Universidade de Aveiro Departamento de Electrónica, Telecomunicações e Informática
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Implementação numa FPGA codificador/descodificador Alamouti para LTE

FPGA implementation of Alamouti encoder/decoder for LTE

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Eletrónica e Telecomunicações, realizada sob a orientação científica do Professor Doutor Adão Paulo Soares da Silva e do Professor Doutor Manuel Alberto Reis de Oliveira Violas, Professores Auxiliares do Departamento Eletrónica, Telecomunicações e Informática da Universidade de Aveiro

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Palavras-chave LTE, OFDM, OFDMA, SC-FDMA, MIMO, SFBC, Alamouti, Xilinx System Generator

Resumo

Motivados por transmissões mais rápidas e mais fiáveis num canal sem fios, os sistemas da 4G devem proporcionar processamento de dados mais rápido a baixa complexidade, elevadas taxas de dados, assim como robustez na performance reduzindo também, a latência e os custos de operação.

LTE apresenta, na sua camada física, tecnologias como OFDM e MIMO que prometem alcançar elevadas taxas de dados e aumentar a eficiência espectral. Especificamente a camada física do LTE emprega OFDMA para downlink e SC-FDMA para uplink.

A tecnologia MIMO permite também melhorar significativamente o desempenho dos sistemas OFDM com as vantagens de multiplexação e diversidade espacial diminuindo o efeito de desvanecimento de multi-percurso no canal.

Nesta dissertação são implementados um codificador e um descodificador com base no algoritimo de Alamouti num sistema MISO nomeadamente para serem incluídos num OFDM transceiver que segue as especificações da camada física do LTE. A codificação/descodificação de Alamouti realiza-se no espaço e frequência e os blocos foram projetados e simulados em Matlab através do ambiente Simulink com o auxílio dos blocos da Xilinx inseridos no seu software System Generator para DSP.

Pode-se concluir que os blocos baseados no algoritimo de Alamouti foram implementados em hardware com sucesso.

Keywords LTE, OFDM, OFDMA, SC-FDMA, MIMO, SFBC, Alamouti, Xilinx System Generator

Abstract Motivated by faster transmissions and more reliable wireless channel, future 4G systems should provide faster data processing at low complexity, high data rates, as well as robustness in performance while also reducing the latency and operating costs.
LTE presents in its physical layer technologies such as OFDM and MIMO that promise to achieve high data rates and increase spectral efficiency. Specifically the physical layer of LTE employs OFDMA on the downlink and SC-FDMA for uplink.
MIMO technology also allows to significantly improve the performance of OFDM systems with the advantages of multiplexing and spatial diversity by decreasing the effect of multipath fading in the channel.
In this thesis we implemented an encoder and a decoder based on an Alamouti algorithm in a MISO system namely to be added to an OFDM transceiver that follows closely the LTE physical layer specifications. Alamouti coding/decoding is performed in frequency and space and the blocks were projected and simulated in Matlab using Simulink environment through the Xilink's blocks in the System Generator for DSP.
One can conclude that the blocks based on Alamouti algorithm were well-implemented.

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Acronyms

1xEV-DO *Evolution Data Optimized*

1xEV-DV *Evolution Data and Voice*

1xRTT *One Carrier Radio Transmission Technology*

1G *First Generation*

2G *Second Generation*

3G *Third Generation*

3GPP *Third Generation Partnership Project*

4G *Forth Generation*

ADSL *Asymmetric Digital Subscriber Line*

AMPS *Analogue Mobile Phone System*

ARIB *Association of Radio Industries and Businesses*

ARQ *Automatic Repeat reQuest*

ATIS *Alliance for Telecommunications Industry Solutions*

AuC *Authentication Centre*

BER *Bit Error Rate*

BLAST *Bell-Labs Layered Space Time*

BS *Base Station*

CAPEX *Capital Expenditure*

CCSA *China Communications Standards Association*

CDD *Cyclic Delay Diversity*

CDMA *Code Division Multiple Access*

CEPT *Conference of European Postal and Telecommunications*

CL *Closed-Loop*

CN *Core Network*

CP *Cyclic Prefix*

CS *Circuit Switched*

CSI *Channel State Information*

D-AMPS *Digital Analogue Mobile Phone System*

dB *deci-Bel*

DC *direct current*

DFT *Discrete Fourier Transform*

DL *Downlink*

DSP *Digital Signal Processing*

E-MBMS *Enhanced multimedia broadcast multicast service*

E-UTRA *Evolved UMTS Terrestrial Radio Access*

E-UTRAN *Evolved UMTS Terrestrial Radio Access Network*

EDGE *Enhanced Data Rates for Global Evolution*

EMM *EPS Mobility Management*

EPC *Evolved Packet Core*

EPS *Evolved Packet System*

ESM *EPS Session Management*

ETSI *European Telecommunications Standards Institute*

eNodeB *Evolved Node B*

FDD *Frequency Division Duplex*

FDE *frequency-domain equalization*

FDM *Frequency Division Multiplexing*

FFT *Fast Fourier Transform*

FSTD *Frequency Switched Transmit Diversity*

FTT *Fast Fourier Transform*

FDMA *Frequency Division Multiple Access*

FPGA *Field Programmable Gate Array*

FSK *Frequency Shift Keying*

GBR *Guaranteed Bit Rate*

GERAN *GSM/Edge Radio Access Network*

GGSN *Gateway General Packet Radio Service Support Node*

GMSK *Gaussian Minimum Shift Keying*

GPRS *General Packet Radio Service*

GTP *GPRS Tunnelling Protocol*

GSM *Global System for Mobile Communications*

HARQ *Hybrid Automatic Repeat reQuest*

HLR *Home Location Register*

HRPD *High Rate Packet Data*

HSDPA *High Speed Downlink Packet Access*

HSPA *General Packet Access*

HSPA+ *High Speed Packet Access Evolution*

HSS *Home Subscriber Server*

HSUPA *High Speed Uplink Packet Access*

ICI *Inter-Carrier Interference*

IDFT *Inverse Discrete Fourier Transform*

IEEE *Institute of Electrical and Electronics Engineers*

IFFT *Inverse Fast Fourier Transform*

IMT *International Mobile Telecommunications*

IMS *Internet Protocol Multimedia Subsystem*

IP *Internet Protocol*

ITU *International Telecommunication Union*

ITU-R *International Telecommunication Union Radio Communication Sector*

IS-95 *Interim Standard*

ISI *Inter-Symbol Interference*

J-TACS *Japanese Total Access Communication System*

LSTI *LTE/SAE Trial Initiative*

LTE *Long Term Evolution*

LTE-A *Long Term Evolution Advanced*

MAC *Medium Access Control*

MATLAB *MATrix LABoratory*

MBMS *Multimedia Broadcast/Multicast Services*

MIMO *Multiple Input Multiple Output*

MISO *Multiple Input Single Output*

ML *Maximum Likelihood*

MME *Mobility Management Entity*

MMSE *Minimum MSE*

MRC *Maximum Ratio Combining*

MRRC *Maximal-Ratio Receiver Combining*

MS *Mobile Station*

MSC *Mobile Switching Center*

MSE *Minimum Squared Error*

MU-MIMO *Multi-User MIMO*

NAS *Non-Access Stratum*

NGMN *Next Generation Mobile Networks*

NMT *Nordic Mobile Telephone*

OFDM *Orthogonal Frequency Division Modulation*

OFDMA *Orthogonal Frequency Division Multiple Access*

OL *Open-Loop*

OPEX *Operational Expenditure*

OSTBC *Orthogonal Space-Time Block Code*

P-GW *Packet Data Network Gateway*

P/S *Parallel-to-Serial*

PAPR *Peak to Average Power Ratio*

PCRF *Policy Control and Charging Rules Function*

PDC *Personal Digital Cellular*

PDCP *Packet Data Convergence Protocol*

PDN *Packet Data Network*

PHY *Physical Layer*

PRB *Physical Resource Block*

PS *Packet Switched*

PSK *Phase Shift Keying*

QAM *Quadrature Amplitude Modulation*

QoS *Quality of Service*

QPSK *Quadrature Phase Shift Keying*

RAN *Radio Access Network*

RAT *Radio Access Technology*

RE *Resource Element*

RF *Radio Frequency*

RLC *Radio Link Control*

RNC *Radio Network Controller*

ROM *Read-Only Memory*

RRC *Radio Resource Control*

RRM *Radio Resource Management*

S-GW *Serving Gateway*

SAE *System Architecture Evolution*

SC-FDM *single-carrier frequency-division multiplexing*

SC-FDMA *Single Carrier - Frequency Division Multiple Access*

SDO *Standards Development Organization*

SDU *Service data unit*

SF *Space Frequency*

SFBC *Space Frequency Block Code*

SGSN *Serving General Packet Radio Service Service Node*

SIMO *Single-Input Multiple-Output*

SINR *Signal Interference Noise Ratio*

SISO *Single Out Single Input*

SM *Spatial Multiplexing*

SMS *Short Message Service*

SNR *Signal to Noise Ratio*

ST *Space Time*

STBC *Space Time Block Code*

STC *Space-Time Coded*

STTC *Space-Time Trellis Code*

SU-MIMO *Single-User MIMO*

TACS *Total Access Communication System*

TCP *Transmission Control Protocol*

TD-SCDMA *Time Domain Synchronous Code Division Multiple Access*

TDD *Time Division Duplex*

TDMA *Time Division Multiple Access*

TR *Technical Report*

TTA *Telecommunications Technology Association*

TTC *Telecommunications Technology Committee*

TSG *Technical Specification Group*

TSTD *Time Shift Transmit Diversity*

UMB *Ultra Mobile Broadband*

UMTS *Universal Mobile Telecommunications System*

UE *User Equipment*

UDP *User Datagram Protocol*

UL *Uplink*

USA *United States of America*

UTRAN *UMTS Terrestrial Radio Access Network*

VoIP *Voice over Internet Protocol*

VLSI *Very Large Scale Integrated Circuits*

W-CDMA *Wideband Code Division Multiple Access*

WiMAX *Worldwide Interoperability for Microwave Access*

WLAN *Wireless Local Area Network*

Chapter 1

Introduction

1.1 Evolution of Mobile Systems

Since the belief of Guglielmo Marconi and his first experiments in 1890s with wireless telegraphy that it is also possible communication without *wires*, researchers bodies, engineers around the world have focused in radio communication, mainly in voice communication systems [1]. The progress in radio transmission field led an era of wireless systems, where the traditional telegraphy service was replaced by mobile service, becoming possible *to speak* on phone while moving.

During the last decade numbers are showing that the number of worldwide mobile subscribers reached one million per day and in 2008, it was reached four billion users [2]. The cellular systems are being used by half of world's population and its fast growth explain why the mobile phones deserve so attention in global technology.

Nowadays wireless communication is one of the most areas that have been being exploited and the techniques deployed along the last decade in radio transmission must satisfied the consumer's expectations to benefit of small, powerful, multimedia applications in one single device. The cellular wireless communication techniques are often split in *Generations*, each of them is the reflex of the demands at that time bringing new specifications and assumptions. In following, it is discussed the main technologies involved at each generation.

1.1.1 First Generation

In early 1980s emerged the first *generation*, known as *First Generation* (1G) systems. It was mainly designed to support voice communication, with speed up to 2.4kbps [3]. The first systems are known as analogue systems based on *Frequency Division Multiple Access* (FDMA) with limited *roaming*. *Analogue Mobile Phone System* (AMPS) was the first commercial cellular system in North of America [4], *Total Access Communication System* (TACS) was used in some parts of Europe, *Nordic Mobile Telephone* (NMT) in some Nordic Countries and *Japanese Total Access Communication System* (J-TACS) was used in Japan and Hong Kong) [5].

1.1.2 Second Generation

One decade later, 1G analogue systems was overcome by digital *Second Generation* (2G) system. The *Global System for Mobile Communications* (GSM) is by far the most dominant technology in the World. Its project was initiated by *Conference of European Postal and Telecommunications* (CEPT) and later move to *European Telecommunications Standards Institute* (ETSI) organization[6].

The original standard supports circuit-switched data at 9.6 kbps, the known, *Short Message Service* (SMS) and voice service. Its air-interface is based on *Time Division Multiple Access* (TDMA) scheme. Furthermore GSM technology takes advantage of *Gaussian Minimum Shift Keying* (GMSK) modulation technique which it is a special case of *Frequency Shift Keying* (FSK), providing good power and spectral efficiency.

Another 2G digital cellular systems were deployed, such as: *Digital Analogue Mobile Phone System* (D-AMPS) (IS-54) used in *United States of America* (USA); *Code Division Multiple Access* (CDMA)(*Interim Standard* (IS-95)) – Qualcomm in USA and *Personal Digital Cellular* (PDC) in Japan.

With exception of IS-95 standard taken in USA which used CDMA as multiple access technology, the rest of the standards adopted TDMA [7].

In a nutshell, *General Packet Radio Service* (GPRS) and *Enhanced Data Rates for Global Evolution* (EDGE) are preceding the *Third Generation* (3G) systems. GSM system and its deployment success prompted the rise of new systems able to offer faster data rates transmission. The higher data rates imposed by *Internet* for example, emphasizes the need of new technology with better services and performance.

The GPRS systems are based on the same GMSK radio modulation as the GSM systems; The system incorporates a new core network's packet switched domain - *Packet Switched* (PS) domain. In addition, the air interface can now handle with data and voice, approaching to theoretical maximum bit rate around 20 Kb/s per radio time slot [2].

EDGE allows theoretical peak data rate of the system is around 472 kbps. It makes use of new modulation, 8-*Phase Shift Keying* (PSK), and also make use of fastest coding scheme.

1.1.3 Third Generation

The *Universal Mobile Telecommunications System* (UMTS) is the key technology for the 3G. It was originally developed by ETSI, as the 3G system for *International Mobile Telecommunications* (IMT)-2000 based on evolution of GSM. Also called UMTS Release 99, it is the world's dominant system and its first commercial deployment happened in October 2002 in Japan[8].

UMTS technology keeps the GSM architecture, while the 3G air interface has adopted *Wideband Code Division Multiple Access* (W-CDMA) introducing the CDMA scheme on *Third Generation Partnership Project* (3GPP) family.

The UMTS radio access specifications provide for *Frequency Division Duplex* (FDD) and *Time Division Duplex* (TDD) variants, so that, TDD mode for 1.6 MHz bandwidth represents low chip rate and FDD mode for 5 MHz bandwidth, high chip rate. It also integrates a new system *Internet Protocol Multimedia Subsystem* (IMS) capable to support multimedia services. The system envisions the theoretical peak data rate of 2 Mbps.

A slightly different implementation on UMTS air interface called *Time Domain Synchronous Code Division Multiple Access* (TD-SCDMA) was launched by 3GPP in Chinese market essentially to reduce the dependence of Western technology[9].

UMTS technology, was extended in a set of two releases: *High Speed Downlink Packet Access* (HSDPA) - Release 5 and *High Speed Uplink Packet Access* (HSUPA) - Release 6. Both were launched in 2005 and are known collectively as *General Packet Access* (HSPA). Its evolution came in Release 7(also known as *High Speed Packet Access Evolution* (HSPA+)).

HSDPA foresees to increase user throughput for packet downlink transmission presenting a new modulation, 16-*Quadrature Amplitude Modulation* (QAM) (theoretically can be achieve peak rate of 14.4 Mb/s). Moreover the technology makes use of *Hybrid Automatic Repeat reQuest* (HARQ) which is basically a fast packet retransmission that allows fast adaptation to radio transmission changes.

Once evolved downlink throughout, 3GPP launched HSUPA technology, an equivalent HSDPA system as described above, but now for uplink packet transmission, making use of the same techniques to reach in theory 5.7 Mb/s to a single terminal.

HSPA+ is an enhancement of HSPA technology and it has brought for cellular communication systems *Multiple Input Multiple Output* (MIMO) operation, as well as, the use of higher modulations(64-QAM in downlink as 16-QAM in uplink) for radio transmission and reception. It is considered the bond between the current HSPA+ and Evolved UMTS because within 5 MHz bandwidth presents the same efficiency as Evolved UMTS networks. The architecture is similar to flat architecture agreed upon for LTE as also ensures compatibility with 3G systems offering to operators a smooth upgrade in their networks.

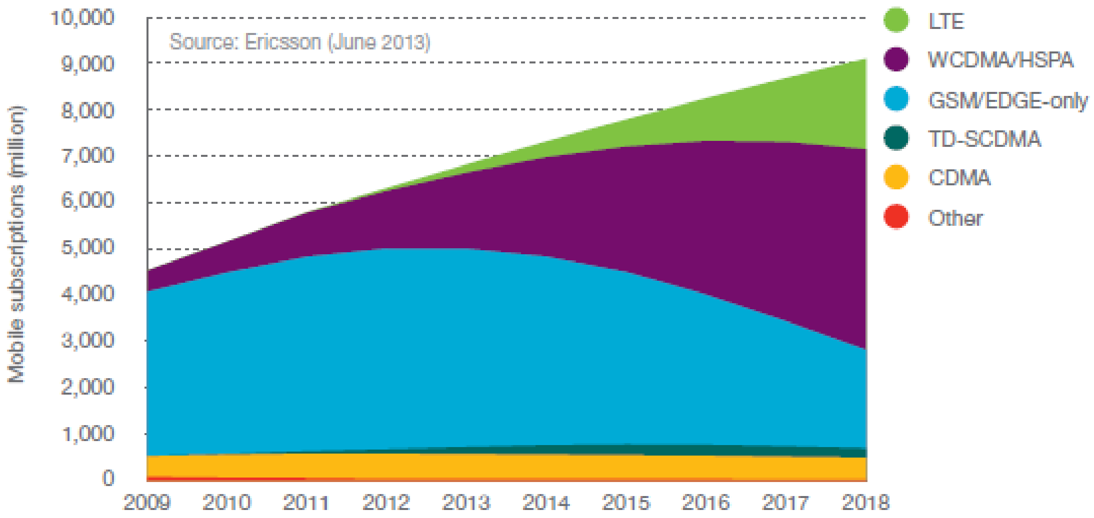

Figure 1.1: Mobile subscriptions by technology (source:[10])

1.1.4 Forth Generation - Beyond LTE

Worldwide Interoperability for Microwave Access (WiMAX) technology was introduced by *Institute of Electrical and Electronics Engineers* (IEEE) family, together with LTE are the mains *Forth Generation* (4G) technologies of the *International Telecommunication Union* (ITU). In parallel, the 3GPP2 has accompanied the 3GPP evolution had launching systems based on CDMA, mainly in USA, Korea and Japan [5]. The *Ultra Mobile Broadband* (UMB) is its 4G technology given that the standard was discontinued in November 2008. 4G provides advanced techniques processing to achieve better spectral efficiency, higher capacity and lower latency than the previous 3G.

LTE - represents a major advance in mobile technology and it takes advantage of multi-antenna transmission techniques known as MIMO and OFDM. In particular, the LTE *Physical Layer* (PHY) uses OFDMA in downlink and SC-FDMA in the uplink. These technologies contributed for higher data rates and robustness against multi-path environment, benefiting the current 4G system but also paving way for future 4G systems - LTE-*Advanced*. The first full 4G system considered by ITU that fills the requirements to be considered as making part of 4G is LTE-*Advanced*, which is still in study phase.

This new technology termed LTE-*Advanced* (Release 10), should be able to include new capabilities of IMT that go beyond those of IMT-2000, significantly enhances the Release 8 to support much higher peak rates, lower latencies resulting in better user experience. The Figure 1.1 illustrates reported mobile subscriptions categorized by technology.

LTE is currently being deployed and will reach around 2 billion subscriptions in 2018.

1.2 Motivation and Objectives

Wireless communications play important role in overall economic development, and are the answer for the increasing demands to provide faster and reliable services to the users. Increasing transmission rates are required as well as a better *Quality of Service* (QoS). To achieve a specific performance level, the wireless system must overcome some of the underlying problems, such as the interference and multipath. The multi-path is the main factor that makes wireless a real challenge when compared with other transmissions systems, such as the fiber, cable or point-to-point radio broadcast. There are other constrains: transmission power level and the decrease in radio spectrum availability. The MIMO technology emerges as a solution to combat both the effects of radio channel and resource limitations. MIMO offers increased capacity in wireless communication systems without requiring an increase in bandwidth or transmitted power. The present wireless systems, such as LTE and LTE advanced, already use MIMO techniques for transmission.

Unlike the 3G systems, LTE specifies multiple antennas in both terminals, *Base Station* (BS) and *User Equipment* (UE), exploiting diversity and spatial multiplexing. The implementation of multiple antennas M_t in the transmitter and M_r antennas in the receiver can be used with different goals: to increase the system capacity or to improve the diversity, and thus improving the *Signal Interference Noise Ratio* (SINR). The MIMO systems need pre/post processing the signals from the multiple antennas, in both sides. Alamouti encoding/decoding, appears as being part of the transmit diversity, in this way not providing higher data rate, but conferring link robustness without increasing total transmission power or bandwidth. For two antennas transmit antennas and one receive antenna it is achieved a diversity gain of 2 assuming an uncorrelated channel. The code presents a remarkable spatial and time diversity by using a simple code at the transmitter and linear decoding a the receiver, this means low complexity in the receiver.

