within 20 MHz spectrum allocation (2.5 bps/Hz)
Spectrum flexibility	LTE can be deployed with different bandwidths allocations ranging from approximately 1.25MHz up to approximately 20MHz, for the uplink and downlink, and can operate in both paired and unpaired spectrum.	
	The system shall be able to support content delivery over an aggregation of resources including Radio Band Resources (as well as power, adaptive scheduling, etc.) in the same and different bands, in both uplink and downlink, and in both adjacent and non-adjacent channel arrangements. A "Radio Band Resource" is defined as all spectrum available to an operator.	
Spectrum efficiency	Downlink	In a loaded network, spectrum efficiency (bits/sec/Hz/site) is 3 to 4 times Release 6 HS-DPA (5 bps/Hz).
	Uplink	In a loaded network, spectrum efficiency (bits/sec/Hz/site) is 2 to 3 times Release 6 HSUPA (2.5 bps/Hz).
Spectrum arrangement	FDD and TDD within a single radio access technology (operation in paired and unpaired spectrum).	
Further enhanced Multimedia Broadcast Multicast Service (MBMS)	Support for MBSFN (Multicast Broadcast Single Frequency Network) for efficient Multicast/Broadcasting using single frequency network by OFDM.	
Architecture	The E-UTRAN architecture shall be packet based, although provision should be made to support systems supporting real-time and conversational class traffic.	
	E-UTRAN architecture shall minimize the presence of "single points of failure".	
	Backhaul communication protocols should be optimised.	
	Support of load sharing and policy management across different radio access technologies.	
	E-UTRAN architecture shall support an end-to-end QoS.	
Control-plane Capacity	At least 200 users per cell should be supported in the active state for spectrum allocations up to 5 MHz.	
Coverage	Throughput, spectrum efficiency and mobility targets can be met for 5 km cells, and with slight degradation for 30 km cells. Cells with a range up to 100 km are also supported with acceptable performance.	

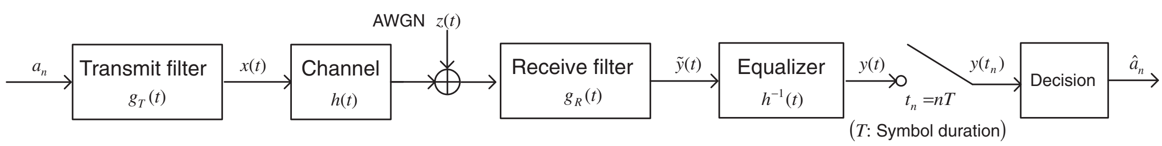
Chapter 3

Multi-carrier Systems

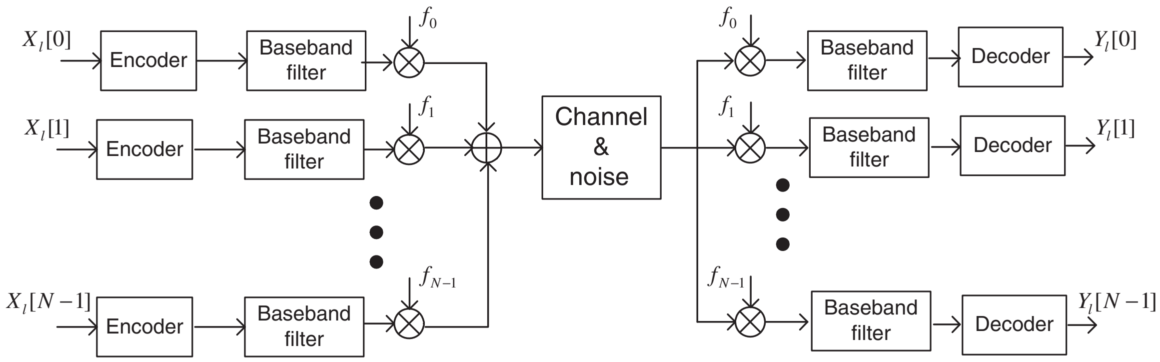
As mentioned above the orthogonal frequency division multiplexing is the modulation scheme chosen to support LTE. Through this chapter, the multi-carrier system and its principles are explained, focusing on the multiple access techniques, such as OFDMA, used for downlink and SC-FDMA for uplink.

Single-carrier transmission limitations are well known, mobile radio channels tend to be dispersive and time-variant, and for achieving high data rates it implies a high bandwidth required. Frequency spectrum become a scarce resource, and already experience high saturation caused by intensive use in several other applications, therefore its use should be as efficient as possible. To join high data rates in transmission and high spectral efficiency, use of multi-carrier systems approach is the natural path to follow.
In LTE particular case the multi-carrier modulation system OFDM, provides robustness to multipath interference, low implementation complexity and of course high broadband transmission rates [19].

In the following Figure 3.1 we can observe the differences between the basic architecture of a single-carrier system and a multi-carrier system.



(a) Single-carrier system



(b) Multi-carrier system

Figure 3.1: Multi-carrier and Single-Carrier Systems.

3.1 OFDM

Orthogonal frequency division multiplexing (OFDM) transmission scheme is a type of multicarrier transmission system. A typical single-carrier system modulates information onto one carrier using frequency, phase, or amplitude adjustment of the carrier. If the bandwidth (data rates) increases, the duration of the data symbols becomes smaller. Thus the system becomes more susceptible to loss of information from impulse noise, signal reflections and other signal degradation mechanisms. These impairments can impede the ability to properly recover the information sent. In addition, as the bandwidth used by a single carrier system increases, the susceptibility to interference from other signals rises.

The breakpoint with single-carrier transmission, is that in OFDM, the used channel bandwidth by one carrier is subdivided in several narrowband subcarriers, so that the bandwidth of each narrowband subchannel is such that they are non frequency-selective. Frequently referenced as an evolution of Frequency Division Multiplexing (FDM) it brings advantages through manipulation in frequency domain. As is well known in FDM, to properly transmit between two points through space, it's required a enough separation between subcarriers in order to prevent the spectrum of one subcarrier from interfering with another [20]. The use of guard bands leads to a loss of spectral efficiency. Making use of the important property of orthogonality, the resultant subcarriers can be overlapped without compromise the data transmitted, avoiding the need to separate subcarriers by guard-bands. Naturally the space occupied in the spectrum is considerably reduced, making OFDM highly spectrally efficient, as we can see in Figure 3.2.

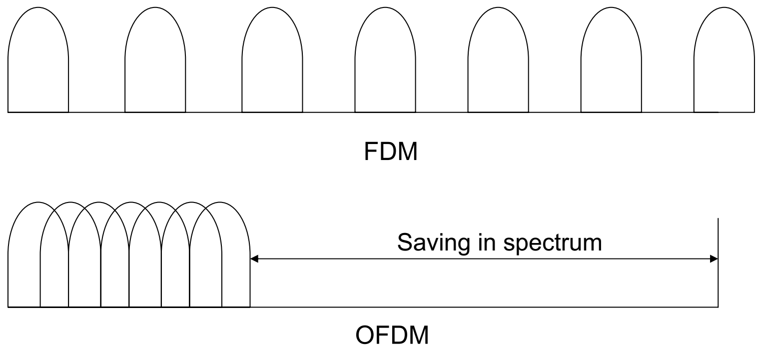


Figure 3.2: OFDM vs FDM Spectrum. [21]

Since the data is transmitted in parallel in determined number of subcarriers, the transmission rate of each subcarrier is as slower as the number of subcarrier rises, causing immunity to interference and time dispersion.

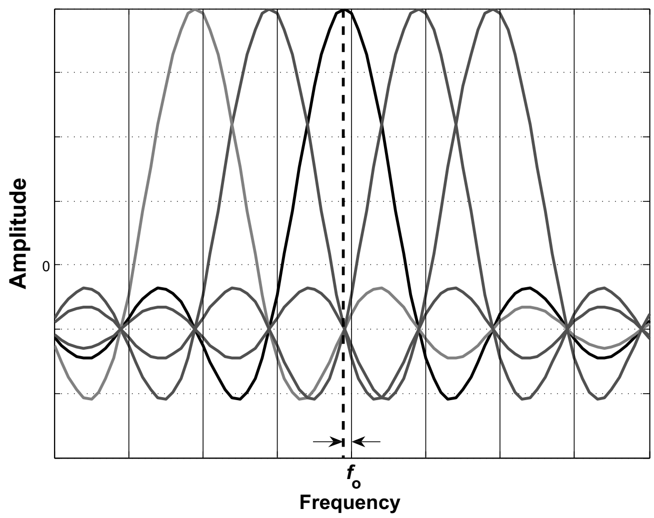


Figure 3.3: OFDM spectrum.

Figure 3.3 shows us that the subcarriers have the exact separation between them, that the maximum of one subcarrier is coincident with the nulls of the rest of them. Despite of the overlap of subcarriers can be easily separated at the receiver with low complexity implementation. The economy in the spectrum can reach over 50% compared to FDM.
In the time domain to generate subcarriers with the precise separation, it have to be very accurate but this process is simplified using a combination of the Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) blocks that are mathematically equivalent versions of the discrete Fourier transform (DFT) and Inverse Discrete Fourier transform

(IDFT), respectively, but more efficient to implement. [11]
All these potential benefits cannot be secured only by the simple use of OFDM, as we will explain in detail in the following sections. OFDM by itself cannot translate into robustness against time-variant channels, in a frequency selective channel some subcarriers are subject to experiencing fades causing symbol detection errors, but with the use of proper techniques such as, channel coding and the insertion of a guard period known as Cyclic Prefix (CP), OFDM can be adapted to better operate in different channel conditions.

Today OFDM is widely implemented in diverse applications from digital television and audio broadcasting to wireless local area networking (WLAN) and wired broadband internet access, they benefits from low complexity of the OFDM receiver, and and low power required for transmission.

The motivation for OFDM utilization, in LTE and other concurrent systems has been due to the following properties [13]:

- robustness to frequency selective fading channels;
- low complexity in receiver;
- good spectral properties and spectral flexibility;
- link adaptation and frequency domain scheduling;
- compatibility with multiple antenna techniques.

3.1.1 Modulation

In OFDM modulation the transmitter maps the message bits into a sequence of symbols (e.g QPSK or 16-QAM) then the serial-to-parallel (S/P) converter takes a block of symbols, subsequently converts it into N parallel streams. Each of N symbols is mixed with one of the subcarriers by adjusting its amplitude and phase. These N modulated subcarriers are then combined to give an OFDM signal.
Distinctly to single-carrier modulation where with an data symbol period T_{symb} transmission is made at baud rate of R symbols per second, $T_{symb} = \frac{1}{R}$. By transmitting N symbols in a parallel form its length is extended to $T_{symb} = \frac{N}{R}$. So the available bandwidth W is divided into N subcarriers separated by $\Delta f = \frac{W}{R}$, equal to 15 kHz defined in LTE specifications. Theoretically it is easy to prove that inter symbol interference (ISI) can be reduced by an simple addition in the number of subcarriers. Since T_{symb} increases, compared to time dispersion imposed by a multipath channel, the robustness to channel distortion and fading is better.
The symbol length is defined by the fact that for OFDM systems the symbol length is equal to the reciprocal of the carrier spacing so that orthogonality is achieved. With a carrier spacing

of $15kHz$ used in LTE, this gives the symbol length of $66.7\mu s$.

The OFDM modulation and demodulation mechanism described above can be exemplified by the block diagram in Figure 3.4.

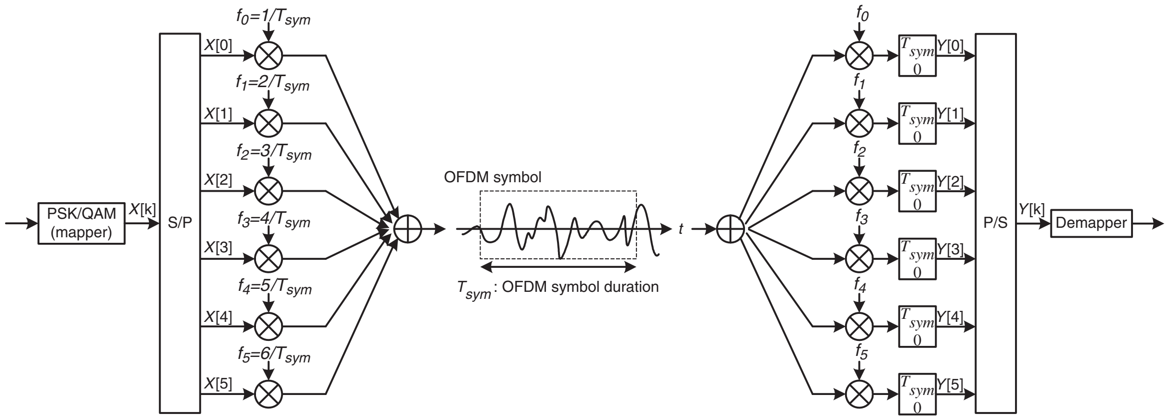


Figure 3.4: OFDM modulation and demodulation.

At the receiver the received OFDM signal is demultiplexed into N frequency bands, and the N modulated signals are demodulated. The baseband signals are then recombined using a parallel-to-serial converter (P/S).
As it has been told, this multi-carrier modulation system can be implemented by IFFT and FFT in the transmitter and receiver, respectively, so that equalization is simplified into single multiplications in the frequency domain [19].

3.1.2 Orthogonality

Orthogonality is the key property in OFDM that leads to high spectral efficiency. Is an essential condition for the OFDM signal be inter-carrier interference (ICI) free, and permits simple separation of the overlapped subcarriers by the receiver. Allows that theoretically the signals can be transmitted over a shared channel without interference. However this property is not always achievable in practice, and loss of orthogonality can occur. Degradation of the transmitted signal is the consequence.

Whereas two signal, they are defined to be orthogonal if the integral of the product between their functions over a symbol period is zero. Equation 3.1 define the fundamental conditions of orthogonality.

$$\int_0^T S_i(t).S_j(t) = \begin{cases} C & i = j \\ 0 & i \neq j \end{cases} \tag{3.1}$$

In the previous Figure 3.3 is showed the resultant spectrum. Each subcarrier as a form of an sinc function, the rate of the phase modulation determine the position of the zero crossings in frequency. They all have the same amplitude and the peaks and nulls line up perfectly.

3.1.3 Cyclic prefix

Passing parallel subcarriers of an OFDM signal through a time-dispersive channel creates ISI at the symbol boundaries. Even the inherent robustness of OFDM to ISI, given by low symbol rate, can not ensure orthogonality. The delay spread in the transmission channel due to multipath propagation causes delay in some subcarriers and arrives to the receiver at different times, spreading the symbol boundaries and causing energy leakage, distorting the received signal.

In order to optimize demodulation performance and reject both ISI and ICI, cyclic prefix is added to extend the OFDM symbol by copying part of the symbol at the end an attaching into the beginning of the symbol thus extending the length of the symbol waveform, see Figure 3.5.

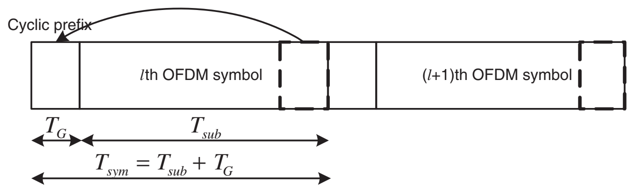


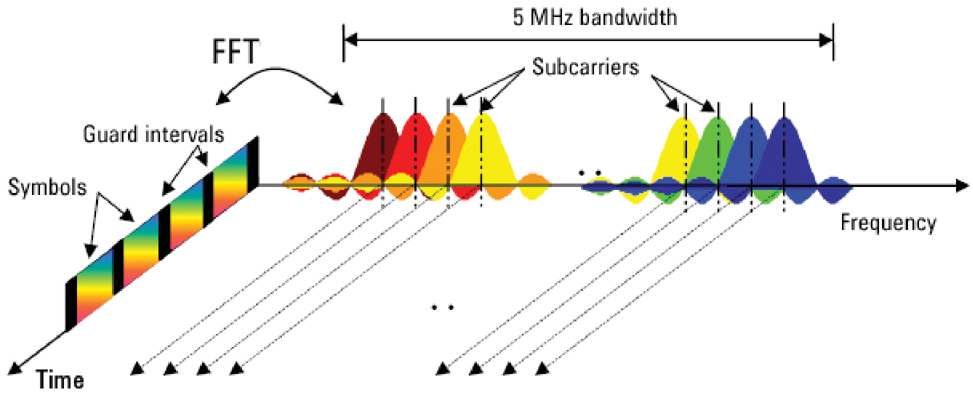
Figure 3.5: Cyclic Prefix. [22]

Then, the extend OFDM symbol now have the duration:

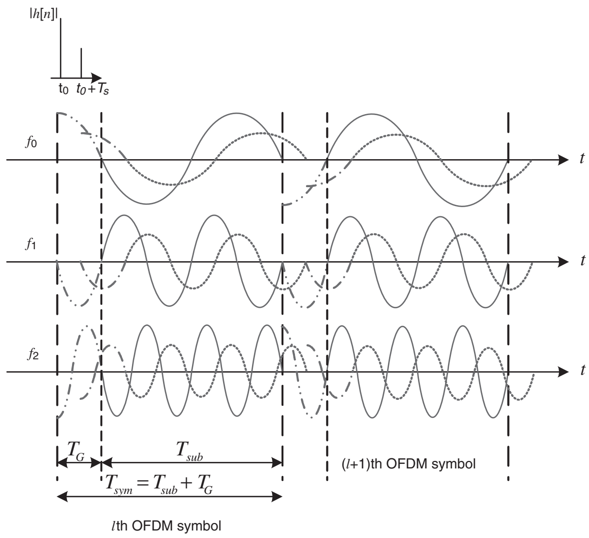
$$T_{symb} = T_G + T_{sub} \tag{3.2}$$

In Equation (3.2) T_G refers to CP length, and T_{sub} to the concrete symbol length and T_{symb} the overall length. The CP adds redundancy through repetition of the signal rather then adding new information. In LTE standards CP has two possibilities, short CP and long CP.

Figure 3.6(a) shows the OFDM symbols with CP added in the time and frequency domains. Figure 3.6(b) shows the ISI effects of a multipath channel on some subcarriers of the OFDM symbol (plotted in a dotted line). As can be seen in the figure, the orthogonality between subcarriers is maintained if the CP length is set longer than or equal to the maximum delay spread of the multipath channel. Thereby the ISI effect of one OFDM symbol do not affects the FFT of the following symbol, taken for the duration of T_{sub}. As the continuity of each delayed subcarrier has been warranted by the CP, its orthogonality with all other subcarriers is maintained.



(a) Time/frequency-domain description of OFDM symbols with CP



(b) ISI effect of a multipath channel in subcarriers

Figure 3.6: Effects of a multipath channel on OFDM symbols with CP.

Thus the choice of T_G is based on the channel impulse response. Guard interval (CP) is set longer than the equal to the maximum delay spread of a multipath channel. However if it is too long, then it will reduce the data throughput capacity. It is also critical have in attention the maximum acceptable duration of T_G, since when it is increased, also the transmitted energy is increased. For LTE, the standard length of the cyclic prefix has been chosen to be $4.69\mu s$ for short CP. This enables the system to accommodate path variations of up to $1.4km$. Long CP duration is $16.67\mu s$ which is suitable for very large cells with high time dispersion.

3.2 LTE Physical Layer

3.2.1 Duplexing

In mobile communications in order to be able to transmit in both directions, a duplex scheme is needed. Duplexing refers to the mechanism of dividing a communication link for downlink and uplink.
As already referenced in Chapter 2 three different duplex schemes are supported in LTE:

- FDD (Frequency Division Duplexing)
- TDD (Time Division Duplexing).
- Half-duplex FDD

Figure 3.7 illustrates the three duplex schemes.

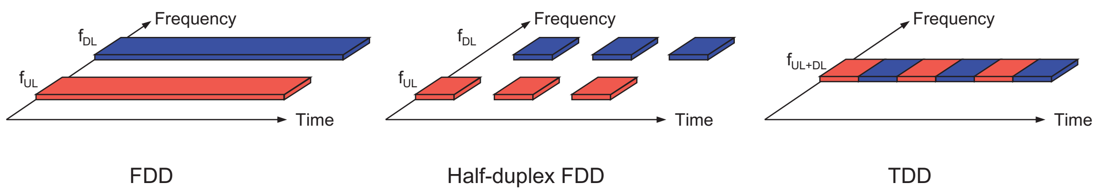


Figure 3.7: Duplex schemes [9].

FDD as figure shows, uses different frequency bands (sufficiently separated) for simultaneous downlink and uplink signal transmission. Although it requires downlink and uplink RF parts separately, it has the drawback of low flexibility.
TDD implies that uplink and downlink communication taking place in the same frequency band but in different non-overlapping time slots, separated by a guard time. TDD, downlink operates in unpaired spectrum, but it has an advantage of high flexibility when downlink and uplink transmissions have different traffic loads because assignment of downlink and uplink time slots can be controlled dynamically [23].
In Half-duplex FDD, transmission and reception are separated both in frequency and time. The main benefit is the reduced terminal complexity as no duplex filter is needed in the terminal.
Despite the differences between the duplex schemes, all of the physical layer processing is identical, the difference is manly is the frame structure which is discussed in next subsection.

3.2.2 Frame structure

The LTE air interface is described both in time and frequency domains. Despite it uses different multiple access schemes, for downlink and uplink, the generic frame structure is similar for both. In addition, two types of frame structures are defined: type 1 for FDD and type 2 for TDD [24].

LTE maps physical channels and physical signal into OFDM symbols and subcarriers. The organization of symbols and subcarriers defines the frame, slot, and symbol in the time domain. The shortest time interval of interest to the physical channel processor is defined as follows:

$$T_s = \frac{1}{2048 \times 15000} seconds \approx 32.6ns, \tag{3.3}$$

Considering that T_s is the sampling interval, if the system uses a fast Fourier transform that contains 2048 points, which is the largest to be used. The $66.7\mu s$ symbol duration is then equal to 2048 T_s.
As shown in Figure 3.8 the symbols are grouped into slots with $0.5ms$ duration of either 6 or 7 OFDM symbols, depending on whether the normal or extended CP is employed, respectively. Each radio frame is 10 ms long and is divided into 10 subframes of 1 ms each. Two consecutive time slots makes one subframe.

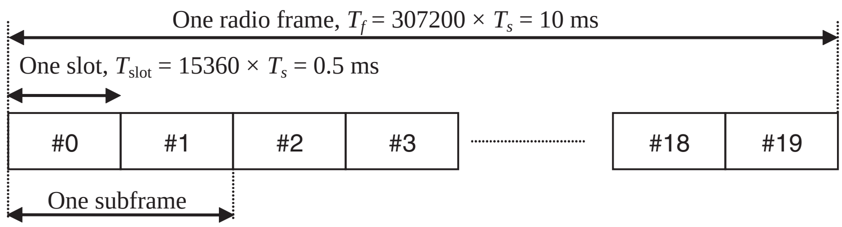


Figure 3.8: Frame structure type 1 (FDD).

Figure 3.8 represent frame structure type 1 for FDD mode (for both full duplex and half duplex operation), for TDD mode, the structure type 2, as shows Figure 3.9 has frames, subframes and slots with the same duration of the type 1, the 10 ms TDD frame consists in two half-frames with a duration of 5ms each each and containing each 8 slots.

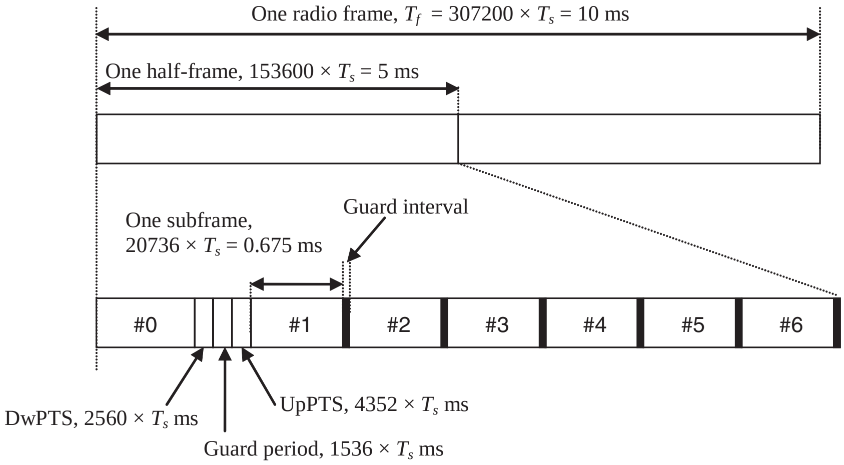


Figure 3.9: Frame structure type 2 (TDD).

Each half-frame is divided into five subframes of each 1 ms. A sub-frame also consists of two adjacent slots, but in this case each subframe can be allocated to either uplink or downlink using one of the TDD configurations shown in Figure 3.10. There are special subframes used at the downlink to uplink transmission, and they contain three fields that consists in Downlink Pilot Time slot (DwPTS), Guard Period (GP) and uplink Pilot Time slot (UpPTS). Both 5ms and 10ms switch-point periodicity are supported. The fields are individually configurable in terms of length, although the total length of all three together must be 1ms. Seven uplink-downlink configurations are supported with both types (10ms and 5ms) of downlink-to-uplink switch-point periodicity. Further details on the LTE frame structure are specified in [25].

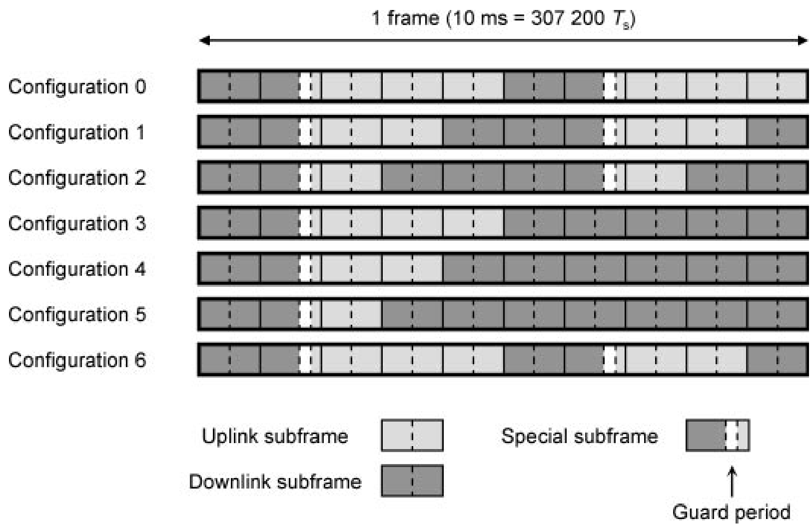


Figure 3.10: Frame type 2 uplink-downlink configurations for TDD [6].

Figure 3.11 shows the resource grid for the case of a normal cyclic prefix organized as a function of frequency as well as time.(A similar grid for the extended cyclic prefix, which uses six symbols per slot rather than seven, also exists).

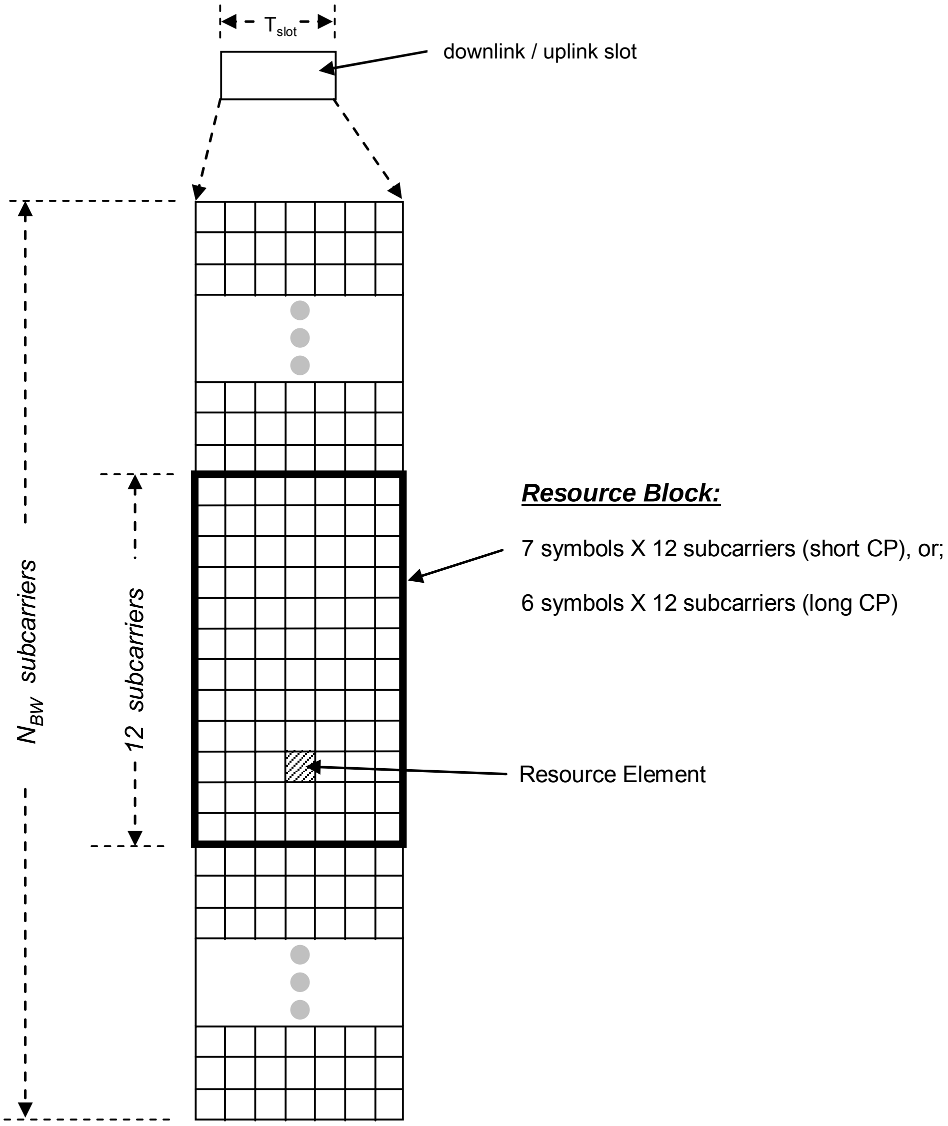


Figure 3.11: LTE resource Grid.

The basic unit is a Resource Element (RE), consisting of one subcarrier during one OFDM symbol. REs are grouped into Resource Blocks (RB), where each RB consists of 12 consecutive subcarriers in the frequency domain and one 0.5ms slot in the time domain, each RE usually carries two, four or six physical channel bits, depending on whether the modulation

scheme is QPSK, 16-QAM or 64-QAM. Each resource block thus consists of $7 \times 12 = 84$ resource elements in the case of a normal cyclic prefix and $6 \times 12 = 72$ resource elements in the case of an extended cyclic prefix. Although RBs are defined over one slot, the minimum scheduling unit for dynamic scheduling consists in two consecutive slots within one subframe (one physical RB per slot). The reason for defining the RBs over one slot is that distributed downlink transmission and uplink frequency hopping are defined on a slot or RB basis.
The uplink uses the same resource structure as the downlink. In frequency domain, 12 subcarriers are grouped together occupying total 180 kHz in one slot duration as illustrated. Uplink modulation parameters (including normal and extended CP length) are identical to the downlink parameters. Table 3.1 shows the detailed modulation parameters specified on LTE Release 8.

Table 3.1: LTE Release 8 modulation parameters [26].

Channel Bandwidth (MHz)	1.25	2.5	5	10	15	20
Frame Duration (ms)	10					
Subframe Duration (ms)	1					
Subcarries Spacing (kHz)	15					
Sampling Frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT size	128	256	512	1024	1536	2048
Occupied Subcarriers (incl. DC subcarrier)	76	151	301	601	901	1201
Guard subcarriers	52	105	211	423	635	847
Number of Resource Blocks	6	12	25	50	75	100
Occupied Channel Bandwidth (MHz)	1.140	2.265	4.515	9.015	13.515	18.015
DL Bandwidth Efficiency	77.1%	90%	90%	90%	90%	90%
OFDM Symbols/Subframe	7/6 (short/long CP)					
CP length (Short) (μs)	5.2(first symbol)/4.69(six following symbols)					
CP length (Long) (μs)	16.67					

3.2.3 Channel estimation

Despite in OFDM system the receiver does not deal with the inter-symbol interference, the received signal is usually distorted by the channel impact for the individual subcarriers that have experienced frequency dependent phase and amplitude changes.
In order to recover the transmitted signal and allow coherent demodulation at UE, the channel effect must be estimated and compensated in the receiver. This can be done by inserting in the OFDM time/frequency grid, known reference symbols (or pilot symbols). With the proper placement of these symbols in both the time and frequency domains at regular intervals , the receiver can interpolate the effect of the channel.
In LTE downlink three types of reference signals are defined [27]:

- Cell specific downlink reference signals are transmitted in every downlink subframe, and span the entire downlink cell bandwidth. Associated with non-MBSFN trasnmission, support a configuration of one, two or four antenna ports [16].
- UE-specifc reference signals are specifically intended for channel estimation for coherent demodulation of downlink-shared-channel (DL-SCH) transmissions. The term UE-specific relates to the fact that each such reference signal is typically intended to be used for channel estimation by one specific terminal. Is only supported in frame structure 2.
- MBSFN reference signals are used for channel estimation for coherent demodulation of signals being transmitted by means of MBSFN.

The basic structure for cell-specific downlink reference signals for an LTE system with one antenna in normal CP mode is illustrated in Figure 3.12.