A wireless testbed is being developed at IT by MOBNET group. Currently an OFDM baseband transceiver has been implemented and will be the basis to include study algorithms for MIMO wireless systems.

The objectives of this dissertation are:

- Study techniques of MIMO in wireless system and in particular one of its more relevant technique, the diversity transmission Alamouti scheme.
- Implement the encoder and decoder in a *Field Programmable Gate Array* (FPGA) to be added to a transceiver that follows closely the LTE physical layer specifications.
- Contribution to a wireless testbed.

In this dissertation we focus in the implementation of the Alamouti algorithm on a MISO system. We used the System Generator from Xilinx to develop and test the Simulink model of the encoder and decoder. The encoder is included in a MISO transmitter chain. The decoder is used to demodulate the single antenna received signal.

1.3 Outline

The thesis is organized in the following way: in Chapter 1, is made an overview evolution of cellular systems, framing LTE technology in the evolution of digital systems, from 2G until the latest technology for cellular devices; Further it is discussed the motivation and the goals of the thesis. In Chapter 2 is introduced the LTE system as a whole, emphasizing some of the key technologies used by LTE, its main targets/specifications and at last is made and overview of the network architecture. In Chapter 3 is presented the multiple access schemes OFDMA and SC-FDMA of LTE. It is described some new technologies that LTE uses such as OFDM, SC-FDMA as well as the MIMO technology. In Chapter 4 is introduced the MIMO schemes and the concept of diversity. Further, it is presented and analysed transmit diversity for Alamouti *Space Time Block Code* (STBC) (2 x 1). In the Chapter 5 is analysed a MISO-OFDM system model based on Alamouti SFBC. Further on , are presented the results the work developed as well as the results obtained. The last Chapter 6 concludes the thesis work and guidelines for future research.

Chapter 2

Overview of the 3GPP LTE

LTE is part of evolutionary path for mobile broadband within 3GPP family and to ensure that the technology remains competitive in the future, in 2004 3GPP began a project to define the long-term evolution of UMTS cellular technology to offer superior performance compared to HSPA according 3GPP specifications, whose describes the basic performance of new, high performance air interface providing high user data rates along with low latency based on MIMO, OFDMA and *System Architecture Evolution* (SAE) as main enablers [11].

LTE was first introduced in Release 8, which was frozen in December 2008. Beyond evolving radio access technology, assuming since the beginning that all services would be packet-switching, the new architecture labelled SAE has reduced the number of network elements and includes *Evolved Packet Core* (EPC) network. The whole architecture system(LTE-*Radio Access Network* (RAN) plus EPC) is known by EPS, where both the core network and the radio access are fully packet-switched. EPS allows inter-working and mobility (handover) with networks using other *Radio Access Technologys* (RATs) namely CDMA2000 and WiMAX. LTE technology offers significant advantages to operators mainly due to its flat architecture(*Internet Protocol* (IP)-based), reducing *Capital Expenditure* (CAPEX) and *Operational Expenditure* (OPEX), and incorporate quality of service with *Voice over Internet Protocol* (VoIP).

In June of 2008, the *Next Generation Mobile Networks* (NGMN) selected LTE as sole technology that matched its requirements successfully. Additionally a global group of equipment vendors and operators have formed *LTE/SAE Trial Initiative* (LSTI) with the purpose to coordinate activities needed to take the technology from the standards to commercial version NGMN [12].

The E-UTRAN is similar to *UMTS Terrestrial Radio Access Network* (UTRAN) and difference comes from the fact that LTE has specified OFDMA for the air interface in the downlink direction and SC-FDMA for uplink.

Notably, OFDM is used with advanced receiver and antennas technologies[13]. In particular, the processing of OFDMA signals provide effectively frequency flat channels and hence, full MIMO technologies can be easily deployed in conjunction with OFDMA [14].

OFDM is the core of LTE downlink radio transmission. The use of relatively narrow-band sub-carriers in combination with a cyclic prefix makes OFDM transmission inherently robust to time dispersion on the radio channel, effectively eliminating the need for complex receiver/channel equalization. As OFDM signal can adapt to a wide variety channel bandwidths by modifying the number of carriers, it enables scalable bandwidth operation; LTE solution system supports flexible bandwidths ranging from 1.4 MHz up to 20 MHz, depending on available spectrum.

SC-FDMA is chosen for uplink because has smaller *Peak to Average Power Ratio* (PAPR) than OFDM resulting in more power efficient and less complex terminals; It also offers multipath resistance and flexible frequency allocation of OFDMA improving the cell-edge performance [15]. Both of these schemes start up the frequency domain as a new dimension of flexibility in the systems.

It is worth to mention also that LTE besides employs multiple transmit and receive antennas schemes, also employs turbo coding and link adaptation in the physical layer in order to achieve better spectral efficiency and user throughput.

Link adaptation is closely related to scheduling and deals with how to set the transmission parameters of a radio link to handle variations of the radio-link quality. This is achieved in LTE through adaptive channel coding and adaptive modulation. In LTE technology the available modulations are QPSK, 16-QAM and 64-QAM. The first two modulations are available in all devices, unlikely 64-QAM modulator in uplink, that concerns to UE capability. LTE can switch dynamically between these different modulation schemes: it uses 64-QAM at high SINR to give a high data rate, and 16-QAM or QPSK at lower SINR to reduce the number of errors [16].

The channel quality measurements for link adaptation and scheduling are designed to cater to multi-antenna transmission, enabling to optimize cell performance dynamically [17]. Furthermore, the assumption that all terminals support at least two receive antennas according with the requirements set, it is possible that networks can be planned assuming at least downlink-receive diversity. In LTE downlink it is supported one, two or four transmit antennas in the *Evolved Node B* (eNodeB) and one, two or four receive antennas in the UE. In uplink direction it is allowed one, two or four antennas as happen in downlink direction but despite of this only one transmitting antenna is allowed in the UE hence, multiple antennas can be only used to obtain receive diversity. Advanced techniques, such as Transmit diversity, spatial multiplexing and beam-forming are also supported on the system [18].

The air interface also supports both paired (downlink and uplink use different frequency bands) and unpaired spectrum (downlink and uplink use same frequency band), using FDD and TDD respectively, where both can share the same downlink subframe structure. Additionally, Half-duplex FDD is also possible avoiding the need for a costly duplexer in the UE. The Table 2.1 give us a resume of the main LTE capabilities.

Table 2.1: LTE attributes

Parameter	**Downlink**	**Uplink**
Peak data rate	100 Mbps (1 x 1) 173 Mbps (2 x 2) 326 Mbps (4 x 4)	50 Mbps (1 x 1 86 Mbps (1 x 2)
MIMO	(1 x 1), (2 x 2) (4 x 2),(4 x 4)	(1 x 1), (1 x 2), (1 x 4)
Multiple access	OFDMA with CP	SC-FDMA with CP
Duplexing	FDD, TDD, half-duplex FDD	
Bandwidth	1.4, 3, 5, 10, 15 and 20 MHz	
Modulation	QPSK, 16-QAM and 64-QAM	BPSK, QPSK and 16-QAM
Channel coding	Turbo code	
Mobility	350 km/h	
Latency	< 10 ms	
Other techniques	Channel sensitive scheduling, link adaptation, power control, ICIC and hybrid *Automatic Repeat reQuest* (ARQ)	

Further developments of the LTE specifications are continuing to follow the IMT-Advanced requirements and therefore the Release 9 includes broadcast/multicast services, location services, an enhanced emergency-call functionality, as well as enhancements for downlink dual-layer beam-forming. The Release 9 enhances also the self optimization capabilities of LTE. At the end of 2010, 3GPP has concluded the work on LTE Release 10 extending the performance and capabilities of LTE beyond Release 8/9 [19][20].

2.1 Requirements for LTE

The starting point for LTE standardization was the 3GPP RAN Evolution Workshop, held in November 2004 in Toronto, Canada. When several companies involved in mobile communications discussed the future evolution of the specifications to be developed in 3GPP. A study item was started in December 2004 with the goal to develop a framework for the evolution of the 3GPP radio access technology. The requirements for LTE were finalized in June 2005 and are following resumed, according [21] [22]:

- Reduced cost per bit, implying improved spectral efficiency;
- Reduced delays (connection establishment and transmission latency);
- Increased cell-edge bit-rate;
- Increased service provisioning – more services at lower cost with better user experience;
- Flexible use of existing and new frequency bands;
- Flexible use of existing and new frequency bands;
- Simplified architecture and open interfaces;
- Reasonable terminal power consumption;
- Seamless mobility, including between different radio-access technologies;

Notably, the requirements and performance targets for LTE were decided when HSPA Release 6 was still being finalized and hence, the targeted improvements are in many cases set relative to HSPA Release 6. A key requirement set for LTE was that its performance should be superior if compared with HSPA. The LTE key performance requirements as comparison with HSPA is shown in Table 2.1.

The requirement for peak data rate - 100 MHz for downlink and 50 for uplink - is reached with *Single Out Single Input* (SISO) within 20 MHz bandwidth delivering. Within 20 MHz bandwidth the system can provide up to 150 Mbps downlink user data rate and 75 Mbps uplink peak data rate with 2 x 2 MIMO, and 300 Mbps with 4 x 4 MIMO. In the first release of the standard the uplink peak data rates are limited to 86 Mb/s, since uplink is specified only for SISO but at different modulation.

In terms of spectral efficiency, LTE offers 3 to 4 times than HSDPA and 2 to 3 times than HSUPA for inter-site distances of 500 m and 1732 m, respectively.

The system offers coverage to support cell sizes of up to 100 km, being optimized for cell sizes up to 5 km. Regarding to mobility the system affords speeds of up to 350 km/h, and is optimized for mobile speeds up to 15 km/h) [23]. The LTE/SAE effort has reduced the latency whereas the radio-interface and network specifications envisions less than 10 ms latency for transmission of a packet from the network to the UE (sub-5 ms latency for small IP packets).

LTE meets the IMT-2000 requirements and hence it is considered as making part of IMT-2000 family of standards. Its performance has been evaluated in so called checkpoints in 3GPP plenary sessions 2007 in South Korea and the results showed that LTE meets and exceed the targets for peak data rates, cell edge user throughput and spectrum efficiency, as well as VoIP and *Multimedia Broadcast/Multicast Services* (MBMS) performance [24]. The results of the study are published in 3GPP *Technical Report* (TR) 36.912. The latest versions of the LTE and SAE documents can be found at http://www.3gpp.org/ftp/specs/latest/Rel-8/.

2.2 Network Architecture

The first version of GSM system and its enhancements defined beyond voice services, data services. The GSM simplified architecture, compose by *Mobile Station* (MS), RAN and *Core Network* (CN) suffered some modifications and the CN was split in two domains: *Circuit Switched* (CS) domain and PS domain. The packet switched component was introduced by GPRS standard.

W-CDMA followed up the continuous evolution of the technologies and acquired a new RAN alongside of a new sub-domain called IMS in the CN was also introduced.

As discussed before, LTE is accompanied by a new architecture called SAE. The SAE initiative defines an all-IP, packet-only core network called the EPC, along with radio access technology recognized as LTE. This new architecture was designed to optimize network performance, improve cost-efficiency and support mass-market IP-based services as high data transmission rates. In addition, supports interworking with circuit-switched systems [24].

LTE core network ensures that mobile devices are efficiently connected to the network but also their communication with service platforms as IMS and *Internet* [25].

The combination of LTE and SAE comprise the EPS, term given to whole system. The architecture represents an evolution from hierarchical to flat network reducing the number of nodes in order to minimize latency in the network, as pictured in the Figure 2.1. Nevertheless, the user plane encompasses only two nodes instead of four while control plane is separated with *Mobility Management Entity* (MME). The 3GPP Release 8 has standardized QoS concept of the EPS at which the bearer is the basic level of granularity for QoS control. EPS routes the IP packet with a given QoS, called an EPS bearer, from the *Packet Data Network Gateway* (P-GW) to UE. Notably the EPS bearer is able to transport both native IPv4 and native IPv6 packets [26].

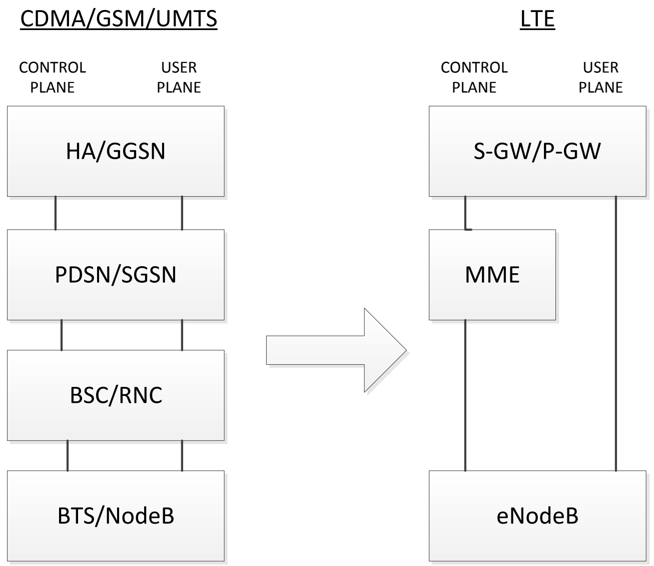

Figure 2.1: Flat EPS network (Source: Adapt from [27])

2.2.1 Core Network

The core network, called EPC in SAE does not involve support for circuit switched domain. The CN manages the control of the UE and establishes the bearers through the logical nodes.

Figure 2.2 shows a simple architecture of the EPS. As it can be seen, the UE is connected to the EPC over E-UTRAN - the LTE access network. The EPC, in this turn is attached to external networks as IMS and is composed by several functional entities: *Serving Gateway* (S-GW), P-GW, MME, *Home Subscriber Server* (HSS) and the *Policy Control and Charging*

Rules Function (PCRF) that are following described.

- S-GW is logically connected to the other gateway, the P-GW. As its name indicates, S-GW is the anchor point for *handover* between eNodeBs and other 3GPP accesses. Specifically it is responsible to deal with data bearers when the UE moves between eNodeBs. By routing the incoming and outgoing IP packets this particularly gateway also retains the information about the bearers when the UE is in idle state and temporarily buffers downlink data while the MME initiates paging of the UE to re-establish the bearers. Additional administrative tasks are carry, as the volume of data sent to or received from the use and legal interception.

- P-GW is the point of interconnect between the EPC and the external IP networks, serving also as mobility anchor for non-3GPP access networks. Notably, it is in charge of IP address allocation for the UE, QoS enforcement for *Guaranteed Bit Rate* (GBR) bearers (settle for VoIP which has stringent requirements for QoS than for example *browsing*) besides also, filtering of downlink user IP packets into the different QoS based bearers.

- MME is responsible for the control plane functions related to subscriber and session management between the UE and the CN in the *Non-Access Stratum* (NAS) protocol layer. The mains functions supported by MME are bearer management and connection management. The establishment, maintenance and release of the bearers are related to bearer management while connection management assumes the establishment of the connection and security functions between the network and UE.

- HSS is based on the 3GPP Release 4 in particular the *Home Location Register* (HLR) and *Authentication Centre* (AuC). The HSS is faced as a database that contains user/subscriber information, namely users SAE subscription data such as QoS profile and any access restrictions for roaming. Further, retains information about the *Packet Data Network*s (PDNs) to which the user can connect and to which user is currently registered or attached.

- The PCRF provides functions for determining the QoS and charging policy to be applied to data packets sent and received by the user. Determining a QoS value, it passes through to the P-GW, S-GW until reach the eNodeB that will perform QoS control on data packets conform to that value.

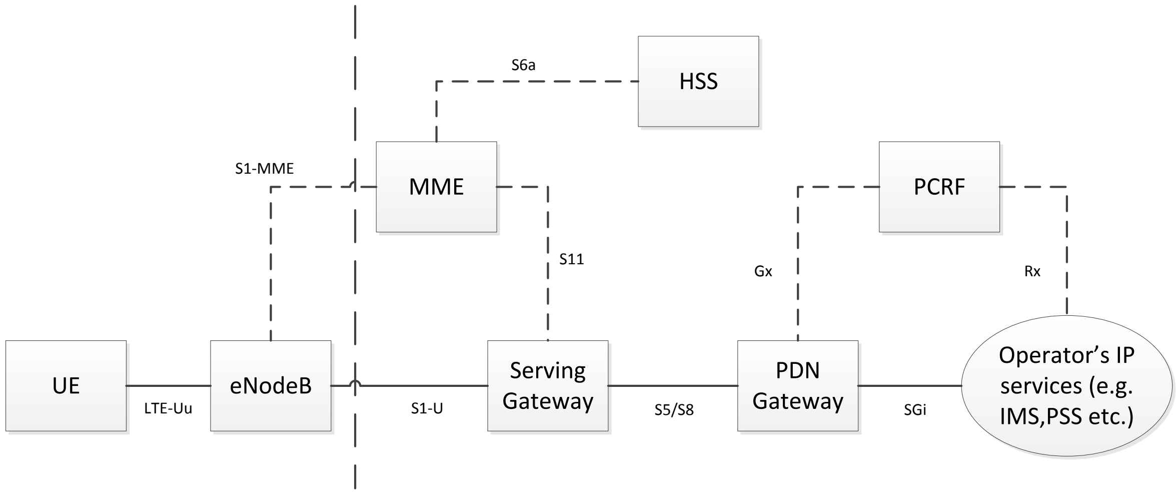

Figure 2.2: The EPS network elements (source: Adapt from [21])

2.2.2 Radio Access Network

The flat architecture of LTE RAN presented in the Figure 2.3 is due to the fact that E-UTRAN does not support macro-diversity or soft handover, in this way allowed that *Radio Network Controller* (RNC) could be eliminated and consequently there is no need of centralized controller. Its functions were assumed by the single node, known as eNodeB.

The base stations - eNodeB are interconnected to each other through the X2 interface and to the EPC through the S1 interface, specifically to the MME by means of S1-MME interface and to the S-GW by means of the S1-U interface. The mobile terminal is denoted as UE in which is not depicted. The protocols that run between them (eNodeB and UE) are known as "AS protocols".

The functions of E-UTRAN are [28] [5]:

- *Radio Resource Management* (RRM) - Ensure that radio resources are efficiently utilized to serve users according to their QoS attributes. This encompasses radio mobility and admission control, dynamic allocation of uplink/downlink traffic and data packet scheduling according to QoS policies.
- Header Compression - Answer to the requirements to maintain privacy over the radio interface and ensures that IP packets are transmitted in the most efficient way, by

compressing IP packet headers avoiding *overhead* for small packets as VoIP.

- Security - Encrypts the data exchanged in the network mainly due to the sensitivity of the signalling messages.
- Connectivity to the EPC

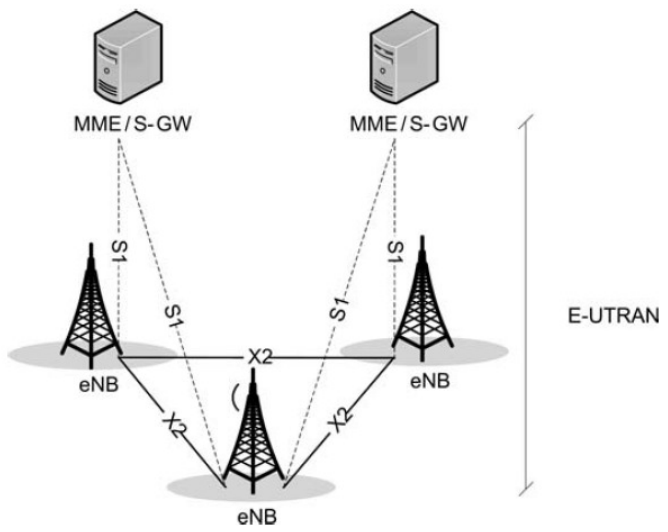

Figure 2.3: LTE architecture with E-UTRAN (source: [5])

The eNodeB combines the earlier functions leading a tight interaction between the protocols layers of the RAN, reducing latency and improving the efficiency. One consequences of the absence of a centralized controller node is that when the UE moves, the network must transfer all the information from one eNodeB to the another may loss data thus, the handovers are handled through packet forwarding over the X2 interface to support loss-less mobility.

The S1 interface, allows more flexibility in the inter-connection between access and core nodes. Known as S1-flex, enable that an eNodeB to be connected to more than one MME/S-GW node(noted that the terminal is only associated to one MME at a time). From S1-flex characteristics, stand-out the common area referred as pool area - a predefined set of eNodeB at which the terminal may move without need to change its CN node may be shared by more than one CNs, making possible load share and remove single points of failure for the CN nodes.

Comparison relative to HSPA	
Metric	Requirement
Peak data rates	100 Mbit/s for downlink 50 Mbit/s for uplink
Average user throughput per MHz	3–4 times higher for downlink 2–3 times higher for uplink
Spectrum efficiency in bit/s/Hz/cell	3–4 times higher for downlink 2–3 times higher for uplink
Mobility	0–15 km/h (optimized for this range) 15–120 km/h (high performance guaranteed) 120–350 km/h (connection maintained)
Supported bandwidths	$<$ 5 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz
Spectrum allocation	Operation in paired spectrum (FDD) and unpaired spectrum (TDD) should be supported
Latency	5 ms user-plane latency at IP layer, for one-way 100 ms control-plane latency from idle to active state km/h (connection maintained)
Number of users per cell	At least 200 at 5 MHz bandwidth At least 400 at bandwidth higher than 5 MHz
Support for interworking with existing 3G systems and non-3GPP specified systems	

Table 2.2: Requirements for LTE

Chapter 3

Multiple Access Schemes of LTE

The 3GPP LTE (Release 8) and its enhancements adopted the multi-carrier modulation system OFDM which is an attractive downlink transmission scheme due to the relatively long OFDM symbol time with a cyclic prefix since it provides high robustness against channel frequency selectivity, it means that in time domain there is corruption of the transmitted signal due to time dispersion on the radio channel. Furthermore, it is well suited to meet requirements for high data rates (with correspondingly large transmission bandwidths), and for MIMO processing [29].

Additional benefits are following resumed:

- OFDM provides access to the frequency domain, enabling an additional degree of freedom to the channel-dependent scheduler.
- Flexible transmission bandwidth to operate in different spectrum allocations(1.4, 3, 5, 10, 15, and 20 MHz).
- Broadcast/multicast transmission is facilitated with OFDM once the same information is transmitted from multiple base stations.

LTE uplink scheme contains a frequency-domain multiple-access component, hence is commonly referred as SC-FDMA. It is based on orthogonal separation of uplink transmissions in the time and/or frequency domain which avoids intra-cell interference. The use of single-carrier transmission in uplink is motivated by the lower peak-to-average ratio of the transmitted signal compared to multi-carrier transmission - OFDM. In this way the power amplifier is efficiently used, increasing coverage and reducing the terminal power consumption. To handle with the corruption of the single-carrier signal due to frequency-selective fading, the equalization is less of an issue once there is more powerful signal processing resources at the base station side, compared to the mobile terminal.

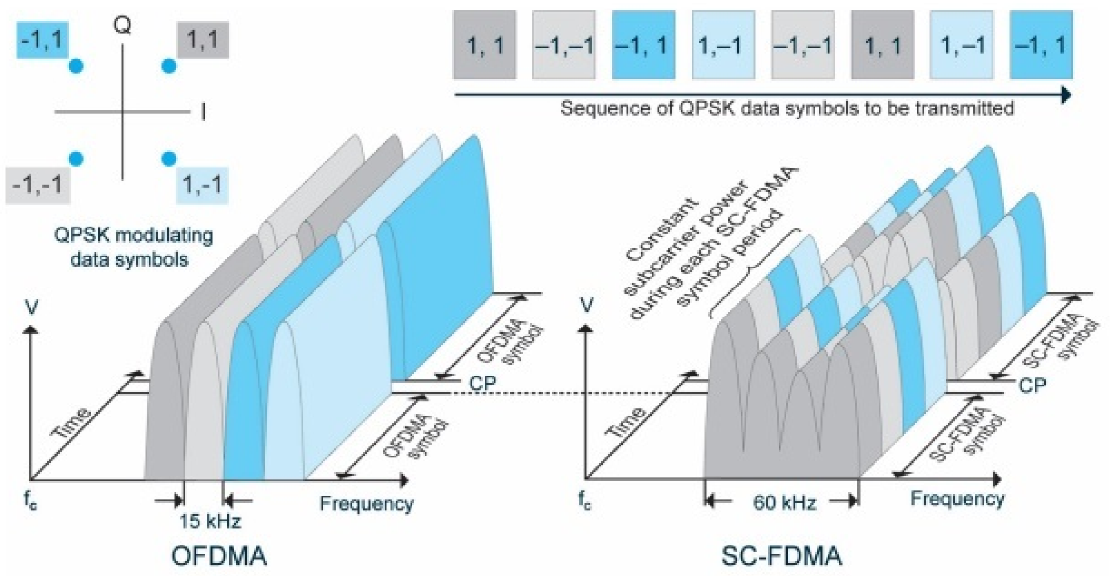

Figure 3.1: Comparison of OFDMA and SC-FDMA transmitting a series of QPSK data symbols (Source: [30])

The graphical 3.1 above compares the differences between both modulation schemes where are considered four (M) sub-carriers over two symbol periods using QPSK modulation. The obvious difference between the two schemes is that OFDMA transmits the four QPSK data symbols in parallel (one data symbol per sub-carrier) while SC-FDMA transmits the four QPSK data symbols in series at four times the rate.

3.1 OFDM

In the past century, OFDM technology was considered a crucial application against multipath channels. Such channels are characterized by a non-flat frequency response, which includes deep holes known as selective fading. OFDM is a special form of multi-carrier transmission and hence presents robustness in frequency selective fading channels, emphasizing the reduced signal processing complexity by equalization in the frequency domain. The basic idea of OFDM is shown in the Figure 3.2. It consists to spread the information over an amount of sub-carriers to create very narrow band channels referred to as sub-carriers and transmit information on these parallel channels at a reduced signalling rate, so that in each of them a frequency response that can be considered as uniform or flat, avoiding *Inter-Symbol Interference* (ISI). Moreover, different reference frequencies used in transmitter and receiver can cause *Inter-Carrier Interference* (ICI) that contributes to lose OFDM orthogonality [11].

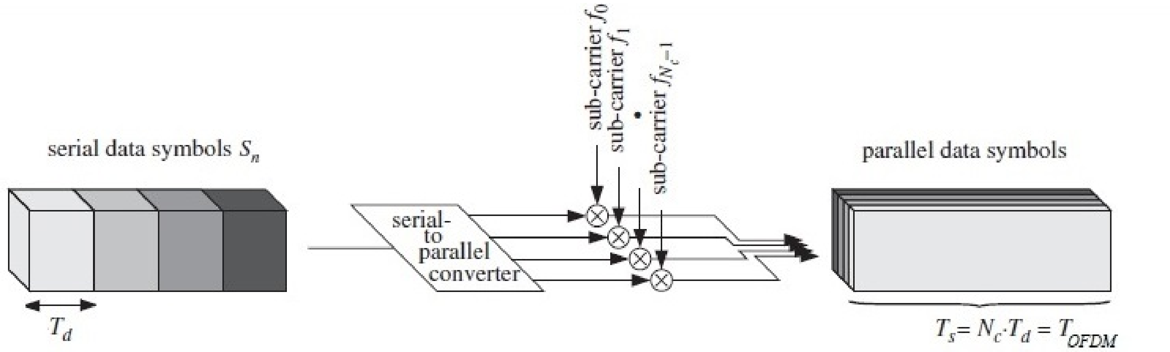

Figure 3.2: OFDM with $N_c = 4$ sub-carriers (source: Adapt from [18])

Ideally, these narrow band channels or sub-channels are overlapping by finding frequencies that are orthogonal (mathematically perpendicular) allowing the spectrum of each sub-carrier to overlap other sub-carriers without interference, avoiding the need to separate sub-carriers by guard-bands and therefore makes OFDM highly spectrally efficient.

This overlapping produces a particular spectral bandwidth significant savings in relation to traditional FDM technique, as shown in Figure 3.3. It is obtained bandwidth savings of approximately 50% [21].

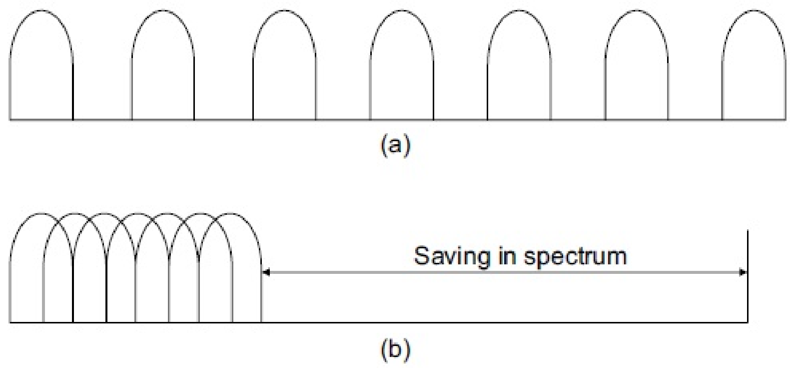

Figure 3.3: Spectral efficiency of OFDM: (a) Classical multi-carrier system spectrum - FDM; (b) OFDM system spectrum (Source: [31])

The orthogonality of OFDM sub-carriers can be lost when the signal passes through a time-dispersive radio channel due to inter-OFDM symbol interference. To reverse this, a cyclic extension of the OFDM signal can be performed to avoid this interference [32]. CP consists on a copy of the last part of the OFDM signal, adding it in the beginning of the OFDM signal.

A generic communication system based OFDM modulation is illustrated in the Figure 3.5. As regards to the transmitter it is notable that the sequence paralleled is moved to time domain by *Inverse Fast Fourier Transform* (IFFT) block and further it is added CP. In the receiver side, happen the inverse processed, i.e. still in the time dimension it is removed CP and then *Fast Fourier Transform* (FFT) processing is performed.

OFDM systems take advantage from the fact that multi-carrier modulation can be implemented in the discrete domain by using an *Inverse Discrete Fourier Transform* (IDFT) or a more computationally efficient IFFT. In addition, the number of OFDM sub-carriers is generally selected as power of 2, such as 512, 1024, etc, which allows using more efficient FFT and IFFT algorithms.

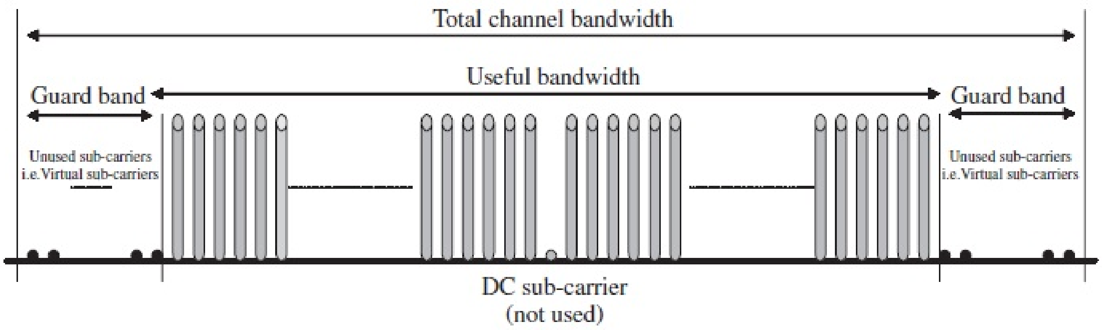

Figure 3.4: Useful bandwidth by using Virtual sub-carriers (Source: [33])

Notably in case of the number of FFT points is higher than that required for data transmission, a simple filtering can be achieved by putting at both sides of the spectrum null sub-carriers (guard bands), called virtual sub-carriers as shown in the Figure 3.4. Additionally, to avoid the *direct current* (DC) problem, a null sub-carrier can be put in the middle of the spectrum (the DC sub-carrier is not used).

In the OFDM system model depicted above, initially, takes place a conversion series-parallel where sets of S words of k bits are mapped into S_n sub-symbols complex X_k, which determine the constellation points of each sub-carrier according to the type of modulation employed. The complex modulations symbols X_k are mapped to the input of IFFT. A cyclic

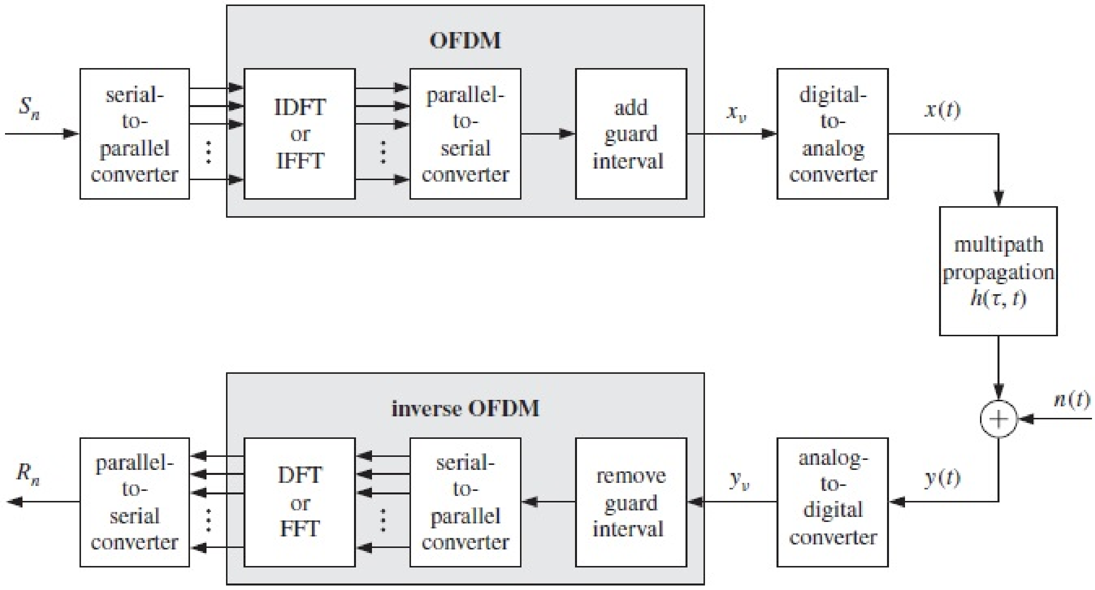

Figure 3.5: Digital multi-carrier transmission system applying OFDM (Source: [33])

prefix is added after IFFT operation at *Parallel-to-Serial* (P/S) converter and the resulting sequence is up-converted to *Radio Frequency* (RF), amplified and transmitted through the frequency-selective channel.

In the receiver side, the received signal is filtered, amplified and down-converted. The cyclic prefix is removed and FFT operation is performed on the received samples sequence.

Under the assumptions that ICI is avoided due to the guard interval/CP insertion (each sub-channel can be considered separately), ISI is removed and at last that the fading on each sub-channel is flat, a multi-carrier system can be simulated in frequency domain since it is more efficient than in time domain. Consequently the OFDM modulation system can be assumed as a simple multiplication of the complex data symbols with frequency channel response. The received signal can be represented in frequency domain by,

$$R_n = H_n S_n + N_n \tag{3.1}$$

where H_n is the flat fading factor and N_n represents the noise of the n sub-channel. The transmitted signal over a multipath channel is converted into a transmission of parallel flat-fading channels. As a result of that, the equalization operation is simplest once only one complex multiplication per sub-carrier is made [21].

Considering then a frequency-domain channel, *frequency-domain equalization* (FDE) operation can be performed using channel estimates obtained from received pilots or reference signals to obtain estimates of the transmitted complex modulation symbols [18][21].

3.1.1 Orthogonality

The main concept in OFDM is the orthogonality of the sub-carriers. This orthogonality allows simultaneous transmission on a lot of sub-carriers in a tight frequency space without interference between them increasing the spectral efficiency.

The aim of OFDM is modulate the N_c data symbols in N_c sub-carriers under the assumption that the spacing between the different sub-carriers is given by,

$$\Delta f_c = \frac{1}{T_{OFDM}} \tag{3.2}$$

guaranteeing the signals at different sub-carrier are orthogonal, for an rectangular pulse. The T_{OFDM} is the duration of an OFDM symbol.

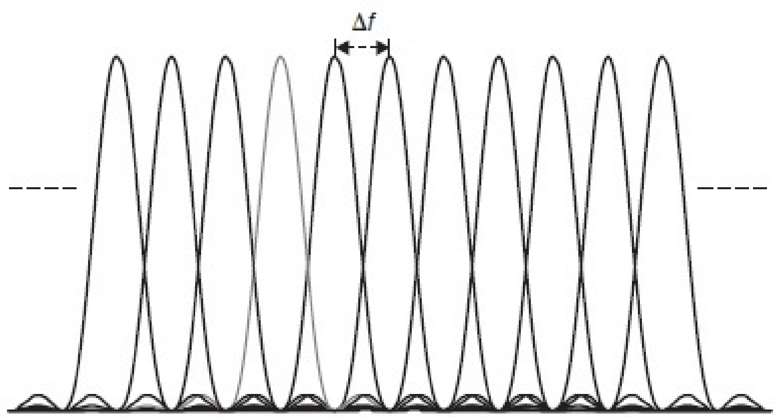

Figure 3.6: OFDM sub-carrier spacing (Source: [31])

The frequency spectrum of an OFDM transmission is illustrated in the Figure 3.6 and it can be seen all sub-carriers overlap. The orthogonality principle between each *sinc*, (a sinusoidal carrier modulated by a rectangular waveform) is easily notice since the frequency spectrum of one carrier exhibits zero-crossing at central frequencies corresponding to all other carriers. Another aspect of orthogonal signals is that they can be separated at the receiver by correlation techniques.

3.1.2 Cyclic Prefix

OFDM takes advantage from the principle of multi-carrier transmission where the symbol rate on each sub-carrier is much less than the initial serial data symbol rate and hence the OFDM symbol duration T_s becomes large compared to the duration of the impulse response τ_{max} of the channel, i. e. due to multipath delay spread. In this way ISI decreases significantly and therefore the complexity of the equalizers is also reduced.

It is expect that the requirement for the OFDM sub-carrier orthogonality, after the transmitted signal has propagated over the radio channel, that the instantaneous channel does not vary during the demodulator correlation interval T_s.

In case of a time-dispersive channel the orthogonality between the sub-carriers may be lost. Since the integration interval for demodulation is applied to overlap symbols. The modulation symbols may differ between consecutive symbol intervals and there will be ISI within a sub-carrier but also ICI.

However, to completely avoid the effects of ISI and thus, to maintain the orthogonality between the signals on the sub-carriers, i.e. to also avoid ICI, a guard interval of duration,

$$T_g \geq \tau_{max} \tag{3.3}$$

has to be inserted between adjacent OFDM symbols. The guard interval is no less than a cyclic extension of each OFDM symbol, by extending the duration of an OFDM symbol.

$$T_s^{'} = T_g + T_s \tag{3.4}$$

The cyclic prefix length is generally chosen to accommodate the maximum delay spread of the wireless channel implying the need for a longer CP. A longer CP for a given OFDM symbol duration corresponds to a larger overhead in terms of energy per transmitted bit. This reduction in bandwidth efficiency can be expressed as as a function of the CP duration, T_{CP}.

$$\beta_{overhead} = \frac{T_{CP}}{T_s + T_{CP}} \tag{3.5}$$

In summary, the CP insertion implies a reduction in transmission rate and consequently it reduces the spectral efficiency. So, its length has to be designed in order to minimized the reduction of spectral efficiency but also taking into account the maximum delay channel to ensure the absence of ISI.

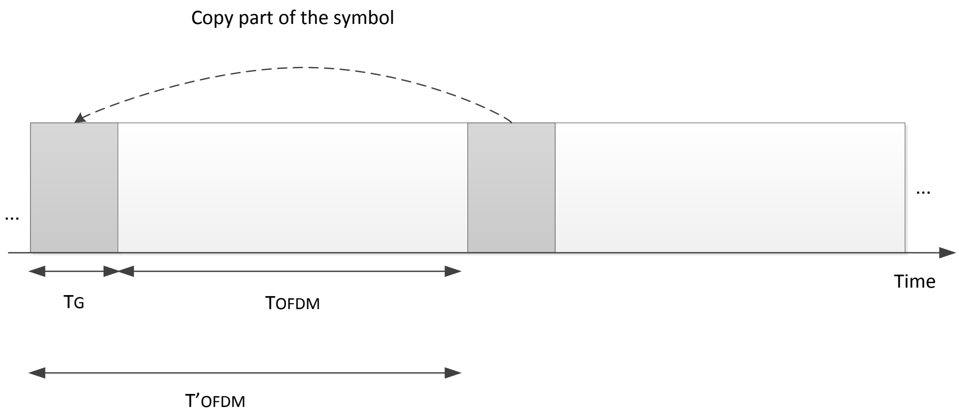

Figure 3.7: OFDM symbol with CP insertion

Generally, the CP is dimensioned to be less than 20% to 25% of the duration of the OFDM symbol [34].

3.2 Physical Layer Parameters for LTE

Data transmission through the radio interface is organized into radio frames, with two possible structures: for FDD, uplink and downlink transmissions are separated in the frequency domain. For TDD, a subframe is allocated either to downlink or uplink transmission. LTE parameters have been chosen such that FFT lengths and sampling rates are easily obtained for all operation modes with a common clock reference.