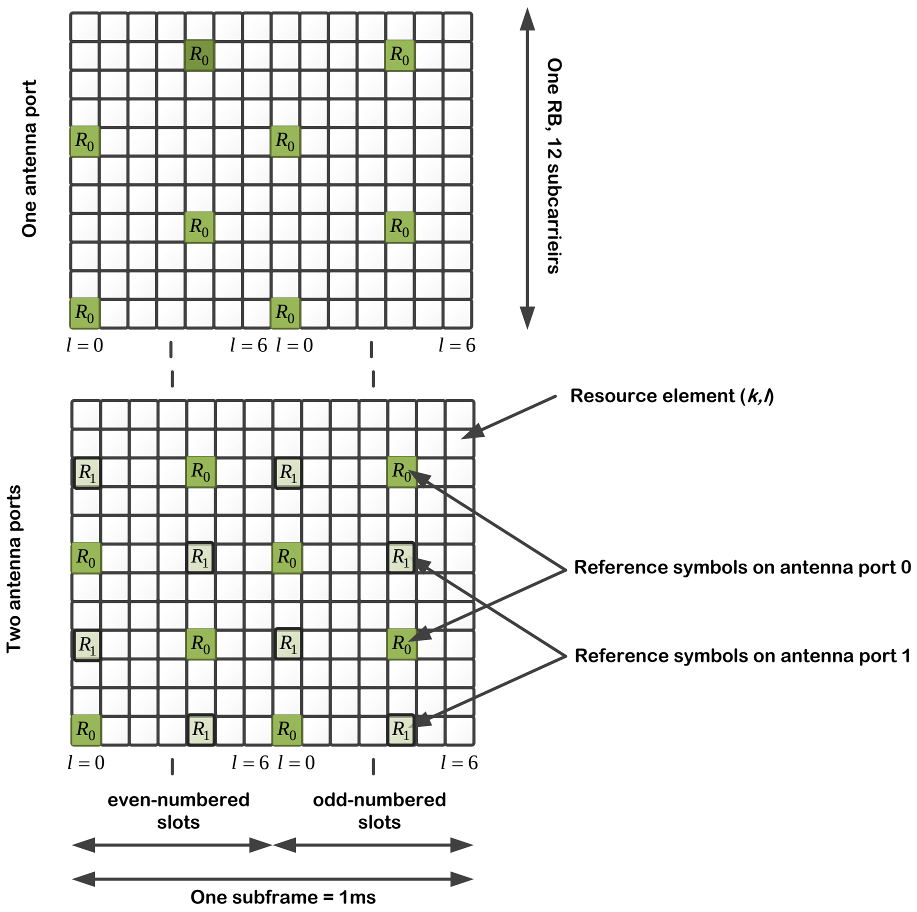


Figure 3.12: Cell-specific downlink reference signals.

The cell-specific downlink reference symbols are inserted within the first and fourth or fifth OFDM symbol of each slot in case of extended or normal cyclic prefix, respectively, with a frequency domain spacing of six subcarriers [19].

In the figure is also present that one resource grid is defined per antenna port, in case of multi-antenna transmission. Each antenna port is defined by its associated reference signal. The resource elements used for resource signals transmission on one antenna port are left blank in all other antenna ports.

As we notice downlink reference signals are implemented following a frequency-time division approach. In the uplink approach since SC-FDMA is used, same principle can not be used, therefore uplink reference signals follows a time-multiplexed approach. Another difference relative to downlink reference signals is that uplink reference signals are always UE-specific.

By the knowledge about the reference symbols, the receiver can estimate the frequency-domain channel around the location of the reference symbols. The channel estimation over antennas can be performed independently for each link between each transmitting antenna and each receiving antenna. The reference symbols should have a sufficiently high density in both the time and the frequency domain to be able to provide reliable estimates, therefore different algorithms can be used for the channel estimation in the receiver.

3.3 OFDMA

So far has been made an introduction to OFDM principles but LTE standard uses a variant of OFDM for the downlink called Orthogonal Frequency Division Multiple Access (OFDMA).

In general OFDM is a transmission technique in which all subcarriers allocated, are fixed for transmitting the symbols of a single user, it is not a multiple access technique. However it can be associated with other existing multiple access techniques, such as TDMA, FDMA or CDMA for a multi-user system. The OFDMA can be seen as a hybrid technique of the FDMA and TDMA techniques.

As depicted in the Figure 3.13 which shows the difference between OFDM and OFDMA subcarrier allocation, in OFDMA all subcarriers can be shared by multiple users and can be allocated dynamically. In this technique to each user is provided a unique fraction of the system bandwidth per each specific time slot. The result is a more robust system with increased capacity, given by the ability to perform resource scheduling based on the channel time and frequency responses in order to avoid narrowband interference and multipath fading. This ability is known as multiuser diversity [12].

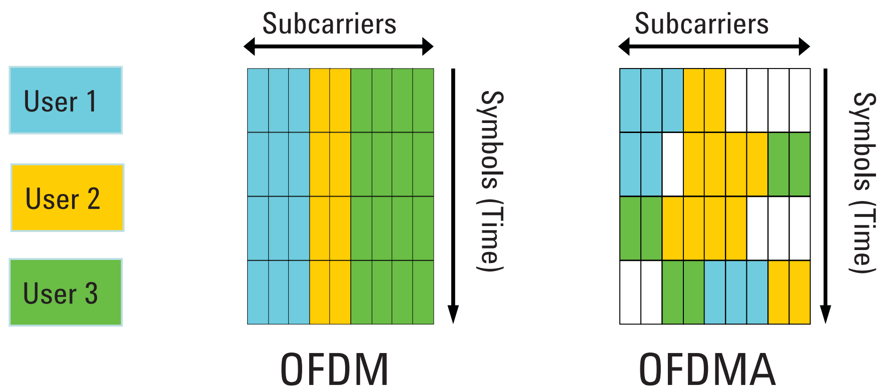


Figure 3.13: OFDM and OFDMA subcarrier allocation [28].

OFDMA meets the LTE requirements for spectrum flexibility, and this resulting flexibility can be utilized in diverse ways, which are summarized next: ·

- Transmission resources of variable bandwidth can be allocated to different users and scheduled dynamically in the frequency domain.

- Frequency re-use and interference coordination between cells are facilitated.
- Different spectrum bandwidths can be utilized without changing the system parameters or equipment design.

OFDMA has not only advantages. The small spacing of the subcarriers, makes it susceptible to frequency synchronization errors, phase noise and also Doppler shift, which can cause ICI. Moreover, the overall efficiency reduces by inserting cyclic prefix. In addition OFDMA creates high peaks to average signals.

3.4 SC-FDMA

The reasons behind the choice of SC-FDMA for the uplink is that, SC-FDMA combines advantages of both single-carrier transmission and OFDMA, respectively low PAPR, and multipath resistance and flexible frequency allocation .

In this technique data symbols in the time domain are converted to the frequency domain using a DFT; then in the frequency domain they are mapped to the desired location in the overall channel bandwidth before being converted back to the time domain using an IFFT. Finally, the CP is inserted. In Figure 3.14 the SC-FDMA architecture and the main differences to the OFDMA architecture are depicted.

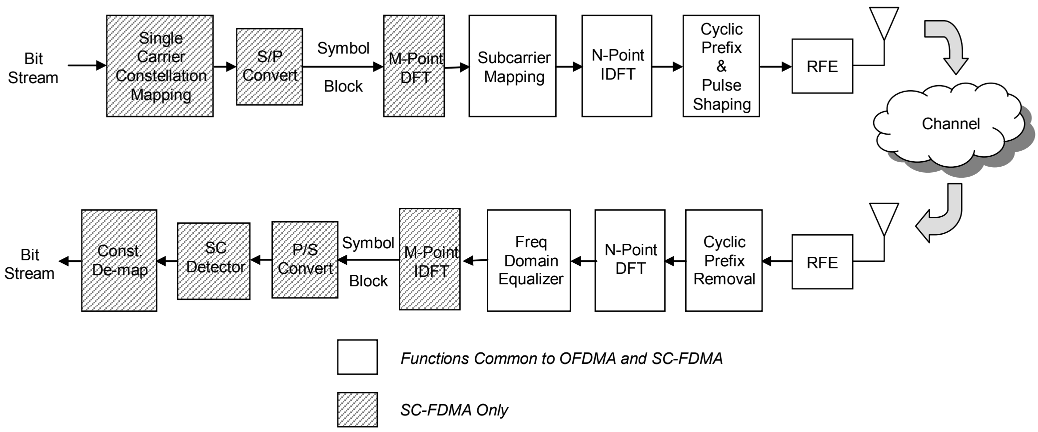


Figure 3.14: OFDMA and SC-FDMA architecture.

Because SC-FDMA uses this technique, it is sometimes called discrete Fourier transform spread OFDM or (DFT-SOFDM). Figure 3.15 shows a graphical comparison of OFDMA and SC-FDMA.

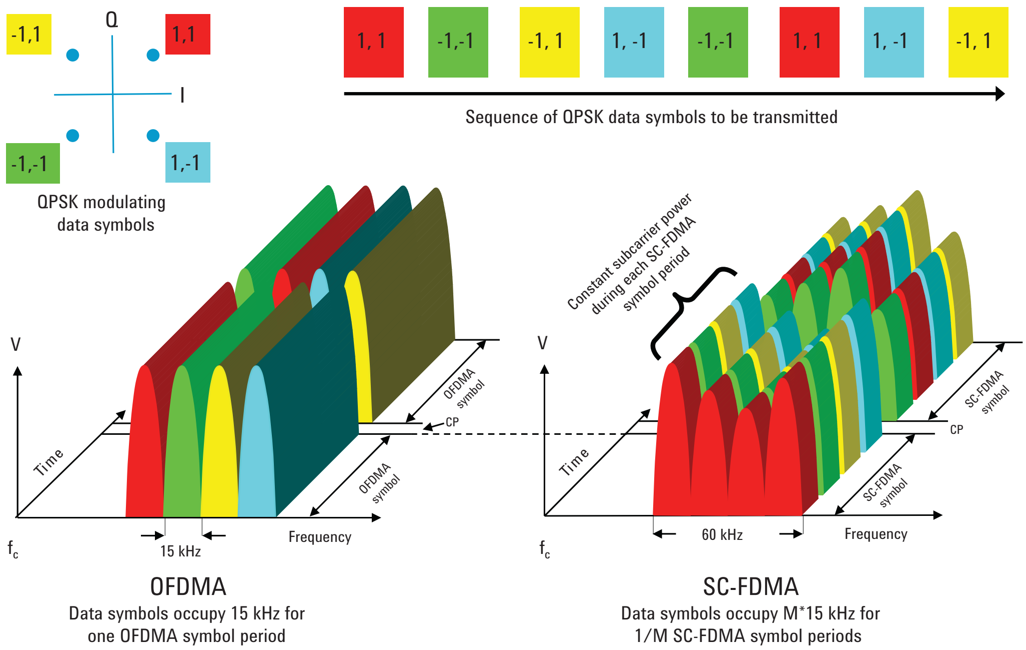


Figure 3.15: OFDMA and SC-FDMA [28].

In this Figure, as title of example, only 4 subcarriers are used to transmit 8 QPSK data symbols over 2 OFDMA symbol periods, instead of 12 adjacent subcarriers presented in LTE specifications. Important to notice is that on the left side of Figure 3.15 OFDMA transmits on each symbol period, the 4 QPSK symbols in parallel, one per subcarrier, while on the left side we can see that in SC-FDMA transmits the 4 QPSK symbols in series at four times the rate, with each data symbol occupying 4 x 15 kHz bandwidth.
It's plausible to say that visually, the OFDMA signal is obvious multi-carrier while SC-FDMA appears to be more like single-carrier.

It is the parallel transmission of multiple symbols that creates the undesirable high PAPR of OFDMA. By transmitting the M data symbols in series at M times the rate, the SC-FDMA occupied bandwidth is the same as multi-carrier OFDMA but, crucially, the PAPR is the same as that used for the original data symbols.

The addition of several narrowband QPSK waveforms, as in OFDMA creates higher peaks, compared what it would be in the wider-bandwidth, single-carrier QPSK waveform as in SC-FDMA. Increasing the subcarriers number, increases the PAPR in OFDMA but remains the same for SC-FDMA.
Since SC-FDMA effectively spreads each modulated symbol across the entire channel bandwidth that makes it less sensitive to the channel frequency-selective fading effect as compared to OFDMA.

Chapter 4

Multiple Antenna Techniques

Multiple antenna techniques adopted by LTE, is one of the fundamental technologies used to achieve high peak data rates, to increase coverage and improve physical layer capacity.

The basic principle of this technique is adding additional antennas to a radio system, both in the transmitter and receiver or only in one of the sides, taking advantage of the different paths that the signals will take, performance improvements are possible. The addition in the number of antennas can be used to achieve different purposes, and there are three main types of techniques.

- The first one is to provide additional diversity gain against multipath fading on the radio channel, by means of transmitting or receiving over multiple antennas at which the fading is sufficiently uncorrelated.
- Multiple antennas can be used to impose a determined direction of the overall antenna beam, in one direction, controlling the phase relationships of electrical signals. Antenna gain can be maximized in a specific direction, it is usually called by beamforming. Because every single antenna in the array makes a contribution to the steered signal, an array gain (beamforming gain) is obtained.
- The third type is multiplexing gain which makes use of spatial separation of multiple antennas on both sides, which form multiple parallel communication channels, through the use of spatial multiplexing. Refers to the ability to send multiple data streams in parallel. It is known as multiple-input, multiple-output (MIMO) system.

Specified on the first LTE release multiple antenna techniques are supported both for downlink and uplink.

Let us remind what Release 8 LTE standards specifies about multi-antenna schemes in the Table 4.1.

Table 4.1: LTE Release 8 multi-antenna schemes [28]

Direction	Schemes supported
Downlink	1x1, 1x2, 2x1, 2x2, 4x2, 4x4
Uplink	1x1, 1x2, 2x2

To yield good performance over a broad range of scenarios, LTE provides an adaptive multi-stream transmission scheme in which the number of parallel streams can be continuously adjusted to match the instantaneous channel conditions.
When channel conditions are very good, up to four streams can be transmitted in parallel, yielding data rates up to 300Mbps in a 20MHz bandwidth.
When channel conditions are less favorable, fewer parallel streams are used. The multiple antennas are used to improve overall reception quality and, as a consequence, system capacity, instead. To achieve good coverage (for example, in large cells), one single stream beamforming transmission can be employed.
In summary, LTE standards besides MIMO, supports other schemes, like SISO,MISO and SIMO including the concepts of transmit and receive diversity as well beamforming. Following in this chapter we will dig deeper into multi-antenna techniques applicable to LTE.

4.1 Antenna Configurations

Figure 4.1 shows the four ways to make use of the radio channel. For simplicity it will be considered a maximum of two antennas on each side.

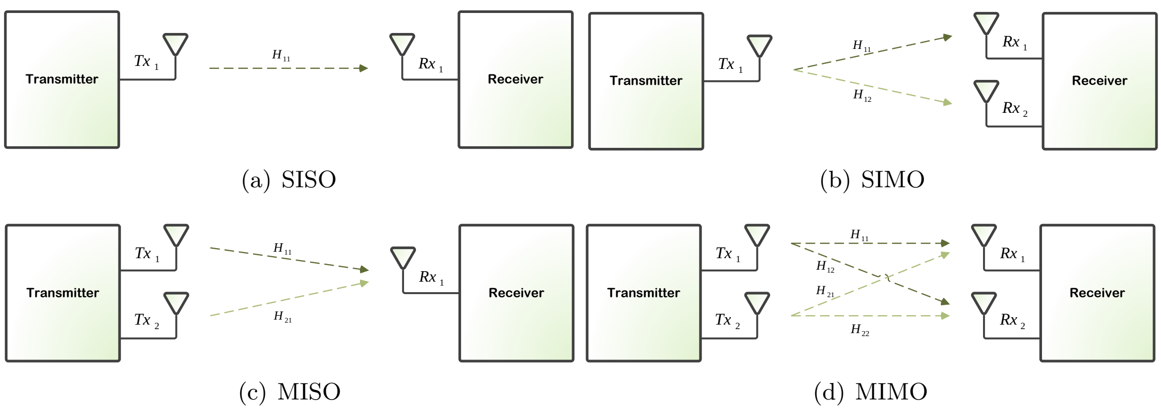


Figure 4.1: Multiple antenna configurations

- **SISO** Single input single output is the most basic scheme, where only one transmit antenna and one receive antenna are used. This configuration is the most commonly implemented in traditional radio systems.

- **MISO** Multiple input single output mode uses two or more transmitters and only one receiver. This mode is usually referred as a transmission diversity technique. Is used to improve signal robustness under fading conditions.

- **SIMO** Single input Multiple output which uses one transmitter and two or more receivers. Describes receive diversity. With this mode is possible a gain of 3 dB with low signal-to-noise(SNR)conditions. Coverage is also improved due to the lowering of usable SNR [12].

- **MIMO** Multiple input multiple Output, at last, requires two or more antennas on both sides. MIMO increases spectral capacity by transmitting multiple data streams simultaneously in the same frequency and time, taking full advantage of the different paths in the radio channel, its called spatial multiplexing.