Each radio frame has 10 ms long, being composed by 20 slots of length, each one has $0.5ms$ long (T_{slot} = $15360 \times T_s$), numbered from 0 to 19. The basic time unit for LTE, T_s is determined by sub-carrier spacing $\Delta f = 15kHz$ and also by the maximum FFT size (2048 points used with 20 MHz system bandwidth) what corresponds to $T_s = \dfrac{1}{15000 \times 2048}$ $= \dfrac{1}{30720000}$seconds. Each subframe is defined as two consecutive slots of $0.5ms$ ($T_{subframe}$ $= 30720 \times T_s$), equal to $1ms$ as illustrated in the Figure 3.8. Slots consist of either 6 or 7 OFDM symbols, depending on whether the long or short CP is employed, respectively.

Notably the structure of OFDM symbol differs for short CP and long CP, according to the delay spread of channel. In the Figure 3.9 can be seen the differences between short CP and long CP so that, apart to the CP, the useful OFDM symbol along the slot ($0.5ms$) is

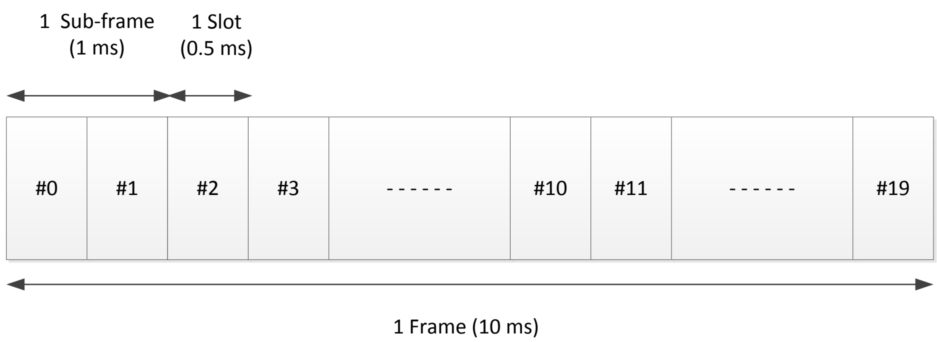

Figure 3.8: LTE Generic Frame Structure

equal in both modes (short and long CP) corresponding to 66.7μs. The structure presented below corresponds to only one OFDM symbol within each slot that may have 6 or 7 symbols.

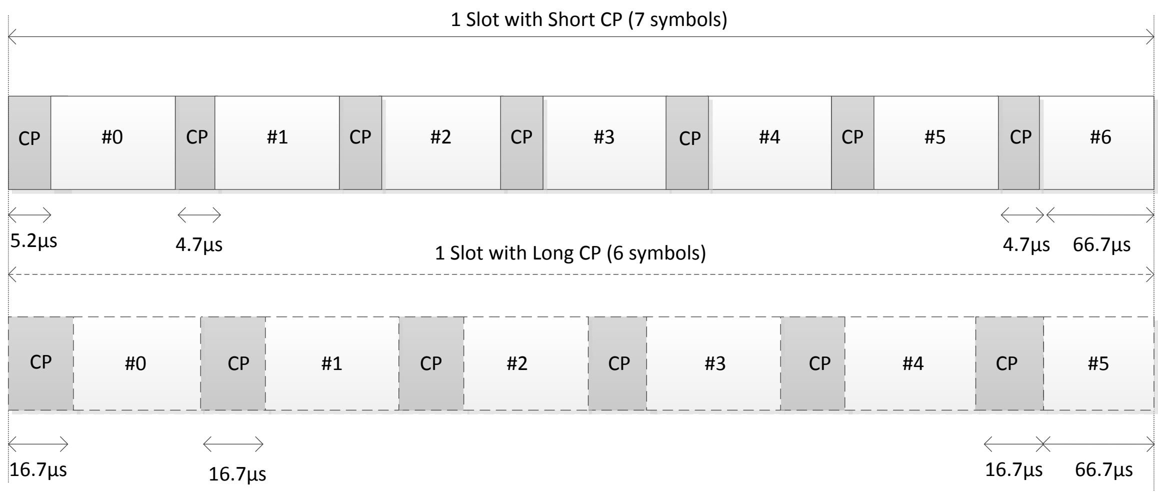

Figure 3.9: Structure of slot for both modes, short and long CP

Regard to short CP(7 symbols) the first symbol has a cyclic prefix of length 5.2μs so that the remaining six symbols have 4.7μs of length, in this way the purpose of having different length of cyclic prefix in the first symbol is to make the overall slot length of $0.5ms \Rightarrow ((7 \times 66.7\mu) + (6 \times 4.7\mu) + 5.2\mu = 500.3\mu s$) as naturally happen for long CP where along each slot composed now by six symbols, the CP length is assumed as being 16.7μs for all OFDM symbols and the overall slot length is $0.5ms \Rightarrow ((6 \times 66.7\mu) + (6 \times 16.7\mu = 500.4\mu\text{s}$).

The transmitted signal in each slot is described by a resource grid of sub-carriers and OFDM symbols as follows in Figure 3.10. This resource grid called *Physical Resource Block* (PRB) is the smallest element of resource allocation assigned by the base station scheduler and consists of 12 consecutive sub-carriers for one slot (0.5ms) or 180 kHz. It is defined also a *Resource Element* (RE), as the unit of the resource grid that consists of one OFDM sub-carrier during one OFDM symbol interval. In MIMO applications there is a resource grid for each transmitting antenna [35].

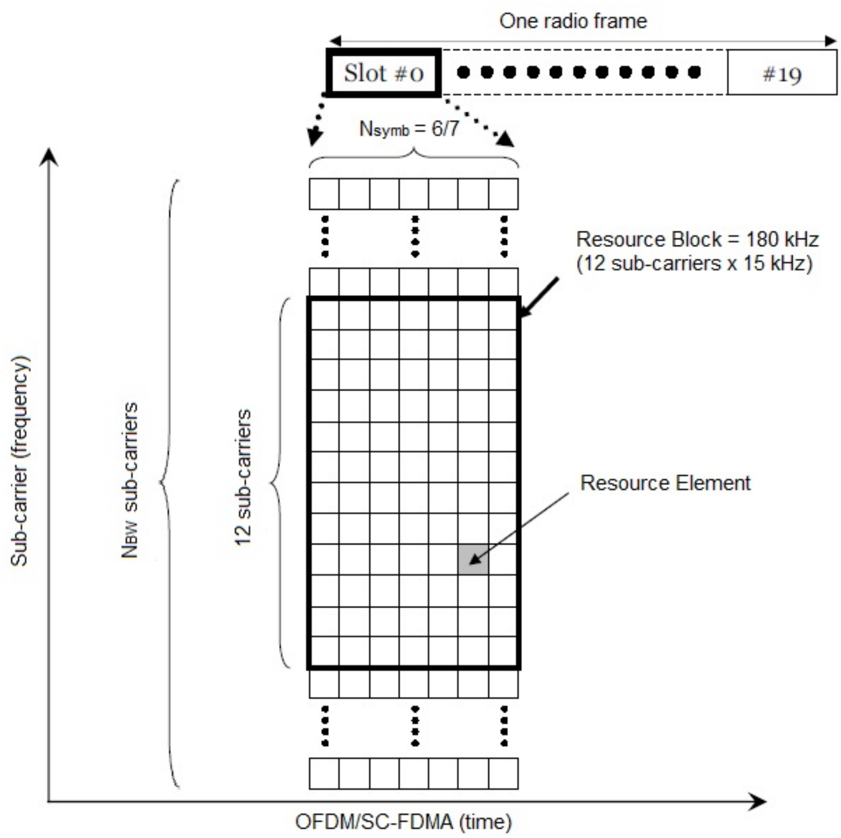

Figure 3.10: Resource Grid of LTE

Pilots signals are embedded in the PRBs as shown in Figure 3.11 for a single antenna transmitter in order to estimate the channel response and synchronization as examples. For time domain when short cyclic prefix is used they are inserted during the first and fifth OFDM symbols of each slot, in case of long cyclic prefix they are inserted in the first and fourth OFDM symbols. Further in frequency domain, it is transmitted a pilot signal in every sixth sub-carrier. Since the pilots signals are staggered in both time and frequency it is possible to perform interpolation on the remaining sub-carriers to estimate the channel response within the slot time interval.

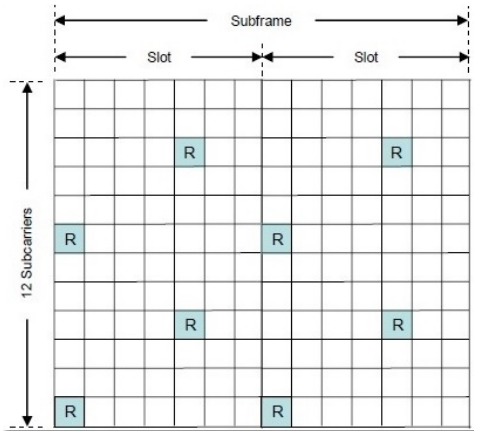

Figure 3.11: LTE Reference Signals for a single antenna transmitter (Source: [35])

When multi-antenna scheme is applied, the pilot signals corresponding to each antenna are transmitted on different sub-carriers so that they do not interfere with each other. For pilot symbol allocation and in case of two antennas transmission, i.e. two resource grids, the transmitting pilot signals on a specific antenna are not reused on other antennas for data transmission as illustrated in the next figure 3.12 [36].

The flexibility provided by OFDMA, i.e. several bandwidths are supported(1.4 MHz to 20 MHz) in downlink , it is also verified in the SC-FDMA uplink. The parameters common for downlink and uplink are given in Table 3.1.

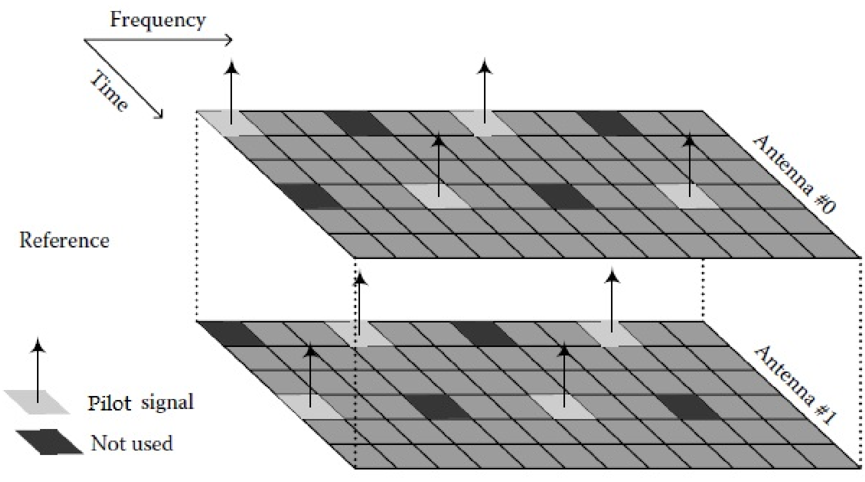

Figure 3.12: Pilot symbol allocation for two-antenna transmission (Source: [37])

3.3 OFDMA

The basis for OFDM consists in split data in two dimensions: time dimension (OFDM symbols) and frequency dimension(sub-carriers). In OFDM, all frequencies or sub-carriers are allocated for a single user so that, for each OFDM symbol only one user can be served. OFDMA goes further and it enables to share each time symbol between multiple users, as it can be seen in the Figure 3.13. At each OFDM symbol there is allocation for several sub-carriers, enabling better use of the radio resources. The result is a more robust system with increased capacity.

By dividing in frequency domain between multiple users, higher granularity can be achieved and radio resources can be used more effectively[38].

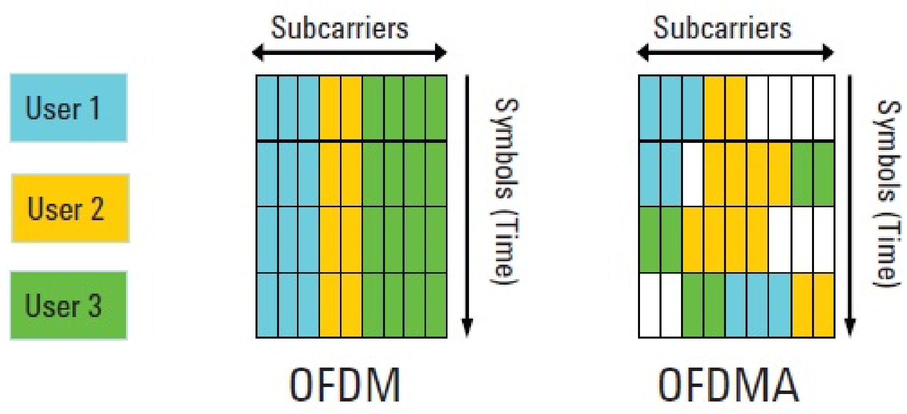

Figure 3.13: OFDM and OFDMA sub-carrier allocation (Source: [30])

The LTE downlink is based OFDMA which offers good flexibility in resource allocation and performance for a reasonable complexity [39]. OFDMA allows fast allocation of radio resources and orthogonal multi-user multiplexing in the frequency domain.

The allocation of the sub-carriers in response to changes in the fading parameters, reduce the impact of time/frequency dependent fading. The bandwidth is divided into orthogonal sub-carriers and hence it is possible to schedule different users at the same time on different frequency bands, enabling an extension of the multi-user diversity concept to include beside temporal fading, but also fading in the frequency domain [8]. This means that frequency-domain channel will consist of orthogonal parts from different users [40].

Among others aspects, the choice of OFDMA for LTE DL basis on the following points [41][11]:

- Better performance in frequency selective fading channels;
- Better spectral properties and usage of so many bandwidths.
- Link adaptation and frequency domain scheduling
- Well suited with MIMO. OFDM can transform a frequency-selective MIMO channel into a set of parallel frequency-flat MIMO channels, decreasing receiver complexity.
- Low complexity of base-band receiver. The OFDM channel equalizers are much simpler, OFDM can be considered resistant to multi-path delay spread by using a appropriate CP length and assuming that the received signal is correctly sampling.

Table 3.1: Supported bandwidths and common DL and UL parameters for LTE

System channel bandwidth (MHz)	**1.4**	**3**	**5**	**10**	**15**	**20**
Slot duration (ms)	0.5					
Sub-carrier frequency spacing, Δf (kHz)	15					
Useful symbol time, T_u (μs)	66.67					
Cyclic prefix/guard time, T_{CP} (μs)	Normal CP: 5.21 / 4.69; Extended CP: 16.67					
OFDMA symbol duration, $T_{sym} = T_u + T_{CP}$ (μs)	Normal CP: 71.88 / 71.36; Extended CP: 83.33					
Guard time overhead, $T_{CP}/(T_{CP}+T_u)$ (%)	Normal CP: 6.67; Extended CP: 20					
Resource block BW	180 kHz / 12 sub-carriers					
Number of resource blocks (N_{RB})	6	15	25	50	75	100
Sampling frequency, (15 000·NFFT (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT size, (NFFT)	128	256	512	1024	1536	2048
Occupied sub-carriers	72	180	300	600	900	1200
Resource mapping	Blockwise contiguous					
Samples per slot	960	1920	3840	7680	11520	15360

3.4 SC-FDMA

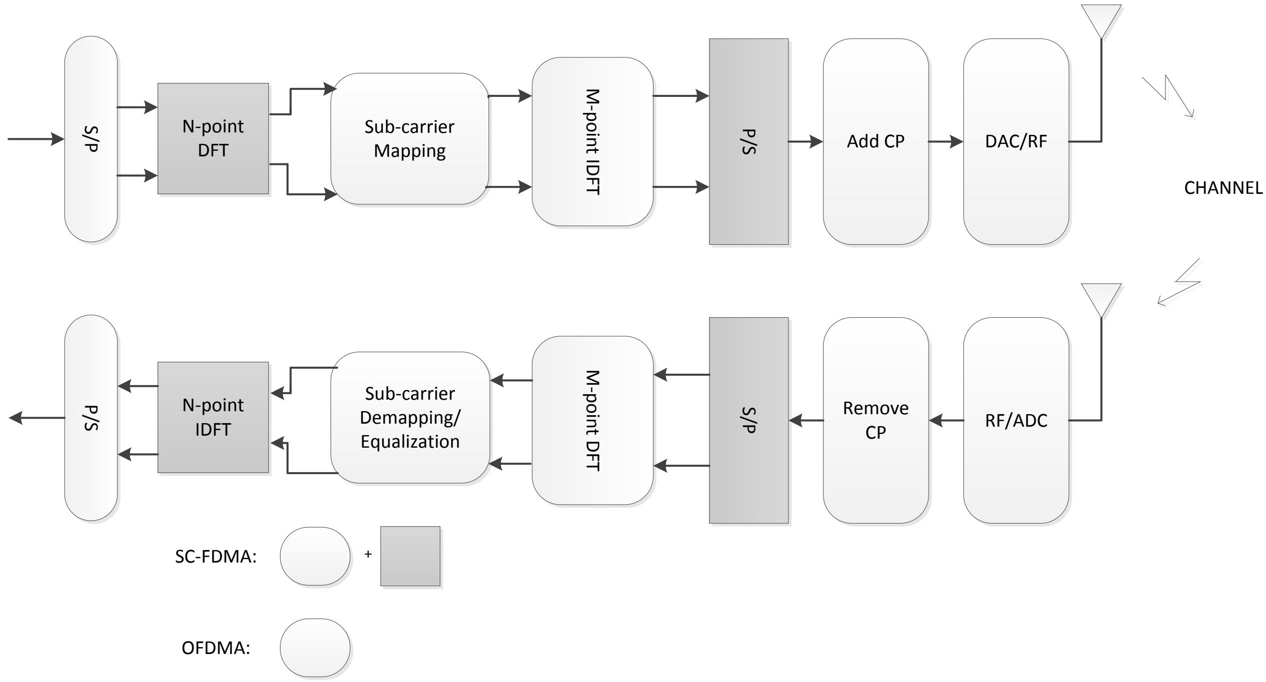

Figure 3.14: Block diagram of OFDMA and SC-FDMA

The SC-FDMA can be seen as a special pre-coding process of the OFDMA symbol, in which each frequency is initially spread by an *Discrete Fourier Transform* (DFT) prior to being sent to the OFDM modulator. It is a hybrid solution that tries to combine the benefits of OFDMA - multipath resistance and flexible frequency allocation, with the good relationship between the peak power and average power of the signal (PAPR) of the single carrier systems.

Power consumption is a key consideration for UE terminals, thereby SC-FDMA is well suited to the LTE uplink requirements since the sub-carriers are not independently modulated as happen in OFDM and hence PAPR is lower. This feature is important once allows less complex and higher-power terminals.

SC-FDMA principle is the same as for OFDM. Although there is a significant commonality between the uplink and downlink signal chains [35], there is still one remarkable block not used in OFDMA chain, N-point DFT, as shown in the Figure 3.14. Basically, its function consists in to spread information on the frequency of the modulated symbols in single-carrier.

DFT spreading allows that the frequency selectivity of the channel could be exploited, since all symbols are present in all sub-carriers. Therefore, in case of some sub-carriers suffer deep fade, the information can still be recovered from other sub-carriers experiencing better channel conditions.

Once converted data symbols to the frequency domain by using a DFT, they are mapped to the desired location in the overall channel bandwidth. In SC-FDMA sub-carriers can be mapped in two ways: localized or distributed. LTE uses localized sub-carrier mapping due to the fact that it is possible to exploit frequency selective gain through channel dependent scheduling. The Figure 3.15 illustrates the SC-FDMA sub-carrier mapping.

A drawback of DFT despreading in the receiver side is that the noise is spread over all the sub-carriers yielding noise enhancement, which will require the use of more complex equalization based on *Minimum MSE* (MMSE) receiver since, it degrades the *single-carrier frequency-division multiplexing* (SC-FDM) performance [34].

SC-FDMA can lose performance in case of deviations in frequency sub-carriers, typically generated by instability of the local oscillator or Doppler. These effects destroy the orthogonality of OFDM, generating interference between carriers and also multiple access interference what brings a major issue for uplink because these interferences occur differently for each user, making synchronization harder[42].

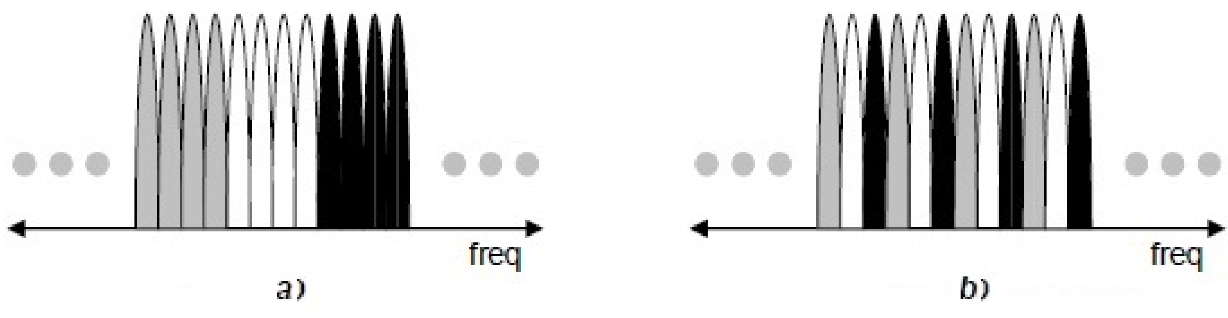

Figure 3.15: SC-FDMA sub-carriers mapped in Localized (a) and Distributed Mode (b) (Source: [35])

Chapter 4

Multiple Antenna Technology

Multiple antenna technology is the center-piece for delivering improved data rates and communication link robustness, exploiting spatial-domain as another new dimension by using multiple, spatially distributed antennas in both sides of the system. It is also considered as part necessary to achieve the initial LTE requirements in terms of coverage, QoS, and targeted data rates.

As the radio link is typically affected by the multipath phenomenon, which produces constructive and destructive interferences (or signal fading) at the receiver, the multiple radio paths or channels established will ideally experience uncorrelated fading whether the distance between antennas or by applying different polarization directions to the transmit antennas [43]. These different paths may be exploited in different ways in order to obtain spatial diversity from the ideally uncorrelated fading or to transmit multiple streams simultaneously.

Thus, generally speaking the MIMO channels can be utilized in different ways that lies on three fundamental principles:

- Diversity gain - The basic principle of multi-antenna diversity is to provide at the receiver multiple copies with uncorrelated fading of the transmitted signal, in order to combat fading on the radio channel, improving the reliability and error performance in the receiver through diversity gain. Spatial diversity may be achieved by having multiple antennas at either the transmitter or the receiver side, namely receive diversity can be used in *Single-Input Multiple-Output* (SIMO) channels thus obtaining diversity order equals to the number of receive antennas. On the other hand transmit diversity can be apply to MISO channels, so that extracting diversity in such channels is possible with or without channel knowledge at the transmitter. The so-called *Space Time* (ST) diversity coding is a transmit diversity technique that can extract diversity in absence of channel knowledge at the transmitter. The diversity order is equal to the number of transmit antennas.

- Array gain - One practical way to realize diversity gains is to beam-form a message across multiple transmit antennas. The beam-forming procedure utilizes limited information about the channel state information, being employed to shape the overall antenna radiation in a way that maximizes the transmitter or receiver beam in a desired direction increasing the received signal strength or suppressing ("nulled") major interfering signals by avoiding directions of significant interference. In general, beamforming can be interpreted as linear filtering in the spatial domain improve the *Signal to Noise Ratio* (SNR) at the receiver that arises from coherent combining effect of the multiples antennas at the receiver or transmitter or both.

- Spatial multiplexing gain - The principle of *Spatial Multiplexing* (SM) techniques is to transmit multiple data streams simultaneously by having multiple antennas at both the transmitter and the receiver sides, exploiting the capacity of MIMO channel. Thereby increasing the transmission rate for the same bandwidth and with no additional power expenditure. The maximum number of data symbols that can be transmitted in parallel in a MIMO system is $N_s = min(M_t, M_r)$. Since multiplexing spatial does not involve pre-coding for simultaneous transmissions may suffers from interference problems in the multiplexed signals. These issues can be minimized by using complex detectors at the receiver. The most known spatial multiplexing architecture is *Bell-Labs Layered Space Time* (BLAST).

It may be stated that the above families of multiple-antenna techniques are quite different but, there are also composite transmission schemes that aim at a combination of the different gains[44]. For a given fixed number of antennas, there are certain trade-offs between multiplexing gain, diversity gain, and array gain. In this way, spatial multiplexing techniques can also accomplish a diversity gain by employing an optimum receiver with *Maximum Likelihood* (ML) detection and spatial diversity techniques can also be used to increase the bit rate of a system when employed together with an adaptive modulation/channel coding scheme.

Transmission and reception techniques for multiple-antenna systems can also be categorized in SIMO, MISO, and MIMO techniques that will be discuss in the next section.

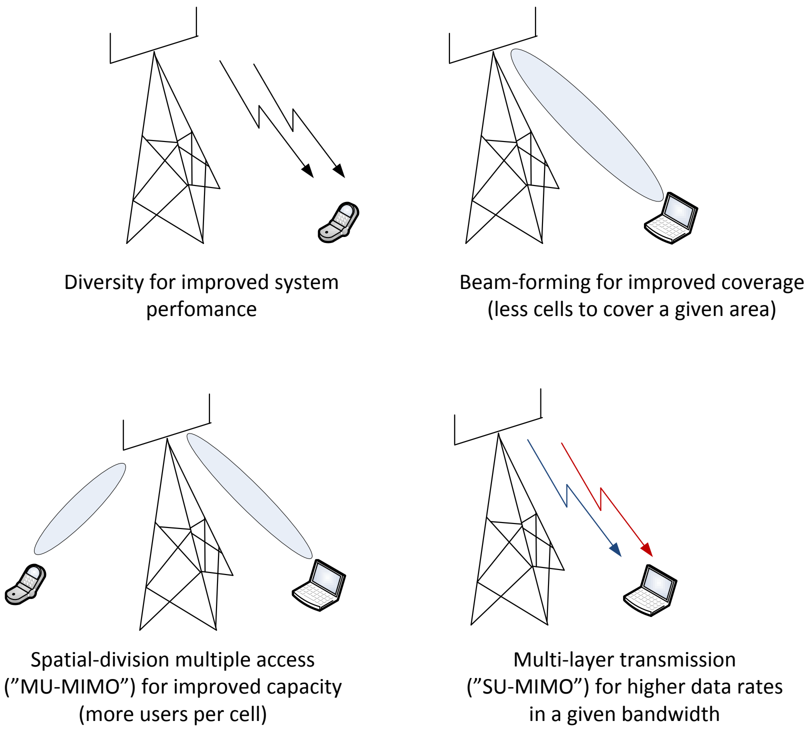

Figure 4.1: Multiple-antenna techniques in LTE

They can also be considered as *Open-Loop* (OL), *Closed-Loop* (CL) techniques and be distinguish between single-user and multi-user MIMO techniques, either for broadcast scenarios or for multiple-access scenarios.

Regard to LTE standard Release 8, the so-called *Single-User MIMO* (SU-MIMO) is adopted - a point-to-point multiple antenna link between base station and one UE. Its basic idea is to transmit independently coded data stream to the same user in the same radio resource in order to increase user peak data rates, hence it is suitable for users experiencing good channel conditions. Remarkably, with SU-MIMO spatial multiplexing, the LTE system provides a peak rate of 150 Mbps for two transmit antennas and 300 Mbps for four transmit antennas and throughput is increased in the center of the cell/near the eNodeB[45]. The *Multi-User MIMO* (MU-MIMO) scheme is not making part of the Release 8 despite its potencial. This scheme allows several UEs communicating simultaneously with a common base station using the same radio resource(frequency and time domain) allowing to increase the system capacity by supporting a larger number of users per cell.

The LTE standard also foresees different MIMO transmission modes as mentioned before, where the knowledge of the channel at the transmitter decides whether we are in presence of OL scheme or CL scheme. In particular, Closed-loop MIMO relies on signal processing, weighting the transmitted signals by considering the channel conditions experienced at each antenna, prior to transmission in order to optimize data reception. In contrast, the Open-loop MIMO transmission mode does not need any feedback of the channel information and has lower complexity and signalling overhead than CL as well as lower performance.

In a nutshell, the baseline antenna configuration in LTE consists of two antennas at eNodeB and two antennas at the UE, utilizing open loop and closed loop MIMO featuring both diversity and spatial multiplexing modes. The networks are planned with at least two receive antennas at terminals, in this way ensuring downlink-receive diversity. Other configurations, up to a maximum of four transmit and four receive antennas are supported as well, such as: transmit diversity, spatial multiplexing (including SU-MIMO and MU-MIMO) and beamforming, where it is possible to use which of the scheme or combination of schemes depending of the scenario as illustrated in the next Figure 4.1.

4.1 Antenna Configurations

LTE standard besides MIMO, supports other schemes, as SISO,SIMO and MISO based on the availability of antennas at the transmitter and/or receiver. The techniques mentioned in the previous section 4 can be configured according to the Figure 4.2.

In the following it is described each MIMO configuration:

- SISO - Traditional wireless communications makes use of this configuration exploiting time or frequency-domain pre-processing and decoding of the transmitted and received data. It is considered as baseline for others configurations and consists only one transmit antenna and one receive antenna.
- SIMO - This mode assumes one transmit antenna at the terminal and two or more receive at base station. Usually SIMO is refereed to as receive diversity for 1 x 2 configuration and it is commonly exploited by using *Maximum Ratio Combining* (MRC), being suitable for low SNR conditions where only one data stream is transmitted.
- MISO - It is characterized by having two or more transmitters (base station) and one receiver (UE). Following the same line of thought as the SIMO, it is referred to as transmit diversity (2 x 1 configuration) and can be enhanced with closed loop feedback from the receiver.
- MIMO - This term is also used in general to refer transmission scheme with multiple

antennas at 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.

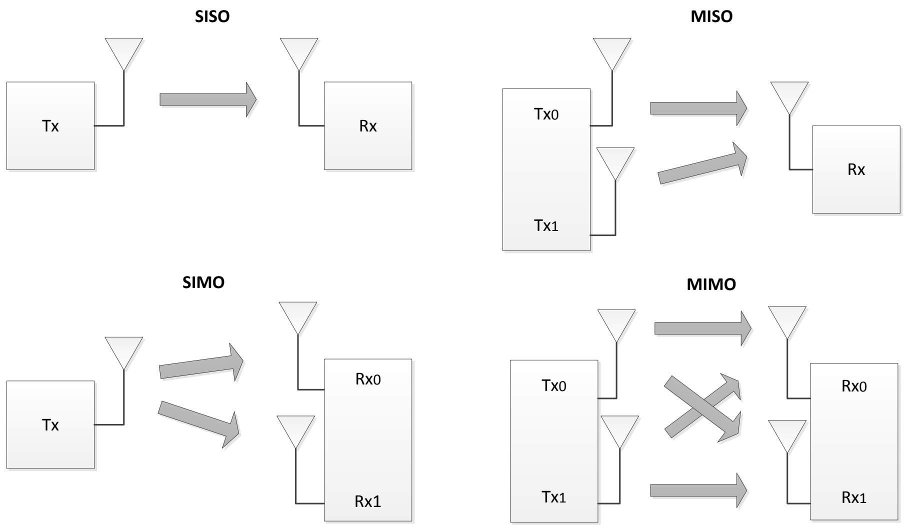

Figure 4.2: Multiple antenna configurations

4.2 MIMO Scenarios

Multi-antenna schemes can be applied independently to each frequency sub-band (set of OFDM sub-carriers) thus making it possible to have different transmission schemes for different frequency scheduled users, in another words, it is possible to have different configurations applied for different scheduled users within the same time slot, as shown in the next figure 4.3.

Considering as example fading for two users that can equivalently represent the signals received by a single user from two different transmit antennas, transmit diversity can avoids the deep fading that occur per antenna over a single radio link.

In lightly loaded or small cell deployments, multi-stream transmission yields very high data rates and makes more efficient use of radio resources. In this case, the multiple transmit antennas are best used for single stream beam-forming in order to enhance the quality of the signal.

In summary, LTE provides an adaptive multi-stream transmission scheme, in which the

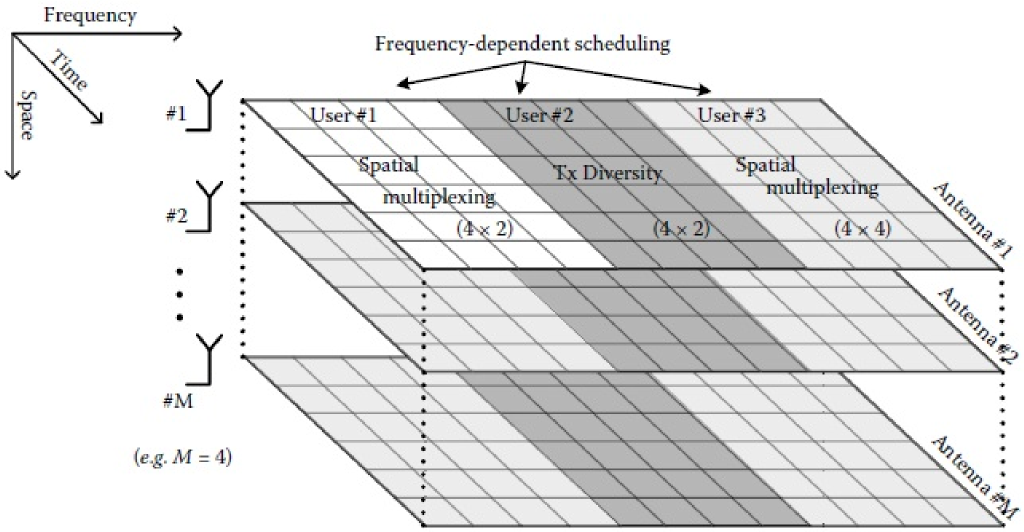

Figure 4.3: Different transmission schemes for different frequency scheduled users (Source: [37])

number of parallel streams can be continuously adjusted to match the channel conditions.

- For good channel conditions, spatial multiplexing scheme (up to four streams in parallel) is suitable yielding data rates up to 300Mbps in a 20MHz bandwidth.
- For less favourable channel conditions multiple antennas are instead partly used in a beam-forming transmission scheme improving overall reception quality.
- In large cells or to support higher data rates at cell borders, single stream beam-forming transmission as well as transmit diversity for common channels are indispensable to achieve good coverage.

4.3 MIMO System and Channel Models

Considering MIMO system with M_t transmit antennas and M_r receive antennas, there is M_t data streams which are emitted simultaneously at the same frequency through the M_t antennas as shown in the figure 4.4.

In each of the M_r receiving antennas the signal is under the effect of flat channel (invariant over T symbol durations or sub-carriers in case of frequency-domain) which is added from the mixture of the M_t transmitted signals from the transmitting antennas and also the additive noise.

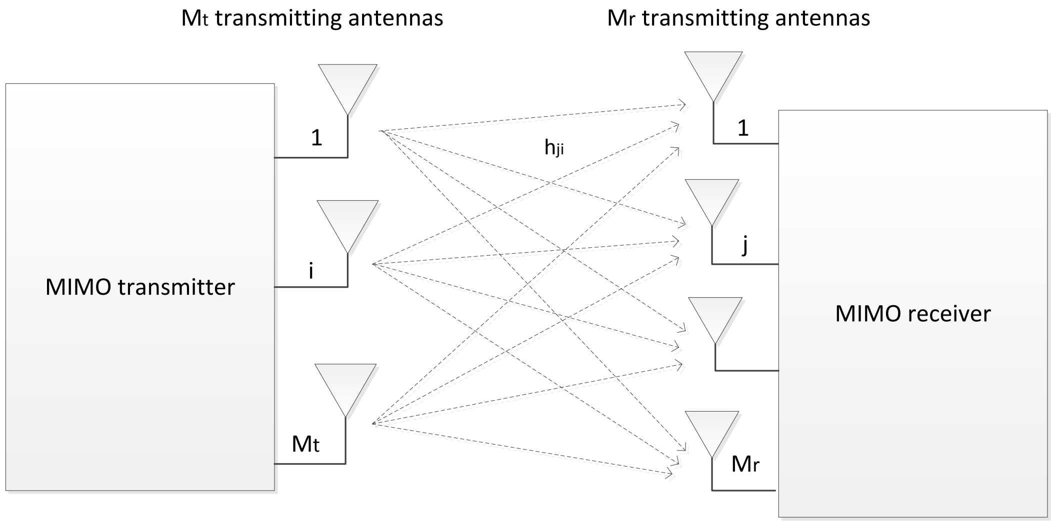

Figure 4.4: Channel response between base station and terminal

Let **r** be a vector of M_t received signals as follows,

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} \tag{4.1}$$

in which **H** denote the $M_t \times M_r$ channel matrix modelling the propagation effects from each of the M_t transmit antennas and **n** is the additive noise with the same size of **s**. Notably in the equation above the index are omitted for simplicity, thus n^{th} row of **s** corresponds to the signal of n^{th} transmit antenna. The MIMO channel can be represented by

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & ... & h_{1,m_r} \\ ... & ... & ... \\ h_{m_t,1} & ... & h_{m_t,m_r} \end{bmatrix}$$

where h_{m_t,m_r} represents the response of the existing channel between M_t transmit antenna and M_r receive antenna. By applying pilot signals it is possible to estimate the characteristics of the channel in the receiver formed by the factors of the channel.

It may be stated also that the capacity of the SU-MIMO system, assuming M streams uncorrelated with equal power, can be expressed in terms of eigenvalues as follows,

$$C = \sum_{i=1}^{m} \log_2(1 + \frac{\rho}{M}\lambda_i) \tag{4.2}$$

where λ_i represent the non-zero eigenvalues of $\mathbf{H}^H\ \mathbf{H}$ ($M_t \geq M_r$ and $M_t < M_r$) and $m = min\ (M_t,\ M_r)$. H^H corresponds to the hermitian of the matrix H.

In this way can be concluded that MIMO systems achieve greater capacity as compared to SISO system by transmitting on the spatial eigen-modes of the MIMO channel. The capacity of a MIMO system grows approximately linearly with the minimum of M_t and M_r without requiring extra bandwidth or extra transmission power. On the other hand for single-antenna systems for a given fixed bandwidth, capacity can only be increased logarithmically with the SNR, by increasing the transmit power [46].

4.4 Transmit diversity

As multiple antennas at the base station allow for uplink receive diversity, transmit diversity can be realized by using multiple antennas at the transmitter side. Thus, multiple copies in the receiver of the transmitted signal are a means to combat fading, resulting in a significant gain in SNR and to achieve reliability. The suit scenario is for low mobility and low correlation between channels of the different antennas, make it possible to reduce receiver complexity while improving the detection performance. Moreover, it becomes interesting for downlink, since it is easier to install multiple antennas at the base station.

Associated with OFDM, transmit diversity can be further sub-divided into: block codes based, *Cyclic Delay Diversity* (CDD), FSTD, and *Time Shift Transmit Diversity* (TSTD) where CDD and TSTD are not used in LTE as a diversity scheme [21].

In LTE transmit diversity is defined for two and four transmit antennas based on SFBC complemented with FSTD in case of four transmit antennas, once the original Alamouti scheme uses two transmitting antennas and one receiving antenna. As mentioned before LTE provides both OL and CL schemes to achieve spatial diversity, in particular transmit diversity can be enhanced with closed loop feedback. Open loop transmit diversity will be further discussed in more detail.

4.4.1 Space-Time Coding

Coding a data stream across transmit antennas (space) and time by introducing redundancy in a way that the receiver can obtain the original data stream is called *Space-Time Coded* (STC). This redundancy is used to combat fading channel in order to minimize detection errors in the receiver. At least one receive antenna and no channel knowledge at the transmit side is needed while multiple antennas are considered at the transmitter. Within transmit diversity, the term space-time coding refers for all spatial diversity techniques (irrespective of the presence of any additional coding gain). Namely STBC can achieve maximum diversity gain for two transmit and one receive antennas while also providing linear decoding and equalization; Similar to the previous one, SFBC can be seen as a frequency domain version thereby the pairs of adjacent sub-carriers are coded together instead of two adjacent time slots (OFDM symbol) as both are based on Alamouti code; *Space-Time Trellis Code* (STTC) can provide both diversity and coding gains but at the cost of increase complexity since channel coding, modulation, transmit, and receive diversity operations are realized together; Unlike previous codes which envisions to combat deep fades, Layered Space-Time Codes aims to improve multiplexing gain by transmitting M_t independent data streams.

It is worth noting that in OFDM systems, a STBC has to be applied under the assumption that the channel coefficients remain constant for two subsequent symbol durations in order to guarantee the diversity gain. This is a tough condition since OFDM symbol duration T_s is N_c the duration of a serial data symbol T_d. On the other hand the coding can be performed over two adjacent sub-carriers and thus the feature of OFDM can be exploited. In this way a SFBC requires only the reception of one OFDM symbol for detection, reducing delay in the detection process. In the scope of this work, only block codes based on SFBC and STBC are considered. In the following section we discuss Alamouti STBC.

4.4.2 STBC and Alamouti concept

One way to combat channel fading (channel frequency selective fading) is to transmit several replicas of the same information through each antenna, introducing redundancy in time through channel coding and also in space. By doing this the probability of loosing the information decreases exponentially. The diversity gain of a MIMO system is defined as the number of independent receptions of the same signal thereby, by using STBC it is possible to reach a maximum order of spatial diversity, equals the number of transmit antennas using a simple and linear processing on the decoding. This technique provides low complexity in channel coding/decoding. A well-known type of STBC scheme is the Alamouti scheme.