There are many schemes standardized in 3GPP LTE, and the base station scheduler has the ability to optimally select the scheme that suits the channel conditions of the mobile.
For high SNR and SINR areas with rich scattering environments, the pure MIMO scheme is appropriated, it requires two or more transmit antennas and two or more receive antennas. This mode is not just a superposition of MISO and SIMO, because multiple data streams are transmitted simultaneously in the same frequency and time, taking full advantage of the different paths in the radio channel. Adding receive diversity (SIMO) to MISO does not create a pure MIMO system, even though there are now two transmit and two receive antennas involved.
It is always possible to have more transmitters than data streams but not the other way around. If a number, N, of data streams is transmitted from fewer than N transmit antennas, the data cannot be fully detected independently of the number of receive antennas are present. Overlapping data streams without the addition of spatial diversity simply creates interference [9].
When channel conditions become less favorable to spatial multiplexing (SM), i.e. relatively low SNR and SINR, such as at high load or at the cell edge, SM provides relatively limited benefits. Therefore instead SM, transmit/receive diversity and beamforming should be used in such scenarios, to raise the SNR/SINR.
Unlike MIMO, which achieves its highest throughput when the radio channel exhibits uncorrelated transmission paths, beamforming exploits correlation so that the radiation pattern from a transmitter is directed toward the receiver. This is done by applying small time delays to a calibrated phased array of antennas. The effectiveness of beamforming varies with the

number of antennas. Little gain improvement is achieved with just two antennas but, with four antennas, considerable improvement in gain is possible.
Transmit diversity using e.g. the Alamouti space-time block code or space-frequency block codes also strives for improving the capacity. In contrast to beamforming, transmit diversity does not improve the average SINR but rather, due to diversity, reduces the variations in the SINR experienced by the receiver [28] [29].

4.2 MIMO System Model

For a system with N_T transmit antennas and N_R receive antennas, assuming frequency-flat fading over the bandwidth of interest, as illustrated on the Figure 4.2.

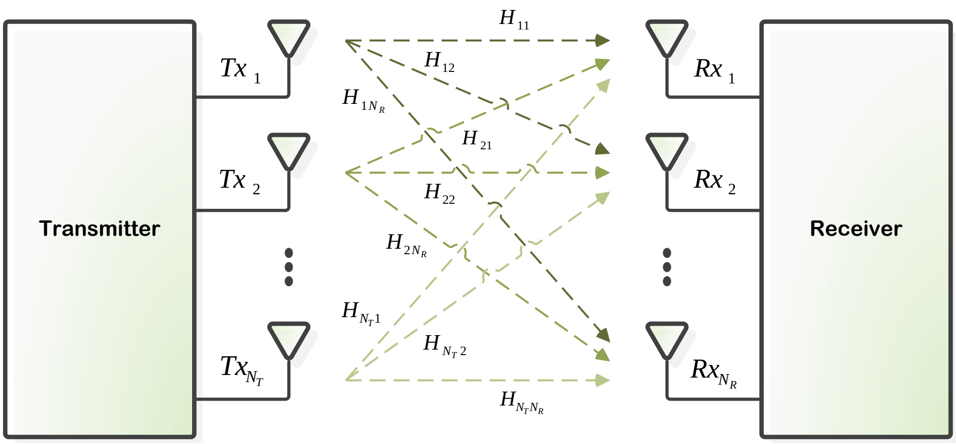


Figure 4.2: Generic MIMO channel model.

Consider $\mathbf{x} \,\epsilon\, C^{N_T \times 1}$, a row vector of N_T symbols, $\mathbf{x} = [x_0, x_1, ...x_{N_T}]^T$ to be transmitted over one radio system like the example above. Through the space the transmitted signal will be experiencing channel frequency response and noise addition. At the receiver the received frequency domain signal is given by

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{z}, \tag{4.1}$$

where $\mathbf{y} \,\epsilon\, C^{N_R \times 1}$ represents the received signals on N_R different antennas and $\mathbf{z} \,\epsilon\, C^{N_R \times 1}$ represents complex additive white Gaussian noise vector. $\mathbf{H}$ consists on a matrix whose size is given by the number of transmitting N_T and receiving N_R antennas.

$$\mathbf{H} = \begin{bmatrix} H_{11} & H_{12} & \cdots & H_{1N_R} \\ H_{21} & H_{22} & \ddots & H_{2N_R} \\ \vdots & \ddots & \ddots & \vdots \\ H_{N_T1} & H_{N_T2} & \cdots & H_{N_TN_R} \end{bmatrix}_{N_T \times N_R} \tag{4.2}$$

where H_{ij} is the complex Gaussian transmission coefficient of the channel between the i^{th} transmitter antenna and j^{th} receiver antenna. In order to enable the estimations of the elements of the MIMO channel matrix, channel estimation through transmission of reference signals is needed, as discussed in Chapter 3.

4.3 Receive diversity

Using multiple antennas at the receiver side to achieve spacial diversity exploring the radio-channel fading, is the most commonly used multi-antenna configuration. SIMO is often referred as a receive diversity scheme, and it isn't generally dependent on the technology being used, it not requires pre-coding or any specific modulation.
Receive diversity is a effective technique in mitigating multipath distortions and fading. This is because multiple antennas offer to a receiver several observations of the same signal. Each signal will experience a different fading environment. Thus, if one antenna is experiencing a deep fade, it is unlikely that another has too.

Lets review the SIMO model in Figure4.3.

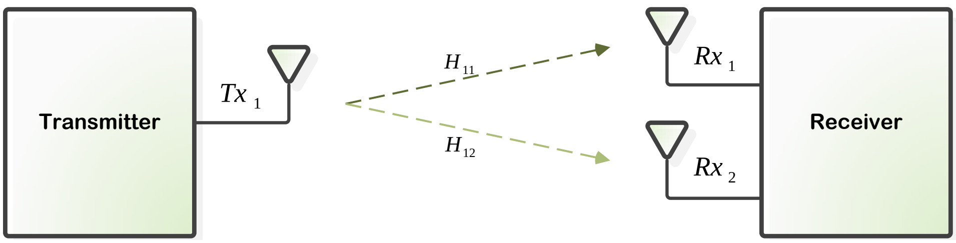


Figure 4.3: SIMO scheme.

Retaking the system model described in previous section, and adapting it to this example, we assume N_T equals one, single transmit antenna and N_R equals 2, two receive antennas. x is an data symbol to be transmitted by Tx_1. Equation 4.1 can be reformulated in two new equations,

$$y_1 = H_{11}x + z_1, \tag{4.3}$$

$$y_2 = H_{12}x + z_2, \tag{4.4}$$

where y_1, y_2 are the received signals on each one of the receive antennas available on the receiver and H_{11} and H_{12} represents the complex gains of channel 1 and 2 respectively. As well as z_1 and z_2 consists on the noise received on each antenna.

In matrix form Equation 4.3 and Equation 4.4 in matrix form becomes

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} H_{11} \\ H_{12} \end{pmatrix} x + \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} \tag{4.5}$$

To obtain an estimate of the transmitted symbols, three approaches can be chosen: selection combining , Equal Gain Combining or Maximal Ratio Combining (MRC). The selection combining approach is the easiest to implement, the receiver selects the antenna with highest SNR and ignore received signals on the other antennas [30]. But it not but brings significant improvements.

For the MRC receiver, the channel equalization matrix is simply the conjugate transpose (Hermitian operation) $\mathbf{h}^H$ of the channel vector $\mathbf{h} = [H_{11}, H_{12}]^T$. The estimates of received modulation symbols in the frequency domain are given by

$$\hat{s} = H_{11}^* y_1 + H_{12}^* y_2, \tag{4.6}$$

making the substitutes of the respective equations, results in

$$\hat{\mathbf{x}} = \left(|H_{11}|^2 + |H_{12}|^2\right) x + H_{11}^* z_1 + H_{12}^* z_2. \tag{4.7}$$

In case of mutually uncorrelated antennas, i.e., sufficiently large antenna distances or different polarization directions, the channel gains $H_{11}, ..., H_{1NR}$ are uncorrelated and the linear antenna combining provides diversity of order N_R.

Also frequency domain equalizers (FDE) can be used, specially in situations which exist interference from other transmitters, to suppress this additional interference. However receive diversity, is most often used in the uplink case, since is from far more feasible having multiple receive antennas on BS that on a mobile terminal. As this work focuses on downlink transmission, FDE won't be considered for now.

4.4 Transmit diversity

Another way besides using multiple antennas on receiver side to explore spatial diversity is applying multiple antennas at the transmitter side, this is known as transmit diversity and is specially useful to improve the SINR and to achieve reliability [31]. This scenario is specially interesting for downlink, since it is easier to install multiple antennas at the base station. To transmit diversity the suitable scenario is when we have low mobility and low correlation between channels of the different antennas, therefore enough physical separation between antennas should be assured. An alternative solution to achieve low correlation, is to use antenna arrays with cross polarizations, i.e., antenna arrays with orthogonal polarizations [13].

The transmit of diversity is one of the main focus of this thesis. Associated with OFDM transmit diversity can be further sub-divided into different approaches: block codes based, Cyclic Delay Diversity (CDD), Frequency Shift Transmit Diversity (FSTD), and Time Shift Transmit Diversity (TSTD). However CDD and TSTD are not used in LTE as a diversity scheme so we will only consider block codes based on SFBC as well FSTD [32] [21].
Transmit diversity increases the robustness of the signal to fading and can increase performance in low SNR conditions. MISO does not increase the data rates, but it supports the same data rates using less power. In LTE standards first release, transmit diversity is only defined for 2 and 4 transmit antennas.
Transmit diversity can be enhanced with closed loop feedback from the receiver to indicate to the transmitter the optimum balance of phase and power used for each transmit antenna.

4.4.1 Space Time block Coding

STBC techniques consists in introducing redundancy over the original data stream, so the codified transmitted data exploit the multipath effect in order to minimize detection errors in the receiver and provide full space diversity.

With this purpose, the principal aim of the space-time coding lies in the design of two-dimensional signal matrices to be transmitted during a specified time period on a number of antennas. Thus, it introduces redundancy in space through the addition of multiple antennas, and redundancy in time through channel coding, enabling us to exploit diversity in the spatial dimension, as well as a obtaining a coding gain.

The Alamouti Concept

The STBC scheme proposed by Alamouti, in which two data symbols are transmitted simultaneously from two transmit antennas, following mapping scheme represented in Table 4.2. The scheme allows transmissions from two antennas with the same data rate as on a single antenna, but increasing the diversity at the receiver [33].

Table 4.2: Alamouti mapping code.

time-slot	Ant.1	Ant.2
t	x_0	x_1
$(t+1)$	$-x_1^*$	x_0^*

The Alamouti concept is demonstrated below. Figure 4.4 reintroduce the multiple input single output scheme.

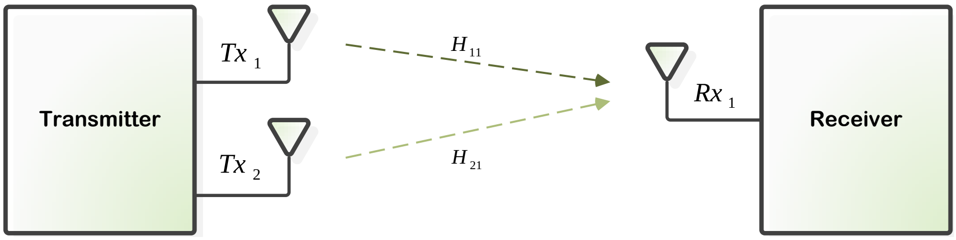


Figure 4.4: MISO scheme.

From the Table 4.2 the matrix coding $\mathbf{X}$ can be given by,

$$\mathbf{X} = \begin{pmatrix} x_0 & x_1 \\ -x_1^* & x_0^* \end{pmatrix}. \tag{4.8}$$

The received vector $\mathbf{y}$ is again expressed by 4.1

$$\mathbf{y}_t = \frac{1}{\sqrt{2}}\mathbf{X}\mathbf{h} + z_t, \tag{4.9}$$

but now $\mathbf{y}_t \in C^{N_R \times 1}$ represents the y_{th} received signal and $\mathbf{z}_t \in C^{N_R \times 1}$ represents complex additive white Gaussian noise vector, both corresponding to t time-slot. h is now the vector of the channel gains between each transmit antenna and the single receive antenna $\mathbf{h} = [H_{11}, H_{21}]^T$.
The factor $\frac{1}{\sqrt{2}}$ is used to constraint the total transmit power to the same as the transmit power of the single transmit antenna.
Equation 4.9 can be decomposed in two equations representing the two consecutive received signals in time intervals t an $t+1$.

$$\begin{cases} y_t = \frac{1}{\sqrt{2}}H_{11,t}x_0 + \frac{1}{\sqrt{2}}H_{21,t}x_1 + z_t, \\ y_{t+1} = -\frac{1}{\sqrt{2}}H_{11,t+1}x_1^* + \frac{1}{\sqrt{2}}H_{21,t+1}x_0^* + z_{t+}, \end{cases} \tag{4.10}$$

In order to be able to estimate the transmitted symbols the equation above can be rewritten as,

$$\begin{cases} y_t = \frac{1}{\sqrt{2}}H_{11,t}x_0 + \frac{1}{\sqrt{2}}H_{21,t}x_1 + z_t, \\ y_{t+1}^* = \frac{1}{\sqrt{2}}H_{21,t+1}^*x_0 - \frac{1}{\sqrt{2}}H_{11,t+1}^*x_1 + z_{t+1}^*, \end{cases} \tag{4.11}$$

which in matrix form becomes,

$$\begin{pmatrix} y_t \\ y_{t+1}^* \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} H_{11} & H_{21} \\ H_{21}^* & -H_{11}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} z_t \\ z_{t+1}^* \end{pmatrix} \tag{4.12}$$

Note that it was assumed that the channel coefficients are constant on two consecutive time intervals, so that $H_{11,t} = H_{11,t+1} = H_{11}$.
Expression above in short notation become

$$\mathbf{y} = \frac{1}{\sqrt{2}}\mathbf{Hx} + \mathbf{z}, \tag{4.13}$$

where $\mathbf{y} = [y_t, y_{t+1}]^T$ and $\mathbf{z} = [z_t, z_{t+1}]^T$.
Matrix $\mathbf{H}$ orthogonality gives the chance of recovering the sent symbols from the received signals y_t and y_{t+1},without ISI.

$$\mathbf{H^H H} = \mathbf{H H^H} = h^2 \mathbf{I}_2, \tag{4.14}$$

where $h^2 = |H_{11}|^2 + |H_{12}|^2$ and $(.)^H$ represents the hermitian operation, $\mathbf{I}_2$ is the 2×2 identity matrix, and h^2 is the power gain of the channel. So using Equation 4.13 and multiplying it the hermitian of the matrix $\mathbf{H}$ we obtain

$$\hat{\mathbf{x}} = \mathbf{H^H y} = \frac{1}{\sqrt{2}} h^2 \mathbf{x} + \mathbf{H^H z}. \tag{4.15}$$

For the two-antenna space-time coding of Figure 4.4, can be said to be of rate one, implying that the input symbol rate is the same as the symbol rate at each antenna, corresponding to a bandwidth utilization of one.

4.4.2 Space Frequency Block Coding

The transmit diversity techniques used in LTE downlink are SFBC and the combination of this scheme with FSTD, to support either two or four transmit antennas respectively. SFBC is a frequency domain derivation of Alamouti concept, described above, but instead of encoding symbols on two different time periods it encodes symbols on two adjacent subcarriers, see Table 4.3. In SFBC, modulation symbols are mapped into frequency and spatial domain to make advantage of diversity offered by multiple spatial channels.
The reason because SFBC instead of STBC was adopted its because SFBC outperforms STBC in high speed scenarios, where fast changing channel conditions in time domain would reduce orthogonality of the code.

Table 4.3: SFCB mapping code.

sub-carrier	Ant.1	Ant.2
n	x_0	x_1
$(n+1)$	$-x_1^*$	x_0^*

Figure4.5 exemplifies a 2 × 2 SFBC scheme, which it will be used as reference in next Chapter.

The received vector $\mathbf{y}$ is again expressed by 4.1

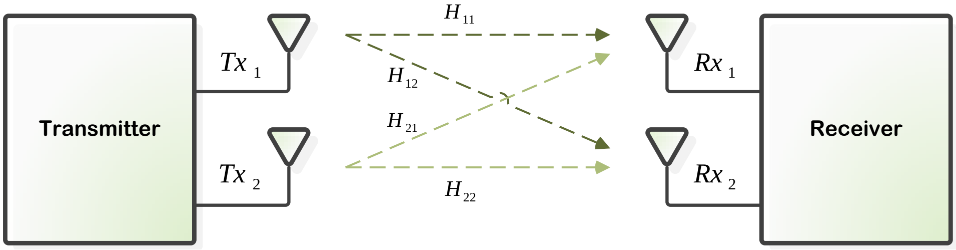


Figure 4.5: Transmit diversity for 2 × 2 scheme.

$$\mathbf{y}_n^r = \frac{1}{\sqrt{2}}\mathbf{H}\mathbf{x} + \mathbf{z}_n, \tag{4.16}$$

but now $\mathbf{y}_n^r \ \epsilon \ C^{N_R \times 1}$ represents the y_{th} received signal on r different receive antenna and $\mathbf{z}_n^r$ $\epsilon \ C^{N_R \times 1}$ represents complex additive white Gaussian noise vector, both corresponding to n subcarrier.