The original Alamouti scheme is a transmit diversity technique using two transmitting antennas and one receiving antenna, as depicted in the table 4.1. The Alamouti code is the first STBC that provide full diversity at full data rate for two transmit antennas, i.e., a code rate of 1 since it transmit two symbols every two time intervals. The scheme can be generalized for M_r receive antennas and can accomplish a maximum diversity order of $2M_r$ [47].

Time/Frequency	Antenna 1	Antenna 2
n	s_1	s_2
$n+1$	$-s_2^*$	s_1^*

Table 4.1: Alamouti Space-Time Block Code for MISO, where n represents time/frequency

A block diagram of the Alamouti space-time scheme is illustrated in figure 4.5 which will be used as reference to shown encoding/decoding process along space and time.

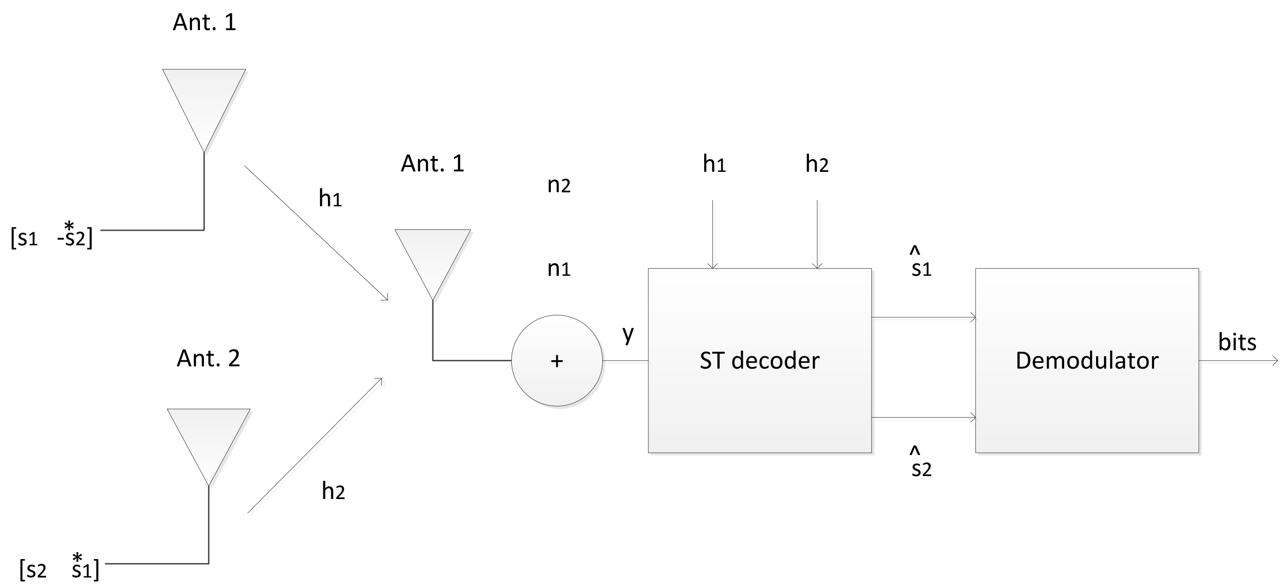

Figure 4.5: MISO scheme

The information bits are first modulated using a digital modulation scheme, then the encoder takes the block of two modulated symbols s_1 and s_2 in each encoding operation and forwards it to the transmit antennas. Taken from the table 4.1, the symbols mapped can be written in following code matrix,

$$\mathbf{S} = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \tag{4.3}$$

where the first row represents the first transmission period, in this step, the symbols s_1 and

s_2 are transmitted from antennas one and two, respectively and the second row represents the second transmission period, in which antenna one transmits $-s_2^*$ and antenna two transmits s_1^*. The mark $(.)^*$ means the complex conjugate. The two rows and columns of $\mathbf{S}$ are orthogonal to each other as happen also for the channel matrix. This property enables the receiver to detect s_1 and s_2 by a simple linear signal processing operation.

Assuming only one receive antenna and also that the fading is constant over two consecutive transmit periods, the received signals for each transmission period, can be expressed as

$$\begin{cases} r_1 = h_1 s_1 + h_2 s_2 + n_1 \\ r_2 = -h_1 s_2^* + h_2 s_1^* + n_2 \end{cases} \tag{4.4}$$

Lets consider h_1 the channel response between the first transmitting antenna and the receiver, and h_2 the channel response between the second transmitting antenna and the receiver and also n_1 and n_2 complex noise and interference of the channel.

Note that the fading coefficients $h_1(n)$ and $h_2(n)$ defined at time n are constant across two consecutive symbol transmission periods, i.e.,

$$\begin{cases} h_1(n) = h_1(n+T) = h_1 \\ h_2(n) = h_2(n+T) = h_2 \end{cases} \tag{4.5}$$

where T is the symbol duration. The received vector $\mathbf{r}$ can be assumed from (4.4) formed by two consecutive received data samples $\mathbf{r} = [r_1, r_2]^T$ in time, results in

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} \tag{4.6}$$

where $\mathbf{h} = [h_0, h_1]^T$ is the complex channel vector and n is the noise vector at the receiver. In order to be able to estimate the transmitted symbols the equation (4.4) can be explicitly rewritten as,

$$\begin{cases} r_1 = h_1 s_1 + h_2 s_2 + n_1 \\ r_2^* = -h_2^* s_1 + h_1^* s_2 + n_2 \end{cases} \tag{4.7}$$

Thus, the vector equation(4.6) can be written in matrix format,

$$\begin{pmatrix} r_1 \\ r_{2^*} \end{pmatrix} = \begin{pmatrix} h_1 & h_2 \\ -h_2^* & h_1^* \end{pmatrix} \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2^* \end{pmatrix} \tag{4.8}$$

Note that the channel coefficients are constant across two consecutive symbol transmission periods, we obtain, $H_1 =$ or in short notation,

$$\mathbf{r} = \mathbf{H}_v \mathbf{s} + \mathbf{n} \tag{4.9}$$

where the vector $\mathbf{r} = [r_0, r_1^*]^T$ and $\mathbf{H}_v$ a orthogonal virtual channel matrix , i.e,

$$\mathbf{H}_v^H \mathbf{H}_v = \mathbf{H}_v \mathbf{H}_v^H = h^2 \mathbf{I}_2 \tag{4.10}$$

From(4.10), wherein $\mathbf{I}_2$ is the (2×2) identity matrix and h^2 is the power gain of the channel with $h^2 = |h_1|^2 + |h_2|^2$ can be realized that the orthogonality provided by Alamouti scheme allows to separate the MISO channel gain into two virtually independent channels with channel gain h^2 and diversity $d = 2$. In addition, the assumption in 4.10 ensures interference free.

By using the equation (4.9) and multiplying it by the hermitian of the matrix H_v^H, can be estimate the symbols according,

$$\widetilde{\mathbf{s}} = \mathbf{H}^H \mathbf{r} = h^2 \mathbf{s} + \mathbf{H}^H \mathbf{n} \tag{4.11}$$

Chapter 5

Alamouti Encoder/Decoder Hardware Implementation

Diversity by means of space-frequency coding SFBC is similar to space-time coding STBC, in which the encoding is performed in frequency domain rather than in the time domain. In LTE for two transmit antennas is used SFBC while in case of four transmit antennas is used SFBC but combined with FSTD, since the orthogonality provided by the family of codes (SFBC/STBC) through Alamouti coding is lost to more than two transmit antennas. There are several reasons to leave behind the STBC in LTE, namely the odd number of OFDM symbols in a subframe (STBC operates on pairs of adjacent symbols while Alamouti SFBC performs over two adjacent sub-carriers in OFDM symbol). Furthermore, in a frequency-flat fading channel for a high-speed UE, the SFBC scheme outperforms the STBC scheme [16].

From the combination of SFBC/FSTD can be said that for the sub-carriers where transmission is on one pair of antennas, there is no transmission on the other pair of antennas, operating in this way over four symbols as well as groups of four resource elements on each antenna. Besides leaving the orthogonality intact, this combination also provides robustness against the correlation between channels from different transmit antennas and easier UE receiver implementation, with a slight coding gain[48] [21]. The next table shows the combination of both techniques.

After an introduction of LTE transmit diversity based on SFBC, it is analysed a MISO-OFDM system model based on Alamouti SFBC. The most popular coding technique in MIMO-OFDM exploits the independent fading of the parallel channels h_n across the frequency sub-carriers. By coding across space and frequency, both space and frequency diversity gains can be extracted [49].

Frequency	Antenna 1	Antenna 2	Antenna 3	Antenna 4
n	s_n	0	$-s^*_{n+1}$	0
$n+1$	s_{n+1}	0	s^*_n	0
$n+2$	0	s_{n+2}	0	$-s^*_{n+3}$
$n+3$	0	s_{n+3}	0	s^*_{n+2}

Table 5.1: SFBC combined with FSTD

An *Space Frequency* (SF)-coded MISO-OFDM system with two transmit antennas, one receive antenna, and N sub-carriers, is shown in Figure 5.1.

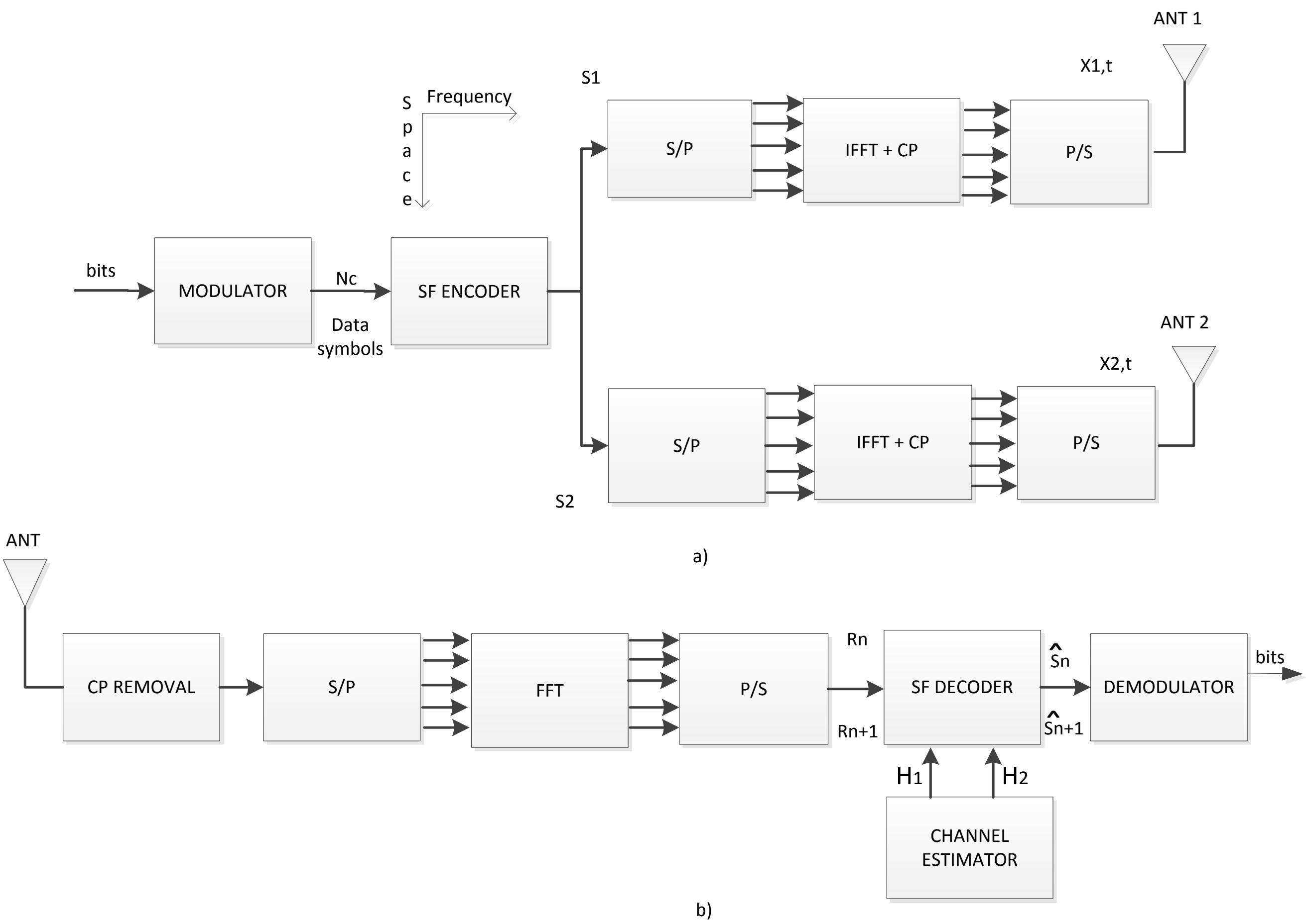

Figure 5.1: Transmitter (a) and Receiver (b) of an Alamouti SFBC coded MISO-OFDM system

The coding is performed across the antennas and OFDM sub-channels it means, by applying the Alamouti code over two adjacent sub-channels/frequencies in one OFDM block as shown in the Table 5.2.

Frequency	Antenna 1	Antenna 2
n	s_n	$-s^*_{n+1}$
$n+1$	s_{n+1}	s^*_n

Table 5.2: Alamouti coding

Let N_s be the number of sub-bands chosen to be $N_s = \frac{N}{q}$, where q is the symbol period of SFBC system and N is the number of sub-channels. Then, all sub-bands are modulated using MQAM or MPSK, where M is determined by the number of allocated bits. In this way the incoming bit stream is mapped into data symbols via to the referred modulation techniques. For two transmitter antennas, for each OFDM symbol, adjacent sub-carriers n, $n+1$ ($n = 1$, ..., N) are used in frequency space code.

The k^{th} OFDM symbol vector, $\mathbf{s}(k) = [\mathbf{s}_1(k) \;\; \mathbf{s}_2(k) \;\; ... \;\; \mathbf{s}_N(k)]$ is provided as the input to the SFBC encoder and then coded into two vectors $\mathbf{s}_1(k) = [\mathbf{s}_1(k) \;\; \mathbf{s}_2(k) \;\; ... \;\; \mathbf{s}_N(k)]$ and $\mathbf{s}_2(k) = [-\mathbf{s}^*_2(k) \;\; \mathbf{s}^*_1(k) \;\; ... \;\; \mathbf{s}^*_{N-1}(k)]$ which are simultaneously transmitted by the first and the second transmit antenna respectively.

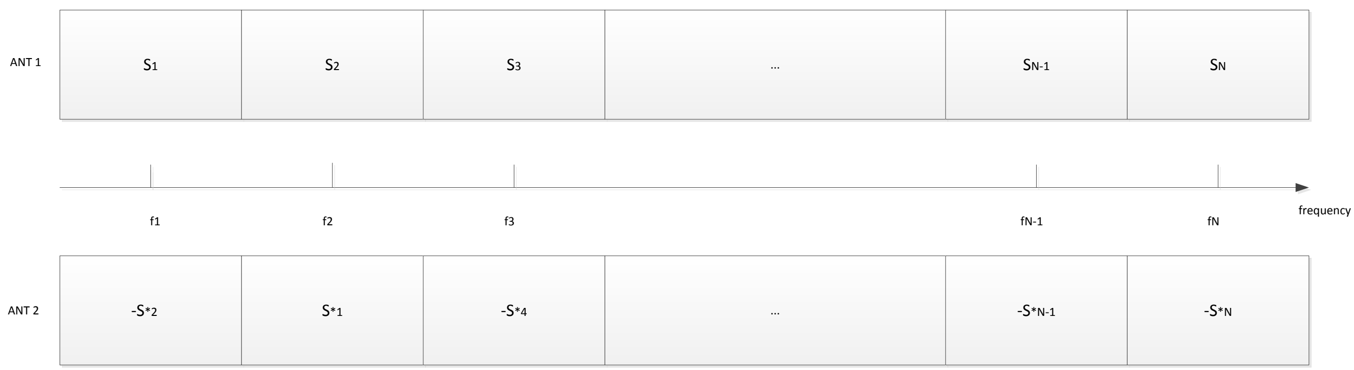

Figure 5.2: Symbol assignment for sub-carriers in SFBC

The symbol assignment of the first OFDM symbol vector is illustrated in the Figure 5.2. The mapping scheme for SFBC is chosen such that on the first antenna the original data are transmitted without any modification, and the data symbol mapping for the second antenna has to be modified, according to the Table 5.2.

The encoded data are passed through a serial to parallel block where data are regrouped according to the number of the sub-carrier and frequency. After removing the cyclic prefix at the receiver side, the FFT output as the demodulated received signal for sub-channels n, $n+1$ can be expressed as,

$$\begin{cases} r_n = H_{1,n} \cdot s_n - H_{2,n} \cdot s_{n+1}^* + n_n \\ r_{n+1} = H_{2,n+1} \cdot s_{n+1} + H_{2,n+1} \cdot s_n^* + n_{n+1} \end{cases} \tag{5.1}$$

where $\mathbf{n}_n$ denotes the AWGN noise in the sub-carrier n, with zero mean and variance of σ^2 and $H_{m,n}$ is the flat fading coefficient of the sub-channel n assigned to the m antenna. As OFDM systems are designed to provide flat fading per sub-channel, the fading between adjacent sub-carriers is inherently considered also as flat. Therefore, one can considers that adjacent sub-channels in the OFDM spectrum have the same channel transfer function, $H_{1,n} = H_{1,n+1}$ and $H_{2,n} = H_{2,n+1}$.

The *Channel State Information* (CSI) is needed at the receiver, i.e., the channels H_1 and H_2 are needed in order to obtain the combined signals $\widetilde{s}_n$ and $\widetilde{s}_{n+1}$,

$$\begin{cases} \widetilde{s}_n = H_{1,n}^* \cdot r_n + H_{2,n} \cdot r_{n+1}^* \\ \widetilde{s}_{n+1} = -H_{2,n} \cdot r_n^* + H_{1,n}^* \cdot r_{n+1} \end{cases} \tag{5.2}$$

the received signals may are sent to the maximum likehood detector,

$$\begin{cases} \widetilde{s}_n = (|H_1|^2 + |H_2|^2) s_n + H_1^* n_n + H_2 n_{n+1}^*, \\ \widetilde{s}_{n+1} = (|H_1|^2 + |H_2|^2) s_{n+1} - H_2 n_n^* + H_1^* n_{n+1}. \end{cases} \tag{5.3}$$

From the equations above can be concluded that the interference caused by the following data symbol is full eliminated. A demodulator may be applied to converts the soft estimated symbols into the original bit stream.

5.1 Encoder and Decoder Alamouti

The whole work is demonstrated in this chapter. In the following the characteristics of an Alamouti Encoder/Decoder projected for a MISO system are highlighted. We used the System Generator from Xilinx to develop and test the Simulink model of the encoder and decoder. Notably in the first phase of the work we resorted to a test chain - MISO, and further on, both Alamouti blocks are included in a MISO-OFDM system which it is under development by other researchers. Both chains were built using System Generator for DSP. These two blocks will be added to the transmitter and to the receiver sides of each chain.

Alamouti Encoder

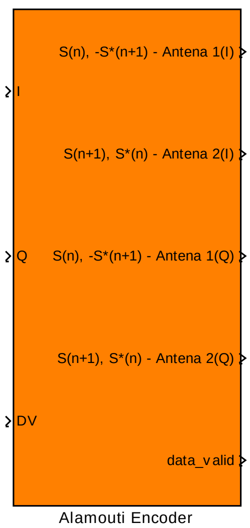

Figure 5.3: Alamouti Encoder

The Encoder block was built having as basis the code 2 from the Table 5.3, regardless of the code used, the block must be able to parallelize a sequence of transmission (one stream per antenna), and to encode each stream simultaneously. This way two symbols are encoded in two instants/frequencies according to the Table.

Code 1

Time/Frequency	Antenna 1	Antenna 2
n	s_n	$-s^*_{n+1}$
$n+1$	s_{n+1}	s^*_n

Code 2

Time/Frequency	Antenna 1	Antenna 2
n	s_n	s_{n+1}
$n+1$	$-s^*_{n+1}$	s^*_n

Table 5.3: Alamouti coding: Code 1 and Code 2

By using two well-defined structures, namely a configuration to perform serial data to the Antenna 1 and another one to swap data/symbols to the Antenna 2, the sequence of transmission is made parallel, making it possible to encode two streams at the same time across independent antennas. This subject is analysed later on.

Note that the Alamouti coding encompasses two codes, namely code 1 and code 2. Both are equivalent and can be applied in frequency or time domains as shown in the tables below. Code 1 provides the original data on the first antenna, without any modification, being compatible with systems where the second antenna is not implemented or switched off and is the one used in LTE. Code 2 is considered the original code.

As depicted in the Figure 5.3, the Alamouti Encoder provides two input ports, I and Q, representing 'in-phase' and 'quadrature' components of the signal respectively, in other wordsthe real and imaginary part of the symbol. In addition, in order to have knowledge of the beginning and end of the data stream it provides a signal of valid, DV. As the input signal is made parallel by two antennas, the output of the block is now composed of five ports, each set of two ports are assigned to each antenna according to the Alamouti coding, also providing a DV signal.

According to the referred table the coding for each antenna/stream is different so, two different configurations are used, namely one to swap and another configuration to perform serial data/symbols. From both it is worth to say that the challenge lies on swapping two data/symbols in consecutive instants/frequencies. Its application lies on three blocks: Counter, Multiplexer and Delay, as shown in the Figure 5.4.

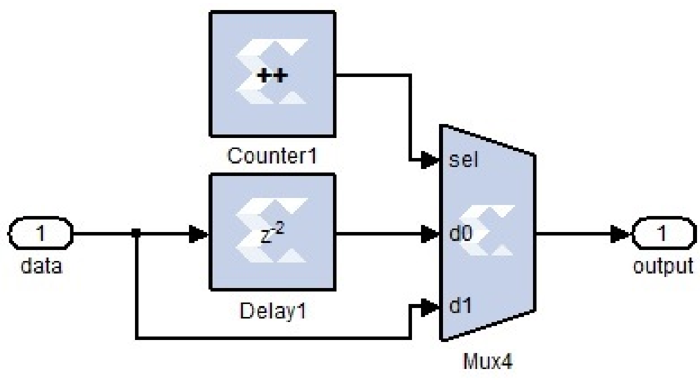

Figure 5.4: Necessary blocks to swap data

As a reply to this challenge, one can assume that:

- The output of the counter block is consecutively zero or one; which is connected to the input of the multiplexer.

- The multiplexer only has two entries of data (d_0 and d_1) and they are connected to each other. By using these two blocks we can choose the first or the second instant/frequency (n, $n+1$) to accomplish additional operations such as to deny the real and/or imaginary part of the symbol.
- The first branch of the multiplexer (d_0) has the delay block, in order to swap the symbol. The explanation is further ahead.

An inverter block may be used in this configuration in one of the multiplexer branches (d_0 and d_1) in order to deny the real or imaginary part of the symbol. Since the major barrier is to swap two data, the following drawing 5.5 suggests the implemented idea through the blocks described above.

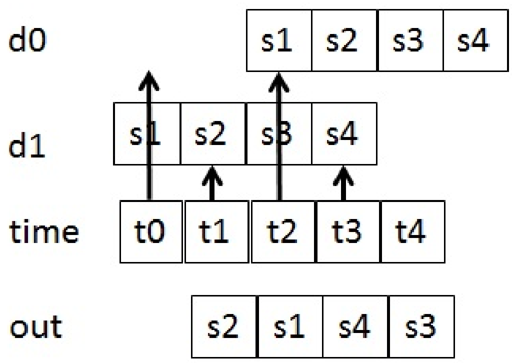

Figure 5.5: Applied Principle

It consists in applying the same signal in both entries of the multiplexer, so that the first sequence is delayed by 2T in relation to the second one. Assuming that the counter starts at zero, it chooses one data /symbol from the first sequence (d_0) or from the second one (d_1). As result of that, two data are swapped and the output of the multiplexer is delayed in 1T in relation to the input sequence.

On the other hand under the same assumptions above (excluding the delay block (2T) on the first branch of the multiplexer) a counter, multiplexer and possibly an inverter block are used for the second configuration, i.e., to perform serial data, in this situation there is no delay in the sequence of transmission but due to the delay imposed by the other structure a delay block is needed on its output in order to synchronize and to parallelize both structures, as shown in the Figure 5.6.

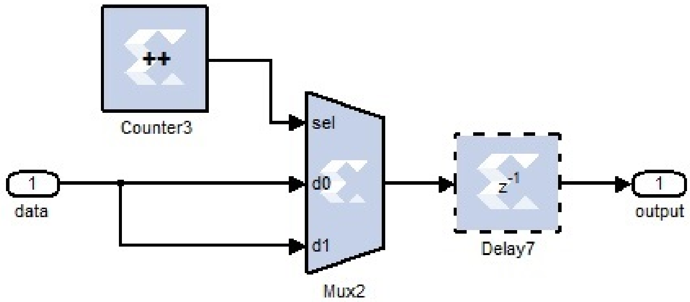

Figure 5.6: Blocks used to perform serial data/symbols

In order to clarify the structure of the encoder, indicated in the Figure 5.7, it is important to remember the table 5.4.

Time/Frequency	Antenna 1	Antenna 2
n	s_n	s_{n+1}
$n+1$	$-s_{n+1}^*$	s_n^*

Table 5.4: Alamouti coding: Code 2

Thus, one can say that in both structures the sequence of transmission is made parallel by the two antennas. Moreover, it can be said that the structure serial data adapts to the Antenna 1. The Table 5.4 tell us that it is necessary to deny the real part or imaginary part of the symbol. In the serial data given by the Antenna 1 it is necessary to deny the real part of the symbol, seeing that $s = -(a + (jb)^*) \Leftrightarrow s = -a + jb$ where a and b are the real and imaginary part, respectively. Therefore, an inverter block is added in the second branch of the multiplexer (d_1) while on the imaginary part no extra block is added as illustrated.

On the other hand, in what concerns the Antenna 2 it is only necessary to conjugate the imaginary part of the symbol. When applying the structure to swap data the inverter block is placed in d_0 input of the multiplexer.

To guarantee the desired performance of the system, each counter presents a port enable, to which the valid signal is connected. As the total delay of the system is 1T, this signal will also be delayed in 1T.

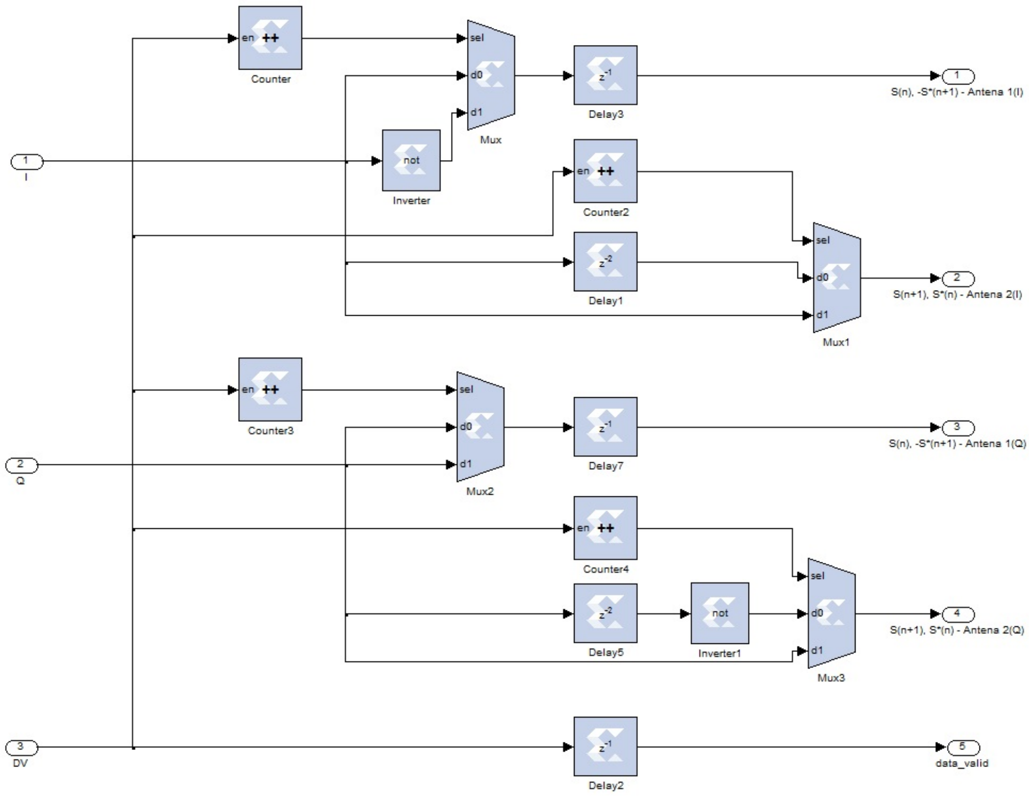

Figure 5.7: Structure of Alamouti Encoder

Decoder

The block was set up according to the equations of Alamouti decoding, which are reviewed here, so, aiming to align the channels, the equations were reorganized in the following manner,

$$\begin{cases} \widetilde{s}_n = h^*_{1,n+1} r_n + h_{2,n} r^*_{n+1} \\ \widetilde{s}_{n+1} = -h_{1,n} r^*_{1,n+1} + h^*_{2,n+1} r_n \end{cases} \tag{5.4}$$

As we can see, the channels are aligned in both instants/frequencies. From the equations above one realizes that the block needs to have knowledge of the channel coefficients (h_1 and h_2), thus we assume that they are recovered perfectly at the receiver. Furthermore, the channels between two adjacent frequencies or instants are considered highly correlated from the start, meaning that $h_n = h_{n+1}$. From now the notation h_1 and h_2 to the channel coefficients will be used for both instants/frequencies.

Once the received signals are in serial, as shown in the simplest case of Alamouti scheme (2 Tx and 1 Rx), in the Figure 4.5 the same principle assumed to the encoder is applied. As result of that, the serial sequence of transmission, in this case r is made parallel and may obtain r_n/r_{n+1} and $r_{n+1}\ /r_n$ over two instants/frequencies through the well-defined structures for the Encoder as the Figure 5.8 shows. The channels are provided in terms of magnitude and phase at the Decoder block.

Therefore the proposed Decoder block lies on three steps:

- Let us consider the channels and the received signal from the equation (5.4) first, which are coding separately. By using across the received signals the appropriate structure, it is possible to adapt serial data configuration to the stream r_n, r^*_{n+1} and to use swap data configuration to the stream r^*_{n+1}, r_n. In Regard to the channels, the serial data configuration is used since there is no swap.

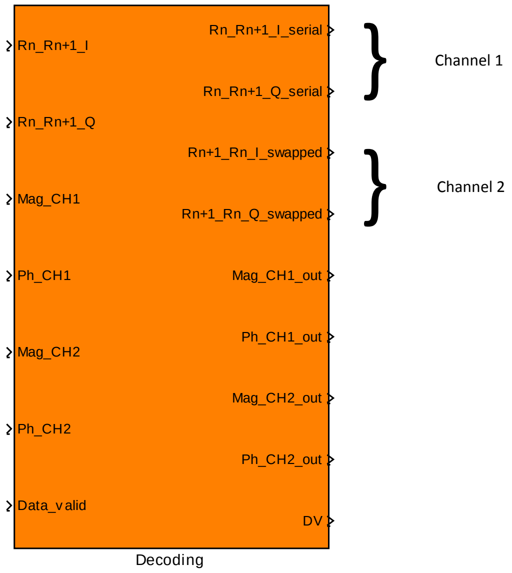

Figure 5.8: Decoding over the received signals and channels

Besides the DV signal at the input of the block there are another three sets of two ports, each set corresponds to the incoming sequence, to the channel 1 and to the channel 2. Once the data stream is made parallel, the output of the block presents two more additional ports when compared to the input. A total of nine ports or four sets of two ports plus the DV signal are provided to the next block as shown in the Figure 5.8.

The content of the block is now discussed and it is shown in the Figure 5.9. As already mentioned the same reasoning of the Encoder is applied to the Decoder so that the main difference between them lies on the fact that Alamouti coding is performed over two streams separately, i.e., $s_n, -s^*_{n+1}$ and s_{n+1}, s^*_n while the Alamouti decoding lies on four data streams, $h^*_1 \cdot r_n, -h_1 \cdot r^*_{n+1}$ and $h_2 \cdot r^*_{n+1}, h^*_2 \cdot r_n$.

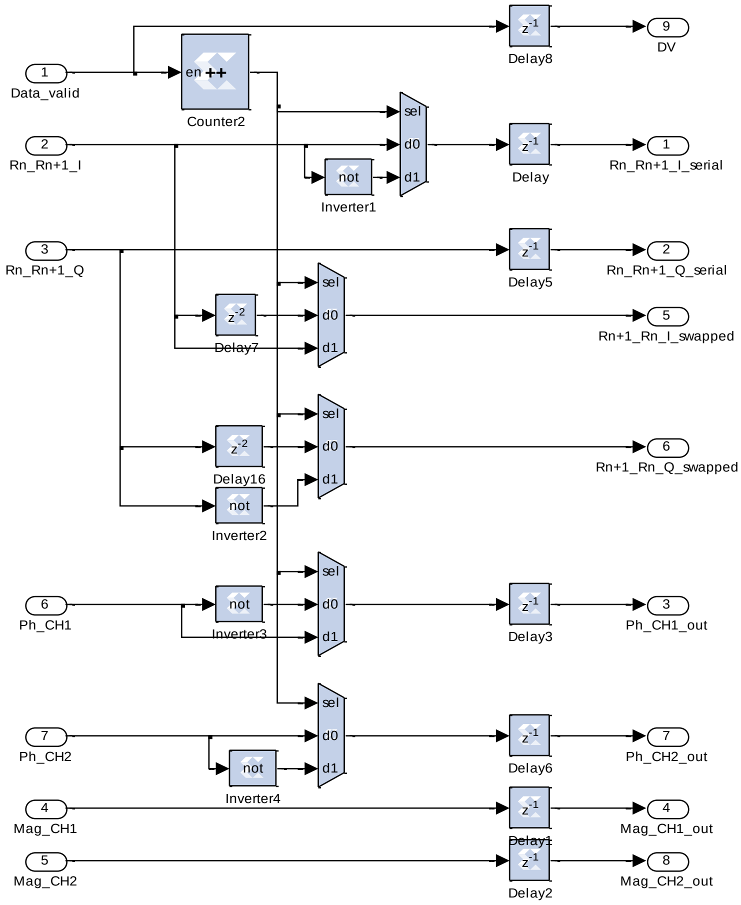

Figure 5.9: Structure of Alamouti Decoder

As it can be seen besides processing the received signals it should also process the channels, h_1 and h_2. As two signals are multiplied (channels and received signals) the signalling of the resulting arithmetic product may change. We consider that the signalization presented in the equation is done over the received signals, meaning that there is no change in the signalling of the channels.

This way, the case that deserves more attention is the one containing signalling, $-h_1 \cdot r^*_{n+1}$ seeing that from the outcome of these two terms, we only consider the effect of the signalization on the received signal. Thus, in the received signal, $-r^*_n$ only the real part is denied since $-(a + (jb)^*) \Leftrightarrow -a + jb$. The imaginary part can be performed by using a delay block since there is no need to use any structure and thus simplifying the whole structure of the Decoder. This is taken into consideration for similar cases. On the other hand, the structure of the channel h_1 remains 'intact', i.e, it is only necessary to conjugate its phase on the first instant/frequency and the magnitude can be done by using the referred delay block.

It may be noted that the structure to swap data over the r^*_{n+1}, r_n stream presents an inverter block at the d_1 input of the multiplexer in order to deny the second received signal, in terms of the real part of the signal, while there is no need to process any data for the imaginary part. As for the channel h_2, there is the need to deny its phase while the magnitude can be performed with the delay block.

- After that, at each instant/frequency the encoded channels and the encoded received signals are multiplied yielding two parts of the sum. The next figure 5.10 illustrates this step.

  The present correction blocks are able to multiply by using the Cordic block inside. From the Figure 5.10 it may be stated that the coding of the channels/received signal is done in such a way that the parameters of the equation (5.4) can be sent in parallel to the correction block, which performs the multiplication as desired, i.e, as the two squares show.

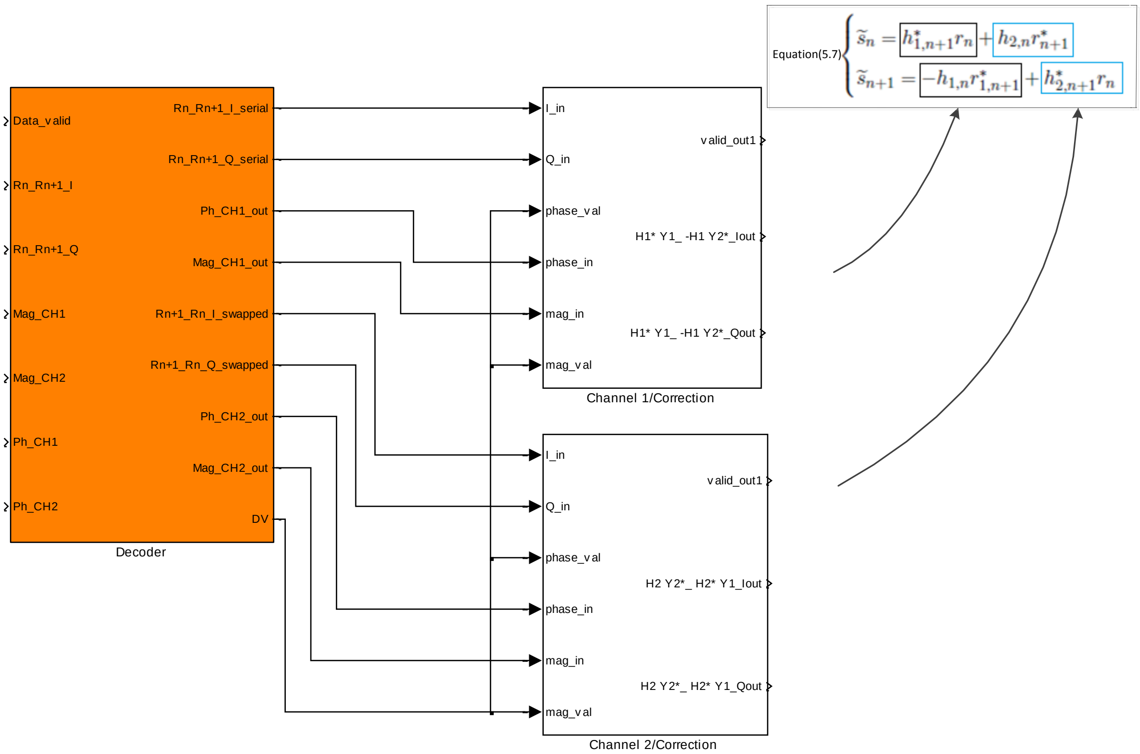

Figure 5.10: The encoded channels and the encoded received signals multiplied

- Finally, once obtained the two parts of the sum, i.e., $h_1^* \cdot r_n$ and $h_2^* \cdot r_{n+1}^*$ at the n instant/frequency and $-h_1 \cdot r_{n+1}^*$ and $h_2^* \cdot r_n$ at the $n+1$ instant/frequency, the resulting sum gives a symbol estimate at each instant/frequency. Then, two soft estimated data symbols are performed. The *Soft data Normalized* block is in charge to normalize the sequence of transmission and the guidelines are given by the equation (5.3). The structure of the Normalize block is shown below.

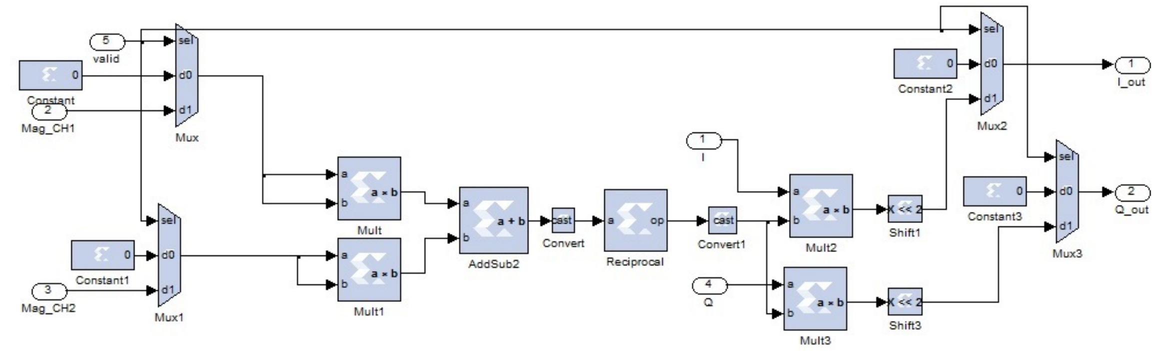

Figure 5.11: Structure of the Normalize block

As one can observe in Figure 5.11 the channel magnitudes are being taken into consideration, so as to obtain the $(|H_1|^2 + |H_2|^2)$ factor, which is precisely the power each channel.