Considering $\mathbf{x}$ is the vector of transmitted symbols $x = [x_0, x_1]$ and respecting Table 4.3 defined by SFBC, Equation 4.16 can be decomposed for each time-slot in

$$\begin{cases} y_n^{(1)} = \dfrac{1}{\sqrt{2}}H_{11,n}x_0 + \dfrac{1}{\sqrt{2}}H_{21,n}x_1 + z_n^1, \\ y_{n+1}^{(1)} = -\dfrac{1}{\sqrt{2}}H_{11,n+1}x_1^* + \dfrac{1}{\sqrt{2}}H_{21,n+1}x_0^* + z_{n+1}^1, \end{cases} \tag{4.17}$$

In order to be able to estimate the transmitted symbols the equation above can be rewritten as,

$$\begin{cases} y_n^{(1)} = \dfrac{1}{\sqrt{2}}H_{11,n}x_0 + \dfrac{1}{\sqrt{2}}H_{21,n}x_1 + z_n^1, \\ y_{n+1}^{*(1)} = \dfrac{1}{\sqrt{2}}H_{21,n+1}^*x_0 - \dfrac{1}{\sqrt{2}}-H_{11,n+1}^*x_1 + z_{n+1}^{*1}, \end{cases} \tag{4.18}$$

which in matrix form becomes,

$$\begin{pmatrix} y_n^{(1)} \\ y_{n+1}^{*(1)} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} H_{11,n} & H_{21,n} \\ H_{21,n+1}^* & -H_{11,n+1}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} z_n^1 \\ z_{n+1}^{*1} \end{pmatrix} \tag{4.19}$$

assuming $H_{11,n} = H_{11,n+1}$ simplifies to

$$\begin{pmatrix} y_n^{(1)} \\ y_{n+1}^{*(1)} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} H_{11} & H_{21} \\ H_{21}^* & -H_{11}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} z_n^1 \\ z_{n+1}^{*1} \end{pmatrix} \tag{4.20}$$

For the second receive antenna, similarly to the first one, the expressions of received signals are

$$\begin{cases} y_n^{(2)} = \frac{1}{\sqrt{2}} H_{12,n} x_0 + \frac{1}{\sqrt{2}} H_{22,n} x_1 + z_n^2, \\ y_{n+1}^{(2)} = -\frac{1}{\sqrt{2}} H_{12,n+1} x_1^* + \frac{1}{\sqrt{2}} H_{22,n+1} x_0^* + z_{n+1}^2, \end{cases} \tag{4.21}$$

In order to be able to estimate the transmitted symbols the equation above can be rewritten as,

$$\begin{cases} y_n^{(2)} = \frac{1}{\sqrt{2}} H_{12,n} x_0 + \frac{1}{\sqrt{2}} H_{22,n} x_1 + z_n^2, \\ y_{n+1}^{*(2)} = \frac{1}{\sqrt{2}} H_{22,n+1}^* x_0 - \frac{1}{\sqrt{2}} H_{12,n+1}^* x_1 + z_{n+1}^{*2}, \end{cases} \tag{4.22}$$

which in matrix form becomes,

$$\begin{pmatrix} y_n^{(2)} \\ y_{n+1}^{*(2)} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} H_{12,n} & H_{22,n} \\ H_{22,n+1}^* & -H_{12,n+1}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} z_n^2 \\ z_{n+1}^{*2} \end{pmatrix} \tag{4.23}$$

assuming $H_{1,2_n} = H_{1,2_{n+1}}$ simplifies to

$$\begin{pmatrix} y_n^{(2)} \\ y_{n+1}^{*(2)} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} H_{12} & H_{22} \\ H_{22}^* & -H_{12}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \end{pmatrix} + \begin{pmatrix} z_n^2 \\ z_{n+1}^{*2} \end{pmatrix} \tag{4.24}$$

Equations 4.24 and 4.20 in short notation can be expressed for each receive antenna by

$$\mathbf{y}^{(1)} = \frac{1}{\sqrt{2}} \mathbf{H}_1 + \mathbf{z}^1 \tag{4.25}$$

$$\mathbf{y}^{(2)} = \frac{1}{\sqrt{2}} \mathbf{H}_2 + \mathbf{z}^2 \tag{4.26}$$

Following the same steps as the Alamaouti scheme, the expressions for the estimation of the transmitted symbols are

$$\tilde{\mathbf{x}}^1 = \mathbf{H_1^H} \mathbf{y}^{(1)} \tag{4.27}$$

$$\tilde{\mathbf{x}}^2 = \mathbf{H_2^H} \mathbf{y}^{(2)} \tag{4.28}$$

which outputs

$$\begin{cases} \tilde{x}_0^{(1)} = \frac{1}{\sqrt{2}} x_0 (|H_{11}|^2 + |H_{21}|^2) + H_{11}^* z1_n + H_{21} + z_{n+1}^{*1} \\ \tilde{x}_1^{(1)} = \frac{1}{\sqrt{2}} x_1 (|H_{11}|^2 + |H_{21}|^2) + H_{21}^* z1_n - H_{11} + z_{n+1}^{*1} \end{cases} \tag{4.29}$$

$$\begin{cases} \tilde{x}_0^{(2)} = \dfrac{1}{\sqrt{2}} x_0(|H_{12}|^2 + |H_{22}|^2) + H_{12}^* z2_n + H_{22} + z_{n+1}^{*2} \\ \tilde{x}_1^{(2)} = \dfrac{1}{\sqrt{2}} x_1(|H_{12}|^2 + |H_{22}|^2) + H_{22}^* z2_n - H_{12} + z_{n+1}^{*2} \end{cases} \tag{4.30}$$

As is noticeable, due to orthogonality transmitted symbols can be successfully estimated without interference, resulting in a signal with a gain plus noise. Since no orthogonal codes exist for antenna configurations beyond 2×2, SFBC has to be modified in order to apply it to the case of 4 transmit antennas. In LTE, this is achieved by combining SFBC with Frequency-Switched Transmit Diversity (FSTD).

4.5 Spacial multiplexing

The use of multiple antennas at both the transmitter and the receiver can simply be seen as a tool to further improve the SNR/SINR and/or achieve additional diversity against fading, compared to the use of only multiple receive antennas or multiple transmit antennas. However, in case of multiple antennas at both the transmitter and the receiver there is also the possibility for so-called spatial multiplexing, allowing for more efficient utilization of high SINR and significantly achieve higher data rates over the radio interface [34].

In this mechanism we need multiple antennas in both ends. To accomplish MIMO if we have N_T transmit antennas we need N_T data streams. However, by spatially separating N_T streams across at least N_T antennas, N_R receivers will be able to fully reconstruct the original data streams whereas the path correlation and noise in the radio channel are low enough [5].

Spatial multiplexing of the radio channel means that MIMO has the potential to increase the peak data rate by a factor of 2 (or 4 with 4-by-4 antenna configuration). For simplicity lets consider the most basic form of an $N_T \times N_R$ MIMO system, shown in Figure 4.6, the 2×2 model.

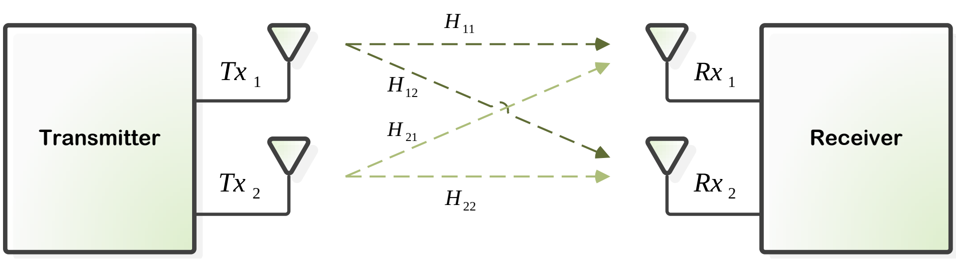


Figure 4.6: MIMO 2×2 scheme.

Once again let $\mathbf{H}$ denote a channel matrix with it $(i, j)_{th}$ entry H_{ij} for the channel gain between the i_{th} transmit antenna and the j_{th} receive antenna, $i = 1, 2$ and $j = 1, 2$.

$$\mathbf{H} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}_{N_T \times N_R} \tag{4.31}$$

The transmitted data and received signals are represented by $\mathbf{s} = [s_1, s_2, \ldots, s_{N_T}]^T$ and $\mathbf{y} = [y_1, y_2, \ldots, y_{N_R}]^T$, respectively, where $\mathbf{s}_i$ and $\mathbf{y}_j$ denote the transmit signal form the i_{th} transmit antenna and the received signal at the j_{th} receive antenna, respectively. The white Gaussian noise with mean 0 and and a variance of σ_z^2 is represented by $\mathbf{n} = [n_1, n_2, \ldots, n_{N_R}]^T$. Finally the $N_T \times N_R$ MIMO system can be expressed as

$$\mathbf{y} = \mathbf{Hs} + \mathbf{n}, \tag{4.32}$$

Similarly with transmit diversity schemes linear signal detection method could be applied. With this method receiver treats all transmitted signals as interferences except for the desired signal from the target transmit antenna. Interference signals from the other transmit antennas is minimized on each detection antenna through the application of ZF and MMSE techniques.

So estimated signals are given by

$$\tilde{\mathbf{s}} = \mathbf{Gy} \tag{4.33}$$

where $\tilde{\mathbf{s}} = [\tilde{s}_1, \tilde{s}_2, \ldots, \tilde{s}_{N_R}]^T$, and $\mathbf{G}$ is the equalization matrix.
The zero forcing technique nullifies the interference by applying the weight matrix

$$\mathbf{G}_{ZF} = (\mathbf{H^H H})^{-1}\mathbf{H^H} \tag{4.34}$$

where $(.)^H$ denotes the Hermitian operator (conjugate transpose). In other words, it inverts the effect of channel as

$$\begin{aligned} \tilde{\mathbf{s}}_{ZF} &= \mathbf{G}_{ZF}\mathbf{y} \\ &= \mathbf{s} + (\mathbf{H^H H})^{-1}\mathbf{H^H} n, \end{aligned} \tag{4.35}$$

With MMSE equalizer the weight matrix is given by

$$\mathbf{G}_{MMSE} = (\mathbf{H^H H} + \sigma_z^2 \mathbf{I})^{-1}\mathbf{H^H} \tag{4.36}$$

where σ_z^c is the noise variance per sub-carrier and I is the identity matrix (4×4).

Replacing eq.4.36 in eq.4.33 we obtain

$$
\begin{aligned}
\tilde{\mathbf{s}}_{MMSE} &= \mathbf{G}_{MMSE}\mathbf{y} \\
&= (\mathbf{H}^{\mathbf{H}}\mathbf{H} + \sigma_z^2\mathbf{I})^{-1}\mathbf{H}^{\mathbf{H}}\mathbf{H}\mathbf{s} + (\mathbf{H}^{\mathbf{H}}\mathbf{H} + \sigma_z^2\mathbf{I})^{-1}\mathbf{H}^{\mathbf{H}}\mathbf{n}, \qquad (4.37)
\end{aligned}
$$

Spatial multiplexing transforms the disadvantage of multipath effects into an advantage. In fact, spatial multiplexing can only increase transmission rates when the wireless environment is very rich in multipath since this situation results in low correlations between the channels enabling the efficient recovery of transmitted data at the receiver. On the other hand, when the correlation between the channels is high then there is a rapid degradation of the performance of spatial multiplexing. MIMO works best in high SNR conditions with minimal line of sight. Line of sight equates to high channel correlation and seriously diminishes the potential for gains. As a result, MIMO is particularly suited to indoor environments, which can exhibit a high degree of multi-path and limited line of sight.

Chapter 5

Double SFBC with Iterative Equalizer for LTE

The LTE standard supports up to 4 transmit antennas and up to 2 receive antennas. For 2 transmit antennas the conventional Alamouti scheme for 2 transmit antennas can be used. Considering 4 transmit antennas, as discussed in Chapter 1, the Alamouti code is performed in pairs of 2 antennas using 2 subcarriers on each pair. This scheme can be improved, in terms of spectral efficiency, by using the same 2 subcarrier to transmit a block of 4 data symbols over the 4 antennas. If the UE is equipped with 2 antennas we have enough degrees of freedom to efficiently separate the data symbols. In this Chapter, we extend the double STBC (D-STBC) scheme proposed in [35] to frequency domain (D-SFBC) and combine it with the iterative frequency domain equalizer (FDE) proposed in [8] for single carrier based systems. First, we briefly describe the SFBC scheme considered in the LTE for 4 antennas. Then, we present in detail the double Alamouti applied to OFDM based systems. After that, we develop the iterative FDE (I-FDE) for the D-SFBC scheme. Two strategies are considered: the first one is based on parallel interface cancelation and the second one on successive interference cancelation. Finally, the developed schemes are evaluated and compared under the LTE specifications.

5.1 SFBC considered in LTE

In Chapter 4 it was presented the transmit diversity scheme for 2×2 MIMO, similar principle is applied in 4×2 configuration. In LTE standards SFBC was adopted for two transmit antennas, in the case of four transmit antennas, transmit diversity is based on balanced SFBC complemented with FSTD [11]. Balanced SFBC-FSTD basically consists in mapping the OFDM symbols alternately between the four antennas,as can be seen in Figure 5.1.

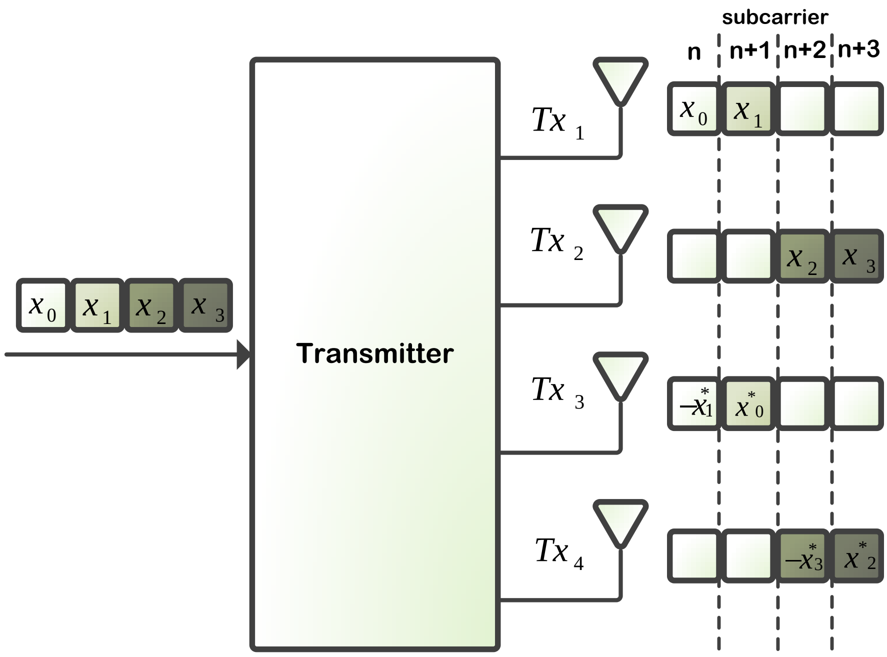


Figure 5.1: Balanced SFBC-FSTD transmit diversity schemes for 4-Tx antennas.

As in the space-time coding, there is no directly applicable extension to SFBC with more than two transmit antennas without compromising orthogonality, and only with code rate reduction, could reinsure orthogonality [11]. Thats the reason why SFBC needs to be modified, to be applicable to the case of 4 transmit antennas, and so SFBC combined with FSTD is used. Note that the mapping of symbols to antenna ports is different in the 4 transmit antennas case, compared to the 2 transmit antennas SFBC scheme. In case of two antenna ports SFBC implies that consecutive modulation symbols are mapped directly on adjacent subcarriers on the first antenna port. On the second antenna port, the swapped and transformed symbols are transmitted on the corresponding subcarriers. As Figure 5.1 shows, symbols x_0 and x_1 are mapped in antennas 1 and 3, while x_2 and x_3 in antennas 2 and 4. This scheme is a combination of two 2×2 SFBC schemes mapped to independent subcarriers. Alternation exists because the RS density on the third and fourth antenna ports is half that of the first and second antenna ports, and hence the channel estimation accuracy may be lower on the third and fourth antenna ports, see Figure 5.2. Thereby this design avoids concentrating the channel estimation losses in just one of the SFBC codes, and balances out the channel estimates resulting in a slight coding gain.

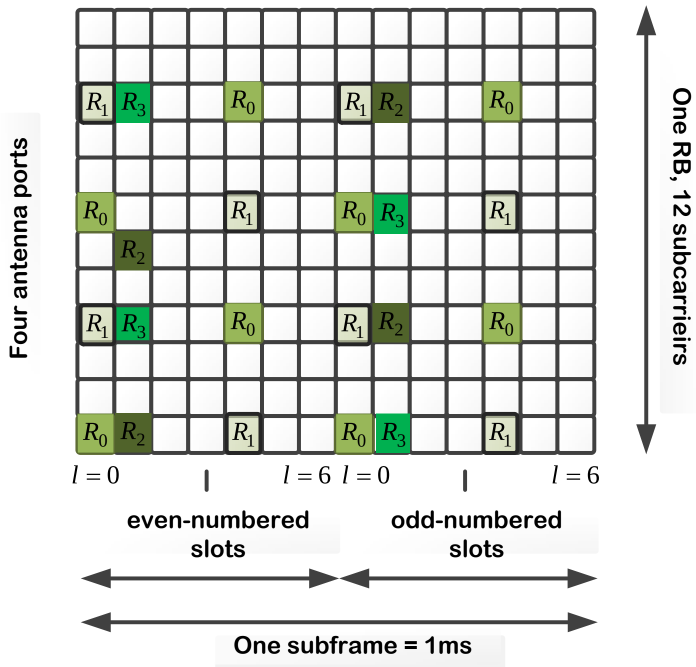


Figure 5.2: Downlink reference signals cell-specific reference signals.

Although the diversity performance improvement given by combined SFBC-FSTD, which is more resistent against spatial correlation than SFBC [31], it can be said that all the resources are not fully explored. SFBC-FSTD is a full rate code scheme, in which four groups of symbols are transmitted over four subcarriers. But when one pair of antenna ports transmits two symbols, using two subcarriers, in the other pair of subcarriers there is no transmission. Here is where lies one opportunity of improvement of the spectral efficiency of this scheme. The objective is transmit the same four symbols, only using two subcarriers.

5.2 Double SFBC

Figure 5.3 shows the 4×2 MIMO model considered in this work. As can be seen, the first pair of data symbols (x_0, x_1) are coded into antennas 1 and 2 and on subcarriers n and n+1 by using the Alamouti code, while the second pair (x_2, x_3) are coded into antennas 3 and 4 and on the same subcarriers of the first pair, as shown in Table 5.1.

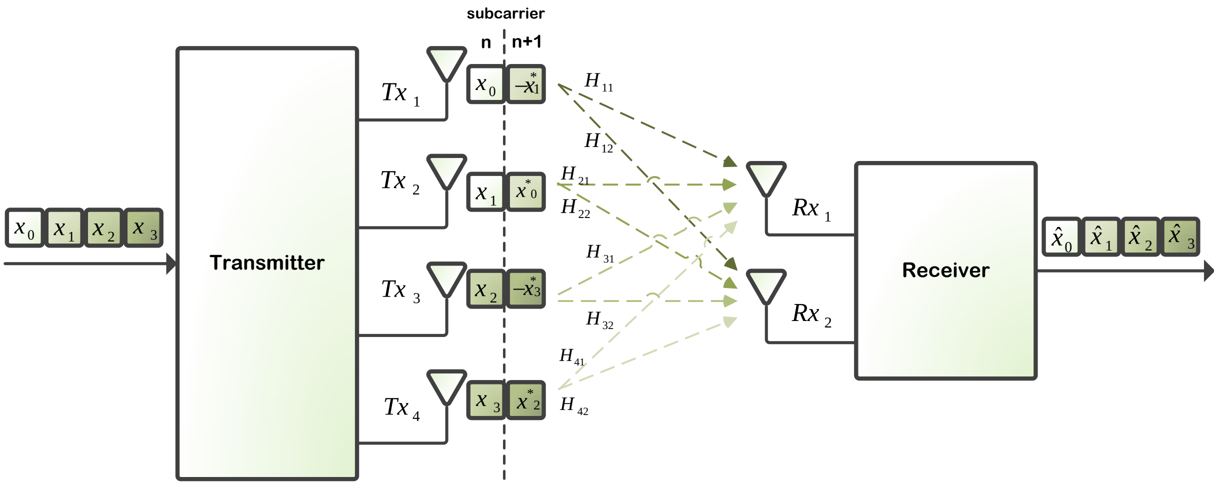


Figure 5.3: D-SFBC block diagram.

Table 5.1: D-SFBC symbols mapping table.

Sub-carrier	Ant.1	Ant.2	Ant.3	Ant.4
n	x_0	x_1	x_2	x_3
$(n+1)$	$-x_1^*$	x_0^*	$-x_3^*$	x_2^*

Distinctively of the previous schemes, notice the particularity that four different symbols are now transmitted using one single pair of subcarriers doubling the throughput but using the same frequency resources. This system can be seen as two parallel 2×2 SFBC systems. The challenge is to try to remove the interference, when each symbol is estimated in the receiver, provoked by the other symbols sent in parallel.

Taking as reference the transmitted symbols given in Table 5.1, and for simplicity considering H_{ij_n} as the channel coefficient between the ith transmit antenna and jth receive antenna on subcarrier nth, the expression of the received signal on the first receive antenna is

$$\mathbf{Rx_1}$$

$$\begin{cases} Y_n^{(1)} = H_{11,n}x_0 + H_{21,n}x_1 + H_{31,n}x_2 + H_{41,n}x_3 + z_n^1, \\ Y_{n+1}^{(1)} = -H_{11,n+1}x_1^* + H_{21,n+1}x_0^* - H_{31,n+1}x_3^* + H_{41,n+1}x_2^* + z_{n+1}^1, \end{cases} \tag{5.1}$$

which is equivalent to

$$\begin{cases} Y_n^{(1)} = H_{11,n}x_0 + H_{21,n}x_1 + H_{31,n}x_2 + H_{4,1,n}x_3 + z_n^1, \\ Y_{n+1}^{*(1)} = -H_{11,n+1}^*x_1 + H_{21,n+1}^*x_0 - H_{31,n+1}^*x_3 + H_{41,n+1}^*x_2 + z_{n+1}^{*1}, \end{cases} \tag{5.2}$$

and for the second receiver antenna

$\mathbf{Rx_2}$

$$\begin{cases} Y_n^{(2)} = H_{12,n}x_0 + H_{22,n}x_1 + H_{32,n}x_2 + H_{42,n}x_3 + z_n^2, \\ Y_{n+1}^{(2)} = -H_{12,n+1}x_1^* + H_{22,n+1}x_0^* - H_{32,n+1}x_3^* + H_{42,n+1}x_2^* + z_{n+1}^2, \end{cases} \tag{5.3}$$

which is equivalent to

$$\begin{cases} Y_n^{(2)} = H_{12,n}X_0 + H_{2,2_n}X_1 + H_{3,2_n}X_2 + H_{4,2_n}X_3 + z_n^2, \\ Y_{n+1}^{*(2)} = -H_{12,n+1}^*X_1 + H_{2,2_{n+1}}^*X_0 - H_{32,n+1}^*x_3 + H_{4,2_{n+1}}^*X_2 + z_{n+1}^2, \end{cases} \tag{5.4}$$

These equations can be arranged in matrix form as

$$\begin{pmatrix} Y_n^{(1)} \\ Y_{n+1}^{*(1)} \\ Y_n^{(2)} \\ Y_{n+1}^{*(2)} \end{pmatrix} = \begin{pmatrix} H_{11n} & H_{21n} & H_{31n} & H_{41n} \\ H_{21n+1}^* & -H_{11n+1}^* & H_{41n+1}^* & -H_{31n+1}^* \\ H_{12n} & H_{22n} & H_{32n} & H_{42n} \\ H_{22n+1}^* & -H_{12n+1}^* & H_{42n+1}^* & -H_{32n+1}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} z_n^1 \\ z_{n+1}^1 \\ z_n^2 \\ z_{n+1}^2 \end{pmatrix} \tag{5.5}$$

Assuming that the neighboring two subcarriers (n, n+1) are experiencing identical channel response, $H_{i,j,n} = H_{i,j,n+1}$, 5.5 is simplified to

$$\begin{pmatrix} Y_n^{(1)} \\ Y_{n+1}^{*(1)} \\ Y_n^{(2)} \\ Y_{n+1}^{*(2)} \end{pmatrix} = \begin{pmatrix} H_{11} & H_{21} & H_{31} & H_{41} \\ H_{21}^* & -H_{11}^* & H_{41}^* & -H_{31}^* \\ H_{12} & H_{22} & H_{32} & H_{42} \\ H_{22}^* & -H_{12}^* & H_{42}^* & -H_{32}^* \end{pmatrix} \begin{pmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} z_n^1 \\ z_{n+1}^1 \\ z_n^2 \\ z_{n+1}^2 \end{pmatrix} \tag{5.6}$$

In matrix form becomes,

$$\mathbf{y} = \mathbf{H^T x} + \mathbf{z}, \tag{5.7}$$

with $\mathbf{x} = [x_0, x_1, x_2, x_3]^T$.

At the receiver the estimated set of 4 data symbols are given by

$$\hat{\mathbf{x}} = \mathbf{G}\mathbf{y} \tag{5.8}$$

which decomposed becomes

$$\begin{pmatrix} \hat{X}_n \\ \hat{X}_{n+1} \\ \hat{X}_n \\ \hat{X}_{n+1} \end{pmatrix} = \mathbf{G} \begin{pmatrix} Y_n^{(1)} \\ Y_{n+1}^{*(1)} \\ Y_n^{(2)} \\ Y_{n+1}^{*(2)} \end{pmatrix}. \tag{5.9}$$

It is now easy to estimate the 4 transmitted symbols by two common linear frequency equalizers like ZF or MMSE,

$$\mathbf{G}_{ZF} = (\mathbf{H^H H})^{-\mathbf{1}}\mathbf{H^H}, \tag{5.10}$$

$$\mathbf{G}_{MMSE} = (\mathbf{H^H H} + \sigma^2\mathbf{I})^{-1}\mathbf{H^H}, \tag{5.11}$$

$$\hat{\mathbf{x}} = \mathbf{G}_{ZF}\mathbf{y} \tag{5.12}$$

$$= \left(\mathbf{H^H H}\right)^{-1}\mathbf{H^H H x} + \left(\mathbf{H^H H}\right)^{-1}\mathbf{H^H z} \tag{5.13}$$

$$\hat{\mathbf{X}} = \mathbf{G}_{MMSE}\mathbf{y} \tag{5.14}$$

$$= (\mathbf{H^H H} + \sigma^2\mathbf{I})^{-1}\mathbf{H^H H x} + (\mathbf{H^H H} + \sigma^2\mathbf{I})^{-1}\mathbf{H^H z} \tag{5.15}$$

The linear ZF equalizer forces the interference to zero, but it also boosts the noise manly when the channel coefficients are in deep fading. The MMSE equalizer minimizes the mean squared error between the transmitted data symbols and the estimated ones. It is a trade-off between the noise enhancement and the interference removal. From (5.10) and (5.11) it can be seen that for high SNR the ZF tens to the MMSE, since the noise variance tends to zero. These schemes are referred to as 4x2 D-SFBC ZF/MMSE when the linear ZF and MMSE equalizers are used to decode the transmitted data, respectively.

5.3 Iterative Equalizer Design

The previous linear equalizers can be improved by combining them with iterative based approaches. In this work we consider an iterative frequency domain equalizer to remove the residual interference. Two approaches are considered: parallel interference cancellation (PIC) and successive interference cancelation (SIC).

5.3.1 Parallel Interference Cancelation

The PIC principle is shown in Figure 5.4, where for each iteration the 4 data symbols are decoded in parallel. The structure of the I-FDE equalizer is presented in Figure 5.5, where it can be seen that at every iteration we have as inputs the received signals on each receive antenna and the set the 4 estimated symbols from previous symbols.

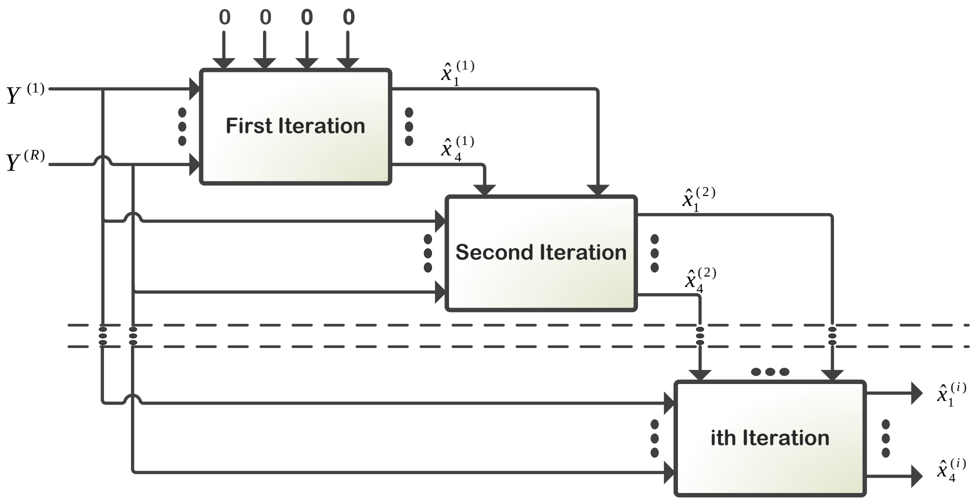


Figure 5.4: I-FDE block diagram (PIC).

Figure 5.4 shows detailed description on each step of the detection on I-FDE proposed.

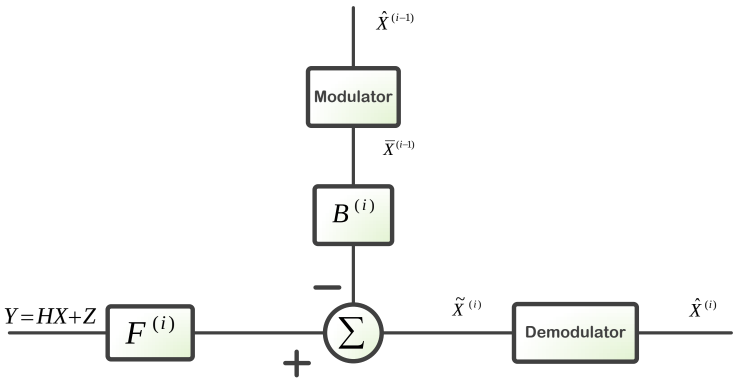


Figure 5.5: I-FDE detailed iteration block.

By observing Figure 5.5, we observe that at every iteration on the output of the detector we will have hard decisions of the 4 estimated symbols $\tilde{\mathbf{X}}^{(i)}$ given by

$$\tilde{\mathbf{X}}^{(i)} = \mathbf{F}^{(i)^T} Y - \mathbf{B}^{(i)^T} \bar{\mathbf{X}}^{(i-1)}, \tag{5.16}$$

where $\mathbf{F}^{(i)}$ is a $N_T \times 4$ matrix composed by the feed-forward coefficients defined by

$$\mathbf{F}^{(i)} = (\mathbf{H}^{\mathbf{H}}(\mathbf{I}_s - \mathbf{P}^{(i-1)^2})^H + \sigma^2\mathbf{I})^{-1}\mathbf{H}^{\mathbf{H}} \tag{5.17}$$

and $\mathbf{B}^{(i)}$ is a 4×4 matrix composed are the feedback coefficients defined by

$$\mathbf{B}^{(i)} = \mathbf{H}\mathbf{F}^{(i)} - \mathbf{I}_k \tag{5.18}$$

It is simple to understand that on the first iteration ($i = 1$) the system is reduced to a MMSE equalizer, since no previous estimative exists,i.e., $\mathbf{P}^{(i-1)}$ is a null matrix. On the next iterations the interference is canceled taking in account previously estimations of the symbols. On each one is used the most updated estimative of the symbols as input of the detection block. Due to decision errors the estimated soft data symbols may be different from the transmitted ones, i.e., $\bar{x}_k \neq x_k$. To take into account these errors, a correlation coefficient $\rho_k, k = 1, 2, 3, 4$ for each data symbol should be computed. It can be shown [36] that,

$$\bar{x}_k \cong \mathbf{P}^{(i)} x_k \tag{5.19}$$

where $\mathbf{P} = diag\left(\rho_1, \rho_2, \ldots, \rho_k\right)$ is a diagonal matrix with the correlation coefficients given by,

$$\rho_k = \frac{\bar{x}_k x_k^*}{\left|x_k\right|^2}, k = 1, 2, 3, 4 \tag{5.20}$$

From the previous equation it can be seen that to compute the correlation coefficients at the receiver side we need to know the transmitted data symbols, x_k, which is not realistic. Thus, these coefficients should be estimated at the receiver. One possible solution proposed in [36] is described here. The soft decisions represented by $\bar{x}$ for normalized QPSK constellations are given by,

$$\bar{x}^{(i)} = tanh\left(\frac{\left|L^{I^{(i)}}\right|}{2}\right) + jtanh\left(\frac{\left|L^{Q^{(i)}}\right|}{2}\right), \tag{5.21}$$

where

$$L^{I^{(i)}} = \frac{2}{\sigma^{2^{(i)}}} Re\left\{\tilde{x}^{(i)}\right\}, \tag{5.22}$$

$$L^{Q^{(i)}} = \frac{2}{\sigma^{2^{(i)}}} Im\left\{\tilde{x}^{(i)}\right\}, \tag{5.23}$$

and

$$\sigma^{2^{(i-1)}} = \frac{1}{2}\left|\bar{x}^{(i-1)} - \tilde{x}^{(i)}\right|^2. \tag{5.24}$$

These soft decisions represented by $\bar{x}_n^{(i-1)}$, as we can see in Figure 5.5 are resultant from re-modulated hard decisions $\hat{x}^{(i)}$, due to $\bar{x}^{(i-1)} \neq \tilde{x}^{(i)}$, we can calculate the correlation coefficients $\mathbf{P}^{(i)} = diag\left(\rho_1^{(i)}, \rho_2^{(i)}, \cdots, \rho_k^{(i)}\right)$ by the following expressions

$$\rho_k^{(i)} \approx \frac{1}{2}\left(\left|\rho_k^{I^{(i)}}\right| + \left|\rho_k^{Q^{(i)}}\right|\right) \tag{5.25}$$

with

$$\rho_k^{I(i)} = tanh\left(\frac{\left|L_k^{I(i)}\right|}{2}\right) \tag{5.26}$$

$$\rho_k^{Q(i)} = tanh\left(\frac{\left|L_k^{Q(i)}\right|}{2}\right) \tag{5.27}$$

This scheme is referred to as 4x2 D-SFBC PIC.

5.3.2 Successive Interference Cancelation

In an attempt to improve performance of interference cancelation other approach was also tested, the Successive Interference Cancelation (SIC) scheme. The principle is that on each iteration, each symbol is detected independently, using the most updated estimative of the other transmitted data symbols. Figure 5.6 helps better understand this scheme [36].

The architecture of the detection block on each iteration is the same used on PIC and is depicted in Figure 5.5. The difference is that on each detection block, only one symbol is detected and the output is used as input of the next detection block. On first iteration and on the first detection block hard data decisions vector is a null vector. On the second detection block is composed only by the first estimative of the first symbol and the remaining elements are zero. Is direct that now on the detection of the second symbol the diagonal matrix $P^{(i)}$ of correlation coefficients is composed by $P^{(i)} = diag\left(\rho_1^{(i)}, 0, \ldots, 0\right)$ contributing to reduce interference caused by the first symbol, providing a better decision on the second symbol detection.
To implement this architecture some alterations are needed to the expressions presented above, in order to estimate each symbol independently we need to isolate each column of the matrix of the forward coefficients, α. Therefore 5.17 is now given by,

$$\mathbf{F}_k{}^{(i)} = \left((\mathbf{H}^H(\mathbf{I}_s - \mathbf{P}^{(i-1)^2})\mathbf{H} + \sigma^2\mathbf{I})^{-1}\mathbf{H}^H\right)\alpha_\mathbf{k} \tag{5.28}$$

where k refers to the index of kth data symbol, $\alpha_\mathbf{k}$ is a column vector $\alpha_\mathbf{k} = [1,0,0,0]^T$ where the element 1 is kth element that corresponds to a given data symbol.
This scheme is referred to as 4x2 D-SFBC SIC.

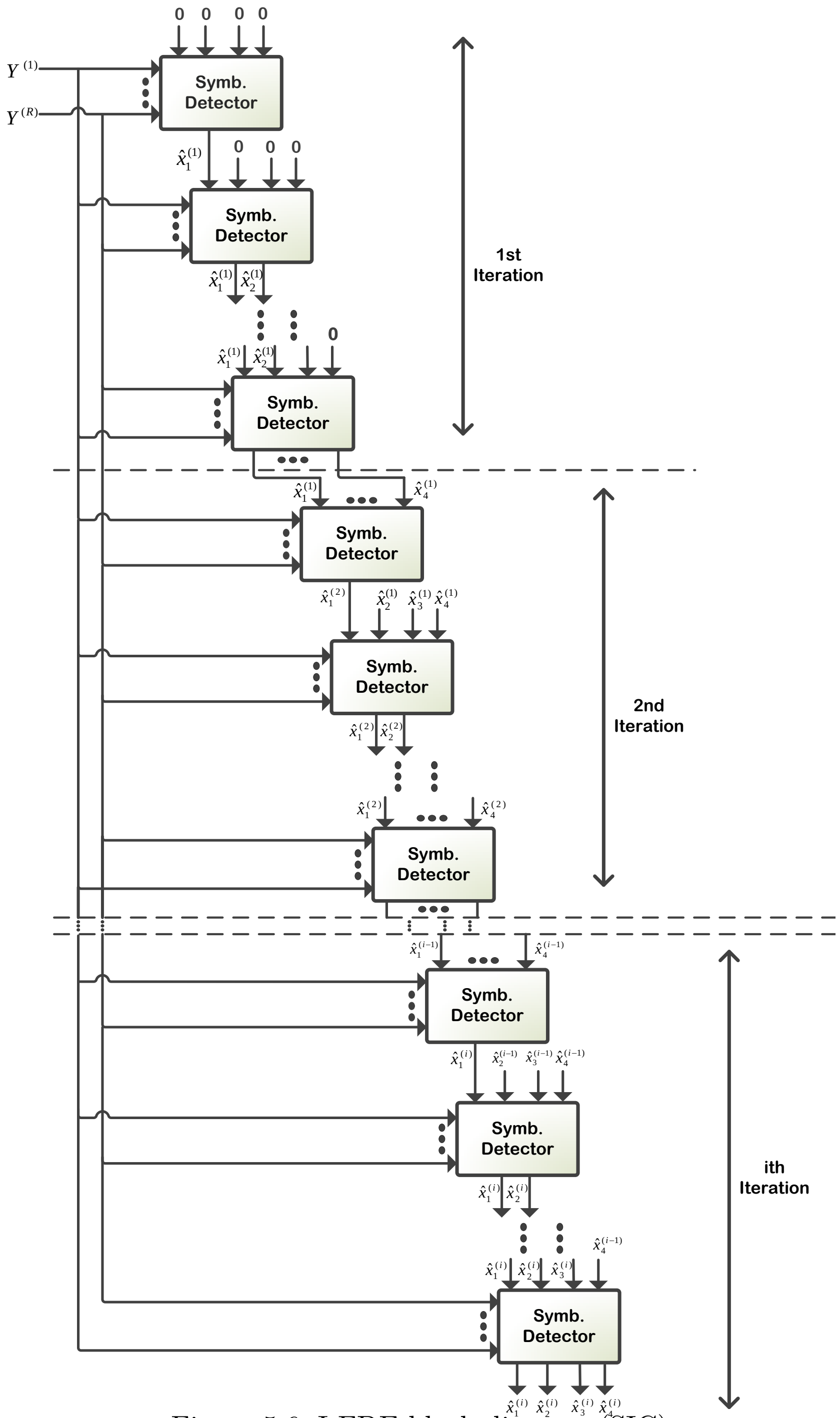


Figure 5.6: I-FDE block diagram (SIC).

5.4 Simulation Chain

The simulation platform is fully developed in *Matlab*, for OFDMA specifications and it is constituted by several block stages for the transmitter and the receiver. The block diagram is displayed in Figure 5.7.

Below we describe the most relevant blocks for this work. The transmitter blocks are,

- **Data Generator -**generates a binary vector of random data with the length of the variable $N_Codeword$ which is the size of a codeword.
- **Coder -**function block that performs the channel coding for a given codeword.
- **Data Modulation -**this function performs the constellation mapping. The input bits are mapped into symbols according the chosen constellation. For this chain it's available three types of constellations, QPSK, 16 QAM and 64 QAM.
- **SF Processing's -** implements the Space-Frequency block coding, maps the symbols in the respective transmit antennas abased on Alamouti scheme.
- **OFDM framing -**performs the sub-carrier mapping and the frame interleaving.

For the receiver, the blocks are

- **OFDM de-framing -**performs the exact inverse operation of OFDM framing block,i.e. the sub-carrier un-mapping and the frame de-interleaving.
- **Equalizer -**performs the channel equalization applying the algorithm chosen (MMSE, ZF, I-FDE).
- **Data Demodulation -**performs the constellation un-mapping, converting the symbols into a bit stream.
- **Decoder -**performs the channel de-coding extracting all data.

This platform also allows that the following parameters could be adapted for each simulation

- **Modulation**
- **Number of UEs**
- **Number of receive/transmit antennas**
- **Coder type**
- **FFT size**
- **Interleaver**

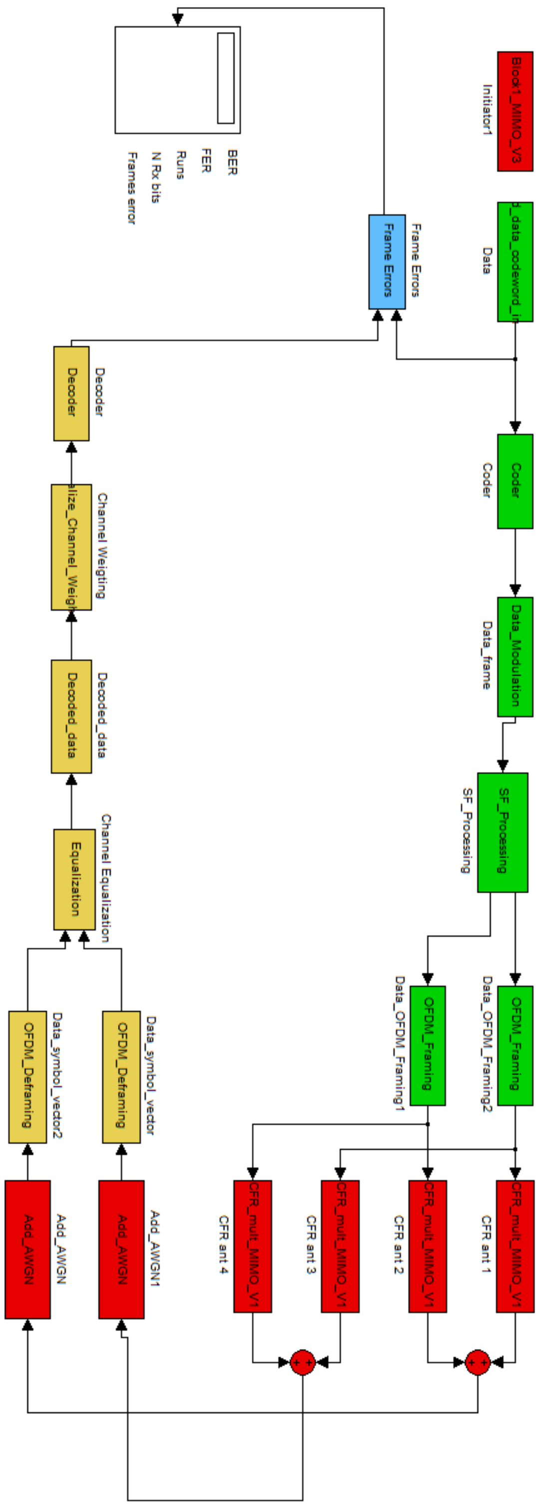


Figure 5.7: Simulation platform bloxk diagram.

5.5 Numerical Results

In the following section we present the results from diverse simulations considering the proposed iterative frequency domain receivers for downlink transmission, using the simulation platform depicted above. In the following Table 5.2 are described the parameters used for the simulations, which are based on LTE.

Table 5.2: Simulation parameters

Modulation	QPSK
FFT size	1024
Available subcarriers	128
Subcarriers separation	15kHz
Sampling frequency	15.36MHz
Frame length	12 symbols
Total OFDM symbols duration	66.67μs
Cyclic prefix duration	4.67μs
Coder type	CTC / none
$E_b \setminus N_0$ range	0:2:20
Number of transmit antennas (BS)	2,4
Number of receive antennas (UE)	2
Channel profile	ITU pedestrian channel model B(LTE)

We present results for the proposed 4×2 D-SFBC I-FDE PIC and SIC schemes discussed above. Also, for comparison we plot the curves for 4x2 D-SFBC using the linear ZF and MMSE equalizers (4×2 D-SFBC ZF, 4x2 D-SFBC MMSE); and the 2×2 SFBC schemes. This last one can be seen as a lower bound of the proposed schemes. Note that for the PIC based structure the 4×2 D-SFBC MMSE corresponds to the 4×2 D-SFBC I-FDE PIC with one iteration. It is assumed perfect channel estimation and synchronization. All the curves presented in terms of average BER as function of Eb/No.

To evaluate the impact of the correlation coefficients on the performance, the 4x2 D-SFBC I-FDE PIC is evaluated for the case where the correlation coefficient is assumed to be perfect, Eq. 5.20, and when is estimated instead by using the procedure discussed above. These results are presented in Figure 5.8 and 5.9, respectively. For the 4x2 D-SFBC I-FDE SIC only the estimated correlation coefficients was considered.

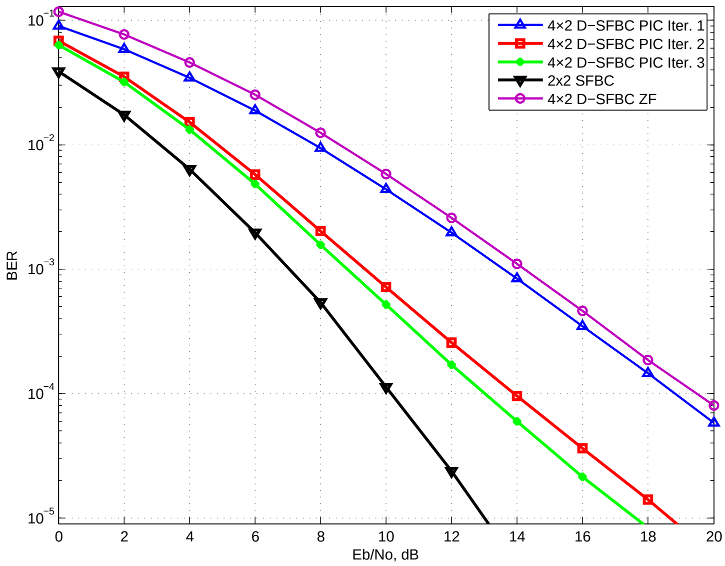


Figure 5.8: Performance of the 4×2 D-SFBC using the PIC structure and for perfect ρ.

The Figure 5.8 compared the results obtained with the proposed 4x2 D-SFBC I-FDE PIC for 1, 2 and 3 iterations, 4×2 D-SFBC ZF and 2x2 SFBC schemes. As mentioned before the first iteration corresponds to the 4×2 D-SFBC MMSE. As can be seen from the figure the 4×2 D-SFBC ZF has the poorest performance. A penalty approximately $0.7dB$ can be observed regarding the 4×2 D-SFBC MMSE or 4×2 D-SFBC I-FDE PIC with 1 iteration. Increasing the number of iteration the performance of the 4×2 D-SFBC I-FDE PIC increases as well. The highest gain happens from the first to the second iteration. For this case, a gain about 5 dB can be observed, assuming a $BER = 10^{-4}$. This is because the iterative algorithm, in the second iterations uses a more reliable estimates of the transmitted data symbols and thus can remove the remaining interference more efficiently. From the second to the third iteration the gain is much smaller. Note that the performance of the 4×2 D-SFBC I-FDE PIC with 3 iteration is close the one given by the 2×2 SFBC scheme. We can see a penalty of approximately 3 dB, but it should be emphasizes that 4×2 D-SFBC I-FDE PIC achieves the double of the data rate when compared with 2×2 SFBC.

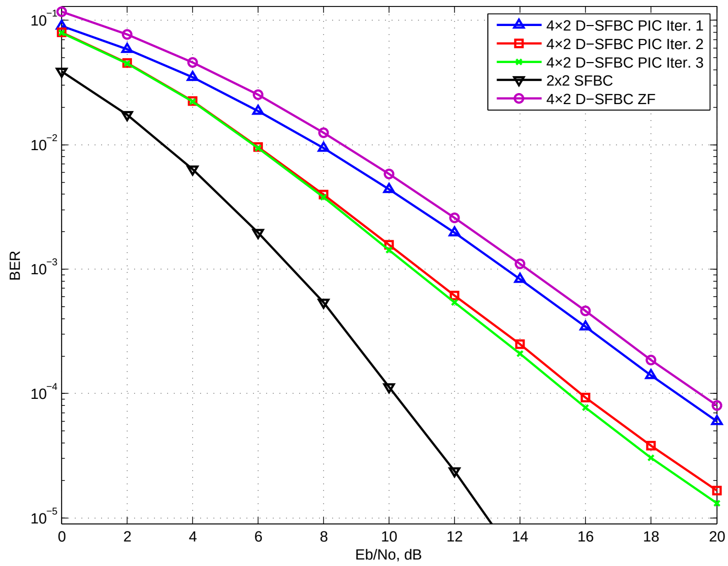


Figure 5.9: Performance of the 4x2 D-SFBC using the PIC structure and for estimated ρ.

The Figure 5.9 depicts the results obtained for 4×2 D-SFBC I-FDE PIC scheme using estimated ρ. Comparing these curves with the ones presented in Figure 5.8 we can see a penalty mainly for high values of Eb/No. A penalty of approximately 2dB can be observed for the 4x2 D-SFBC I-FDE PIC with 2 iteration, assuming a $BER = 10^{-4}$.

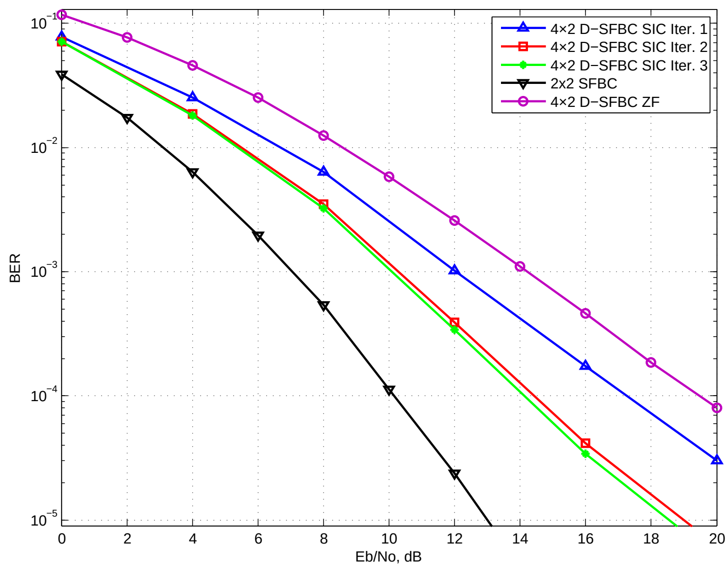


Figure 5.10: Performance of the 4x2 D-SFBC using the SIC structure and for estimated ρ.

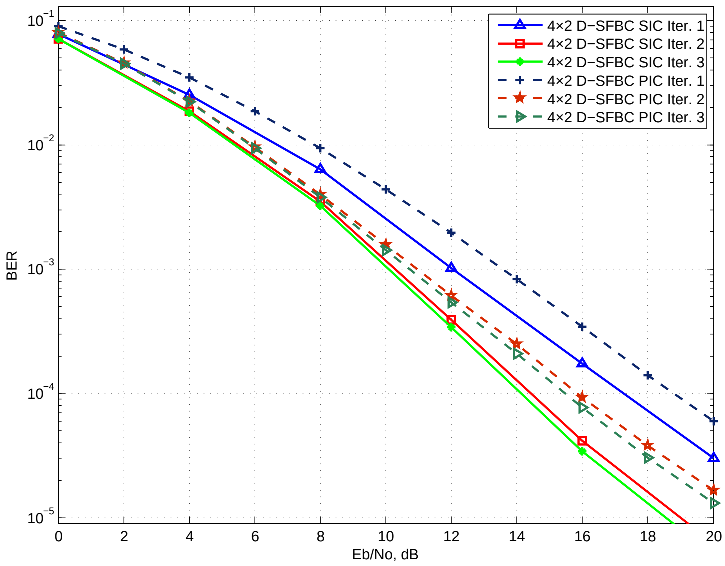


Figure 5.11: Comparison between 4x2 D-SFBC using the PIC and SIC structures.

Figure 5.10 displays the results obtained for 4×2 D-SFBC I-FDE SIC scheme using estimated ρ, for 3 iterations. Once again it is also compared with the schemes 4x2 D-SFBC ZF, which as can be seen from the figure has a penalty of 1dB against the 4x2 D-SFBC I-FDE SIC with 1 iteration, and with the 2×2 SFBC, which outperforms the 4×2 D-SFBC I-FDE SIC in the third iteration in 4dB, for $BER = 10^{-4}$. It's also noticeable that the second and third iterations are almost coincident and the gain is negligible.

A comparison between the 4×2 D-SFBC I-FDE for the PIC and SIC structures, using both estimated ρ, is made in Figure 5.11. The results achieved shows that using the 4×2 D-SFBC I-FDE SIC has a gain of $1.5dB$ in the first iteration compared with 4×2 D-SFBC I-FDE SIC, on the others iterations the gains are of 1dB, for $BER = 10^{-4}$.

5.5.1 Channel Coding

The results of the previous section were obtained without channel coding. In this section we present results for the same schemes of the previous section but considering channel coding. LTE uses channel coding techniques in order to maintain robustness against frequency selective fading channels, where errors are detected due to deep fading which may be encountered on the individual channels, and allows symbols recovery, improving then the error rate performance [21].

We used a convolution turbo code (CTC) with a half code rate. For the decoder a Max Log Map algorithm with 8 iterations was considered.

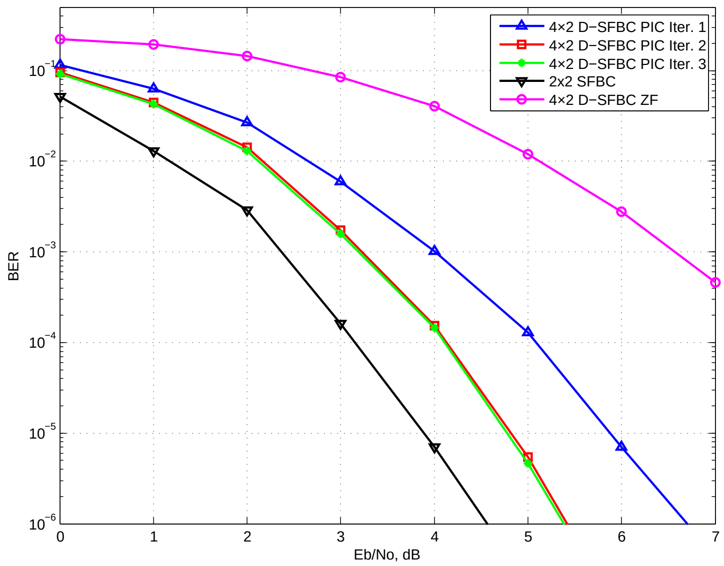


Figure 5.12: Performance of the 4×2 D-SFBC PIC using channel coding.

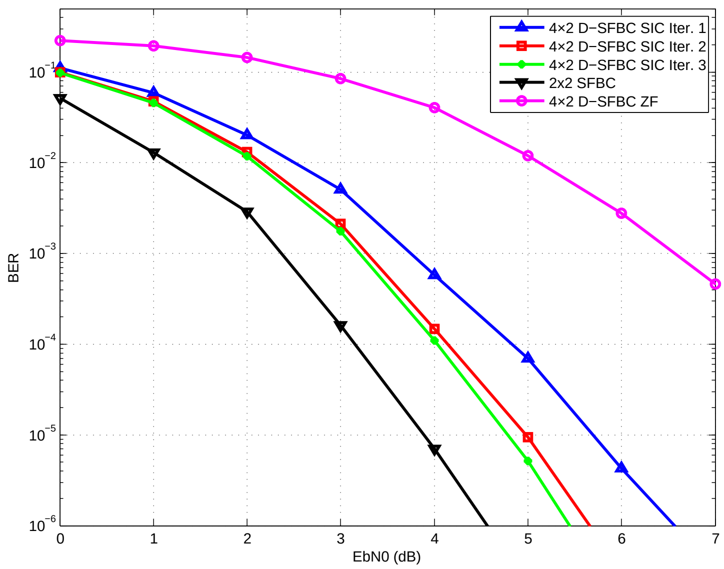


Figure 5.13: Performance of the 4×2 D-SFBC SIC using channel coding.

As expected the results obtained, show significant improvements in BER curves for both 4×2 D-SFBC PIC/SIC structures. Also 4×2 D-SFBC ZF and 2×2 SFBC. Figure 5.12 depicts that now, the penalty of 4×2 D-SFBC ZF against 4×2 D-SFBC PIC on the first iteration, is with $BER = 10^{-3}$, $2.5dB$, and for the second and third iterations, $3.3dB$, which

are almost coinciding.
In comparison 4×2 D-SFBC PIC with the 2×2 SFBC scheme the penalty for the first iteration is $1.6dB$, and $0.6dB$ for the second and third iterations.

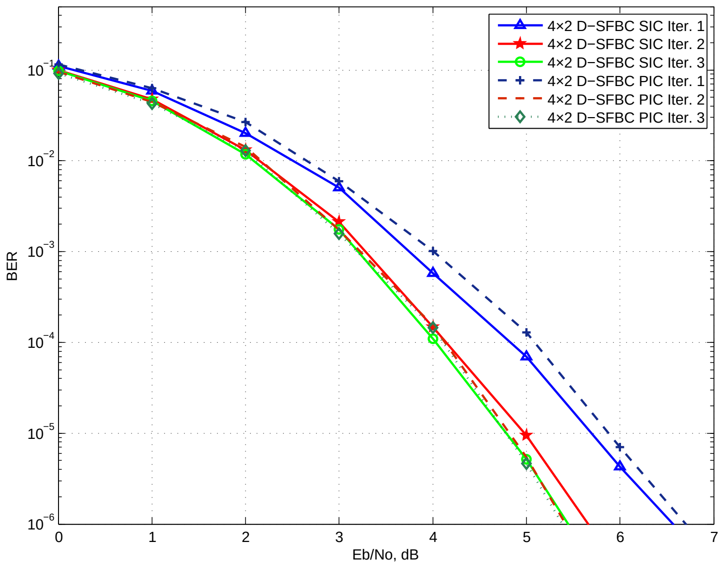


Figure 5.14: Comparison between 4×2 D-SFBC PIC and SIC structures with channel coding.

The Figure 5.13 shows the results for 4×2 D-SFBC SIC and compares it with the curves discussed for Figure 5.12. Figure 5.14 compares both approaches. With 4×2 D-SFBC SIC, gains are only considered on the first iteration, on higher iterations are negligible. Once again 4×2 D-SFBC SIC outperforms 4×2 D-SFBC PIC solution, but now the penalty is only $0.2dB$, for $BER = 10^{-4}$, which we can't consider satisfactory, taking into account the complexity introduced with SIC implementation, is significant.

Chapter 6

Conclusion

Mobile communications is fundamentally shaping how we live. By 2016, is expected that users living on less than 1 percent of the Earth's total land area are set to generate around 60 percent of mobile traffic [3]. We are living in an extraordinary period of time, global mobile penetration is about 82 percent, and growth in mobile subscriptions is overwhelming, we tend to a new era were people and devices are always connected.
The Evolutionary path of mobile communications development is constantly adapting to these new challenges. LTE is a step toward the 4G of radio technologies designed to increase the capacity and speed of mobile telephone networks.
LTE uses multi-carrier systems and multi-antenna transmission schemes to improve communication performance. Data throughput, coverage and transmission reliability in a wireless communication system can be improved by exploiting spatial diversity provided by several transmit antennas. While Spatial Multiplexing provides maximum throughput, it does not provide the maximum available diversity. Transmit diversity is an effective means to combat fading by exploiting the spatial diversity of a system with multiple transmit antennas and improve the reliability of transmission and coverage.

Orthogonal SFBC schemes provide transmit diversity while maintaining a low decoding complexity, and requires no channel state information at the transmitter side. For a system with two transmit antennas and one receive antenna, the Alamouti code provides the maximum available rate and the maximum available transmit diversity [31]. The Alamouti SFBC maintains its orthogonality with more than one receive antennas, but not for more than two transmit antennas, without loosing spectral efficiency. So that was the motivation in conceive an iterative frequency domain equalizer, that could provide good performance on these conditions, and improve spectral efficiency.

In this work we proposed a double Alamouti scheme for a scenario with 4 transmit antennas and 2 receive antennas. Since 4 data symbols are transmitted by using only 2 subcarriers the systems suffers from interference. To efficiently remove this interference we implemented an iterative frequency domain equalizer which outperforms the linear conventional ones. Two approached were considered: PIC and SIC. The results have shown that with 2 or 3 iteration the performance of both schemes is basically the same. Also, the proposed 4×2 D-SFBC I-FDE PIC/SIC cannot achieve the performance of the 2×2 SFBC, but achieves the double of data rate. Besides that the results also show that the I-FDE, can in fact, improve the error performance with only two or three iterations, specially if channel coding is used. Thus 4x2 D-SFBC I-FDE PIC/SIC approaches can be useful for application that requires high data rates. Comparing both approaches, only relevant improvements for the first iteration were achieved, with 4×2 D-SFBC I-FDE SIC, so the choice in its use will be an complexity-performance commitment.

6.0.2 Future Work

As complement to work developed here it would be interesting if other scenarios could be tested, such as,

- LTE Release 8 standards also includes the 4×4 scheme, adapt the iterative receiver to this scheme and compare the results, seems interesting.
- All the simulations were done using QPSK modulation, as title of comparison, high order modulation techniques could be simulated.
- Include a channel estimation algorithm to the simulation chain architecture in order to achieve more realistic results.

Bibliography

[1] 4GAmericas. *Website*. Available:http://www.4gamericas.org/, 2012.

[2] Cisco. "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update". Whitepaper, 2012.

[3] Ericsson. "Traffic and Market Data Report ". Whitepaper, 2012.

[4] Brough Turner and Marc Orange. "3G Tutorial". Fall VON 2002, NMS Communications, 2002.

[5] 3GPP. *Website*. Available:http://3gpp.org/LTE, 2012.

[6] C. Cox. *"An Introduction to LTE: LTE, LTE-Advanced, SAE and 4G Mobile Communications"*. John Wiley & Sons, 2012.

[7] 3G Americas. "3GPP Mobile Broadband Innovation Path to 4G: Release 9, Release 10 and Beyond: HSPA+, SAE/LTE and LTE-Advanced". Whitepaper, 2010.

[8] P. Silva. *"Multiuser Detection for CDMA Systems"*. Phd thesis, Universidade Técnica de Lisboa, July 2010.

[9] E. Dahlman, S. Parkvall, and J. Skold. *"4G: LTE/LTE-Advanced for Mobile Broadband"*. Academic Press. Elsevier Science, 2011.

[10] Erik Dahlman, Anders Furuskär, Ylva Jading, Magnus Lindström, and Stefan Parkvall. "Key features of the LTE radio interface", 2008.

[11] Farooq Khan. *"LTE for 4G Mobile Broadband: Air Interface Technologies and Performance"*. Cambridge University Press, New York, NY, USA, 1st edition, 2009.

[12] M. Rumney and A. Technologies. *"LTE and the Evolution to 4G Wireless: Design and Measurement Challenges"*. Wiley, 2013.

[13] H. Holma and A. Toskala. *"LTE for UMTS - OFDMA and SC-FDMA Based Radio Access"*. John Wiley & Sons, 2009.

[14] P. Lescuyer and T. Lucidarme. *"Evolved Packet System (EPS): The LTE and SAE Evolution of 3G UMTS"*. Wiley, 2008.

[15] Ericsson. "Long Term Evolution (LTE): an introduction". Whitepaper, 2007.

[16] 3GPP TS 36.300 V8.12.0. "Evolved Universal Terrestrial Radio Access (E-UTRA)and Evolved Universal Terrestrial Radio Access Network (E-UTRAN)", 2010.

[17] 3GPP TS 36.913 V8.0.1. "Requirements for further advancements for Evolved Universal Terrestrial Radio Access (E-UTRA)", 209.

[18] L.L. Hanzo, Y. Akhtman, L. Wang, and M. Jiang. *"MIMO-OFDM for LTE, WiFi and WiMAX: Coherent versus Non-coherent and Cooperative Turbo Transceivers"*. Wiley - IEEE. Wiley, 2011.

[19] E. Dahlman. *"3G Evolution: HSPA and LTE for Mobile Broadband"*. Academic Press. Academic, 2008.

[20] M. Ergen. *"Mobile Broadband: Including WiMAX and LTE"*. Information Technology: Transmission, Processing and Storage. Springer, 2009.

[21] S. Sesia, I. Toufik, and M. Baker. *"LTE - The UMTS Long Term Evolution: From Theory to Practice"*. John Wiley & Sons, 2011.

[22] Y.S. Cho, J. Kim, W.Y. Yang, and C.G. Kang. *"MIMO-OFDM Wireless Communications with MATLAB"*. John Wiley & Sons, 2010.

[23] H. Ekstrom, A. Furuskar, J. Karlsson, M. Meyer, S. Parkvall, J. Torsner, and M. Wahlqvist. "Technical solutions for the 3G long-term evolution". *Communications Magazine, IEEE*, 44(3):38 – 45, march 2006.

[24] 3GPP TS 36.201 V8.2.0. "LTE Physical Layer-General description", 2008.

[25] 3GPP TS 36.211 V8.7.0. "Physical Channels and Modulation", 2009.

[26] Jim Zyren. " Overview of the 3GPP Long Term Evolution Physical Layer". White paper, 2007.

[27] 3GPP TS 36.212 V8.4.0. "Multiplexing and Channel Coding", 2008.

[28] Agilent Technologies. "Agilent 3GPP Long Term Evolution: System Overview, Product Development, and Test Challenges". *Application Note, Industry White Papers*, 44(3), June 2009.

[29] Agilent Technologies. "MIMO in LTE Operation and Measurement - Excerpts on LTE Test". *Application Note, Industry White Papers*, January 2010.

[30] H. Schulze and C. Lueders. *"Theory and Applications of OFDM and CDMA: Wideband Wireless Communications"*. Wiley, 2005.

[31] L. Safatly, G. Andrieux, and J.F. Diouris. "LTE multi-antenna techniques based on Alamouti SFBC with correlated channels". In *Software, Telecommunications and Computer Networks (SoftCOM), 2010 International Conference on*, pages 214 –218, sept. 2010.

[32] 3GPP TDocs. "Transmit Diversity Way Forward for E-UTRA Downlink Shared Data Channel", 2007.

[33] S. M. Alamouti. "A simple transmit diversity technique for wireless communications". *IEEE J.Sel. A. Commun.*, 16(8):1451–1458, September 2006.

[34] Helmut Bölcskei and Arogyaswami J. Paulraj. *"Multiple-input multiple-output (MIMO) wireless systems"*. 2002.

[35] Joaquim Bastos and Atilio Gameiro. "Performance of extended space-time coding techniques for MIMO MC-CDMA systems". In *Antennas and Propagation, 2006. EuCAP 2006. First European Conference on*, pages 1 –5, November 2006.

[36] F.C. Ribeiro, R. Dinis, F. Cercas, and A. Silva. "Iterative Frequency-Domain Receivers for the Uplink of Cellular Systems with Base Station Cooperation". In *Computer Communications and Networks (ICCCN), 2012 21st International Conference on*, pages 1 –5, 30 2012-aug. 2 2012.