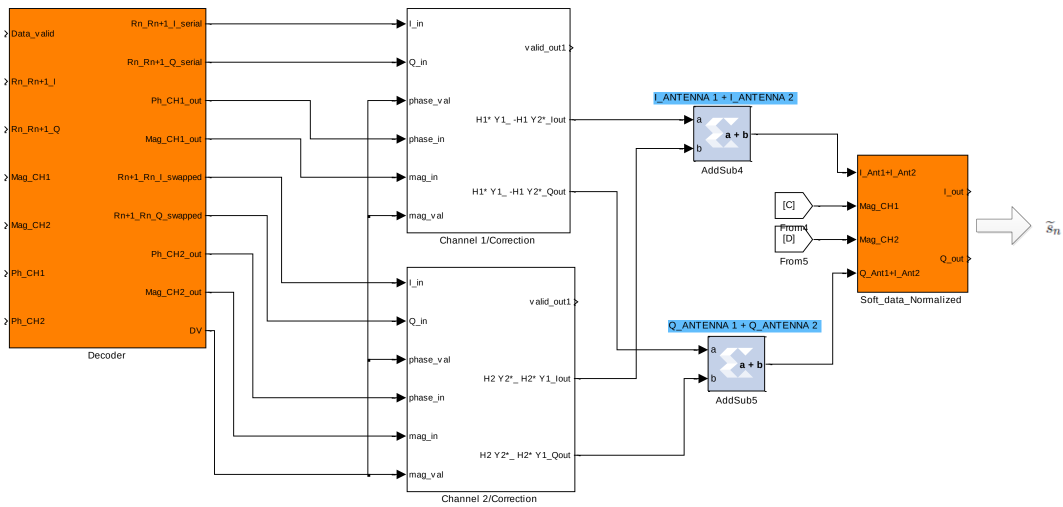

Figure 5.12: Overall Decoder

The Figure 5.12 encompasses all steps considered so far, specifically the incoming stream from each correction ('channel') is summed in terms of the real and the imaginary part to perform the symbol estimate. The next two section envisions to test the proposed Encoder/Decoder Alamouti blocks.

5.2 MISO chain simulated in Matlab

In order to validate the analized blocks they were integrated in the following MISO chain illustrated in the Figure 5.13, as an equivalent block diagram of the Alamouti scheme with 2 Tx and 1 Rx.

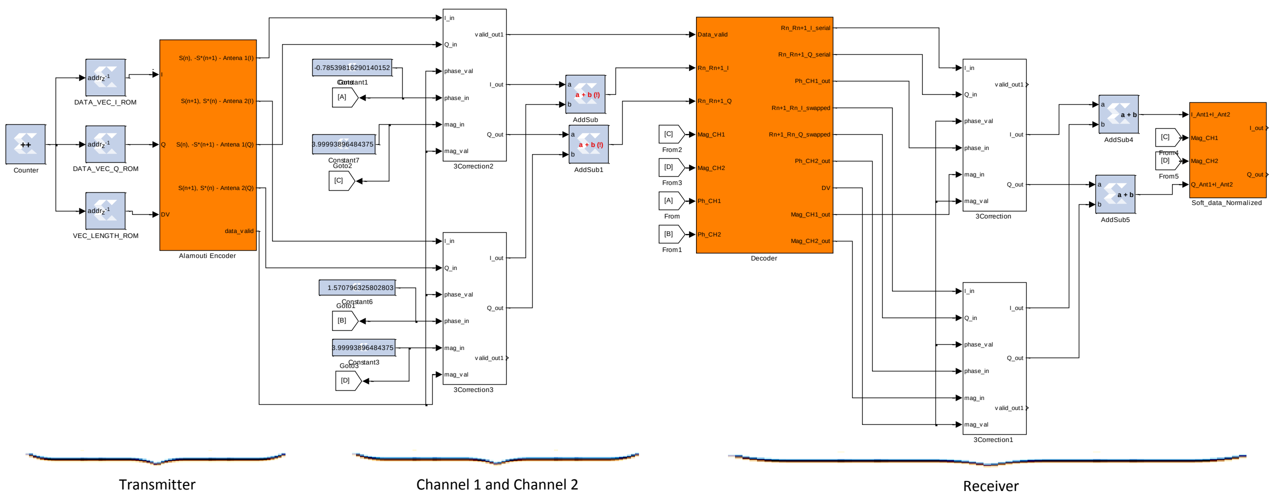

Figure 5.13: Alamouti Encoder/Decoder for MISO(2×1) in Matlab

The encoder is added to the transmitter side while the decoder is added to the receiver side of the test chain.

Practical considerations in the established chain

- On the transmitter the typical Modulator block is replaced by *Read-Only Memorys* (ROMs), where I and Q vectors represent real and imaginary part of the symbol. Moreover a signal of valid is provided to the Encoder, so that it may be able to detect the beginning and the end of the sequence of transmission.

- After encoding the data, it passes through the channels, namely Channel 1 and Channel 2 and then is summed according to the real and imaginary part of the symbol, and thus obtaining the equations described in (4.4).
- The coefficient channels $h_1 and\ h_2$ are represented by constants, specifically they can assume values of magnitude greater or equal than 0.5 and lower or equal than 3. These values are accomplished by using shift blocks to divide the signal, since the Cordic 4.0 blocks accept values between -1 and 1. For this reason for higher values of magnitude it is necessary to add more shift blocks (to the right of a house) to guarantee the range of the Cordic 4.0. The phase may assume any value.
- At the receiver side the already analysed decoder block is guided by the equation given in 5.4.

With the purpose of testing the developed Encoder and Decoder blocks we considered the equation 5.3 from which it can be concluded that, noise terms apart, if varying magnitude or phase values of the channels the soft decision of data symbol it is still valid.

5.2.1 Results

The results of the deployed MISO chain with the inclusion of the Encoder and Decoder blocks are presented and analysed in this section. One will consider the following parameters to run the chain:

- The simulation is performed with time-scale of 1000;
- It is necessary to load the random I, Q vectors through a m-file;
- Six plots are displayed, so that the symbols estimates are shown in the first set of plots and the valid signal propagates through the chain. The second set shows the input signals of the system, shifted by 116T (the total time of the chain).
- In order to obtain more comparisons between the input of the chain and its output, it is necessary to re-load the I and Q vectors seeing that they are randomized.
- In the simulation, two different values of magnitude and phase are assumed for the channels.
- Two two simulations are made.

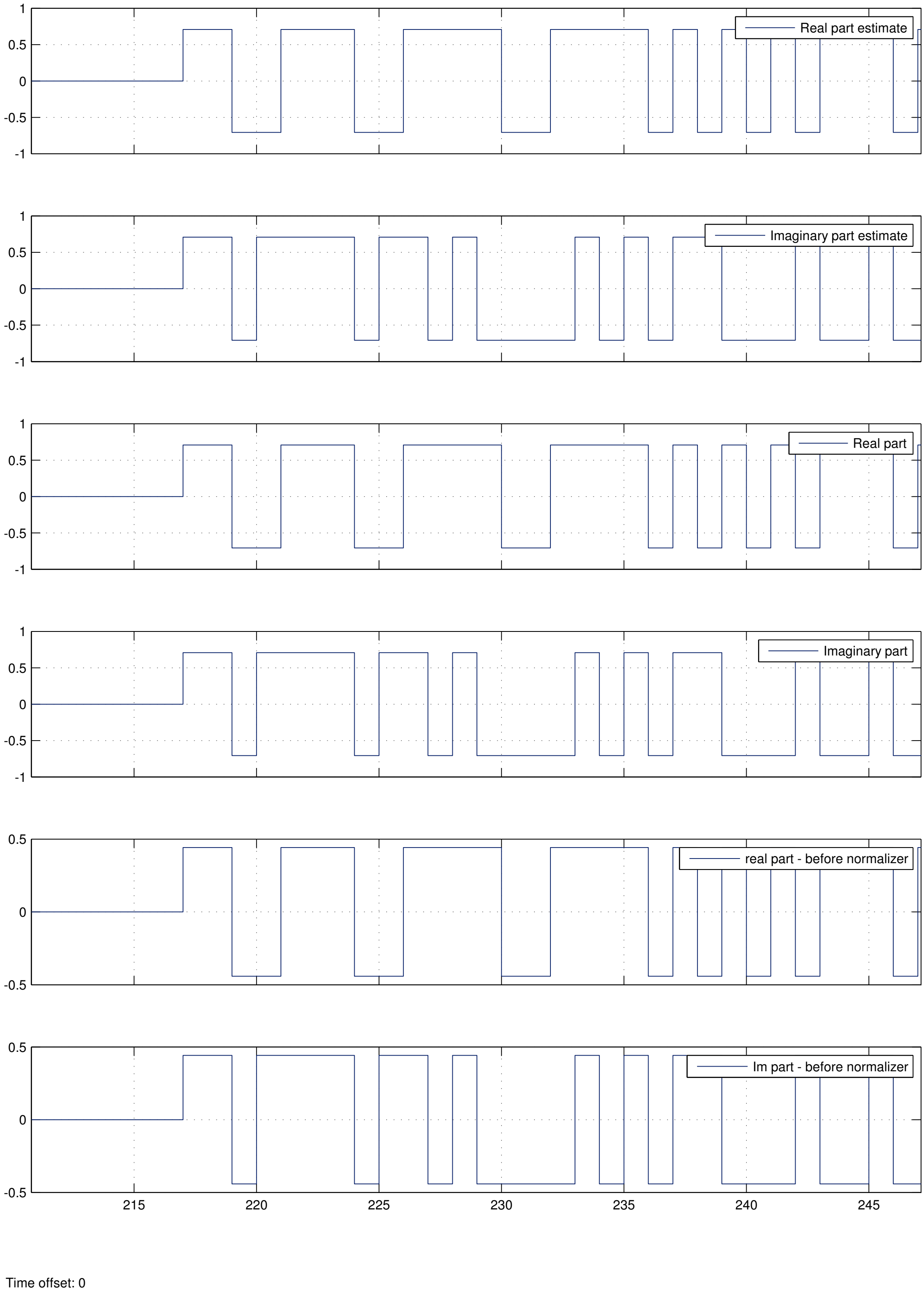

Figure 5.14: Channel 1 - Magnitude=1 and Phase=$\frac{\pi}{2}$; Channel 2 - Magnitude=3 and Phase=$\frac{\pi}{10}$

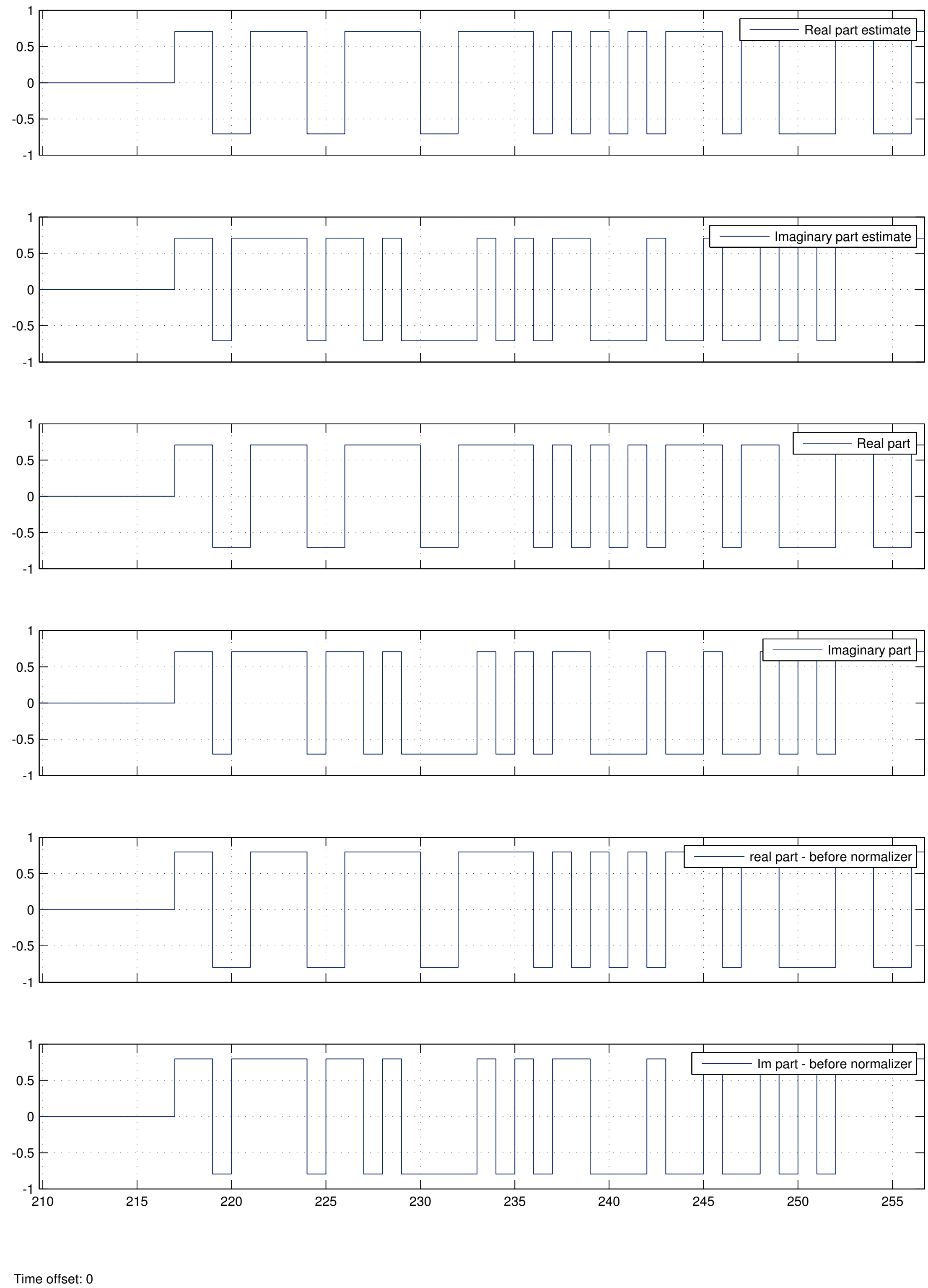

Figure 5.15: Channel 1 - Magnitude=3 and Phase=$\frac{\pi}{2}$; Channel 2 - Magnitude=3 and Phase=$\frac{\pi}{2}$

In the first simulation, which concerns Channel 1, the magnitude is equal to 1, and phase is equal to $\frac{\pi}{2}$ rad while as for Channel 2 these values are equal to 3 and $\frac{\pi}{10}$ rad respectively. In the second simulation each channel assumes other values of magnitude and phase, namely for Channel 1 these values are 3 and $\frac{\pi}{2}$ rad respectively and 3 and $\frac{\pi}{2}$ rad for Channel 2.

From the plots above one can consider that the input signals, namely real and imaginary, correspond to the signal/symbol before passing through the encoder, while the output signal represents the decoded signal, in other words, the symbol estimate. The input signal is presented as a means of comparison to the output signal. From the simulations above, it can be said that by varying the values of magnitude and phase in the channels, the soft decision data symbol remains without change. Since symbol estimate depends on the factor $(|h_1|^2 + |h_2|^2)$ which corresponds to the power of each channel, the simulations above allow us to conclude that the equation (5.3) is verified. Therefore it can be concluded that the proposals for Encoder/Decoder presented were successfully performed and also that the chain was well implemented.

5.3 MISO-OFDM chain

After testing the encoder and decoder in the previous test chain, the created blocks are included in an OFDM system, more specifically in a MISO type OFDM chain. So as to do that it is necessary to double the modulation OFDM channels. Besides that we have to clear the sequence of transmission which results from the two antennas, given that it contains not only data but also the pilots of each antenna.

The supplied MISO chain does not follow the LTE specifications to their full extent, for it is not necessary to be so rigid in LTE PHY for testing purposes. Thus, the bandwidth used is close to 10 MHz (the LTE offers bandwidth options that range from 1.25 to 20 MHZ), which results in a total of 50 PRBs per slot. The utilized frame is based only on the first transmission slot. Note that each slot may contain 6 or 7 OFDM symbols, in this case we used 6 OFDM symbols.

Path	Delay 1 (ns)	Delay 2 (ns)	Relative Power (dB)
1	0.0	0.0	0.0
2	89.28 (T)	65.1 (T)	-0.7
3	267.86	260.4 (4T)	-0.8

Table 5.5: System parameters of the MISO chain

The applied channels are considered to be uncorrelated, this way they are based on the stapped delay line model in agreement to the Table 5.5. A model with 3-n tap is considered.

The next table summarizes the main characteristics of the considered MISO-OFDM system.

Baseband sampling frequency/Bandwidth	15.36 MHz / 10 MHz
FFT size/Number of used subcarriers	1024/606
Modulation	QPSK and 16-QAM
Coded bits per sub-carrier/Coded bits per symbol	2/1332 (random) and 4/2664 (random)
Useful symbol duration (μs)	66.66 (1024 T)
Prefix Cyclic (μs)	16.667 (256 T)
Overall symbol duration (μs)	83.3267 (1280 T)
Sub-carrier separation (kHz)	15
OFDM symbols per block	3
IF sampling frequency/Central frequency	61.44 MHz/7.68 MHz

Table 5.6: System parameters of the MISO chain

5.3.1 Results

With the addition of the block created in this chain, one can say that the encoder and decoder remain unchanged when compared with the chain used previously. Thus, only the total delays of the chain and their respective magnitude and phase of the channels are considered, being that these values have to be within the defined range of the Cordic block.

The next two figures, namely Figure 5.20 and Figure 5.21 illustrate the MISO chain with the encoder and decoder included at the transmitter and receiver side, respectively and are shown at the end of the document.

Firstly, the signal QPSK is evaluated before and after the Normalize block. Further on, we vary the amplitude of the transmitted signal.

As far as the plot 5.16 is concerned, one can say that the 'X' displayed in the constellation demonstrates that the magnitude of the channels are not corrected.

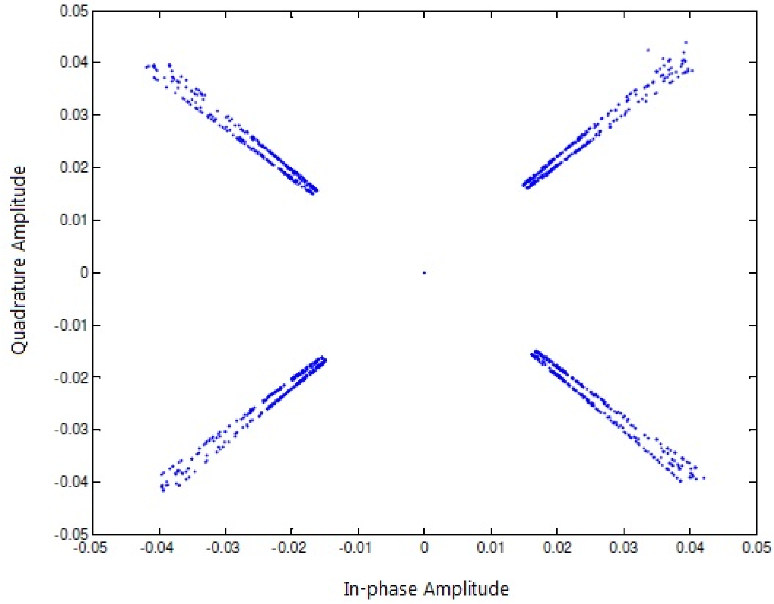

Figure 5.16: QPSK signal before the Normalize block

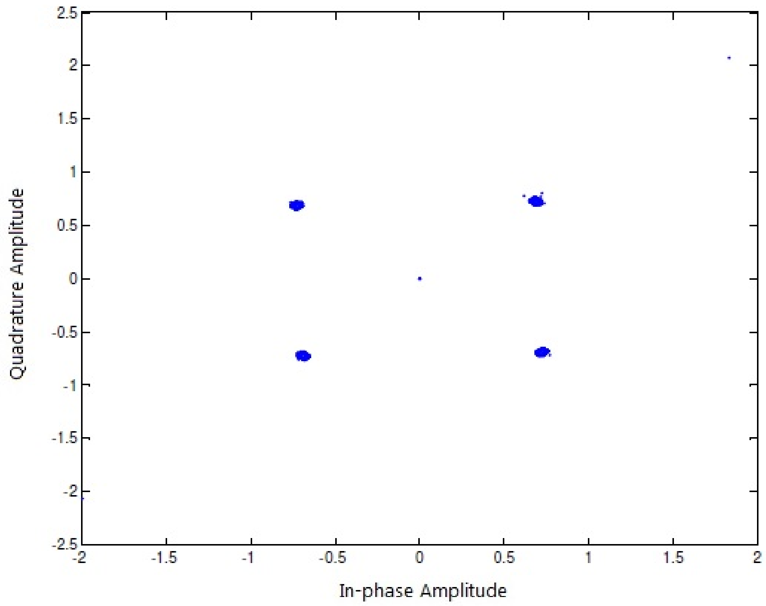

Figure 5.17: QPSK signal after the Normalize block

From the Figure 5.17 it can be observed that the magnitude of the QPSK is corrected. Finally, the signal QPSK amplitude is changed to the double.

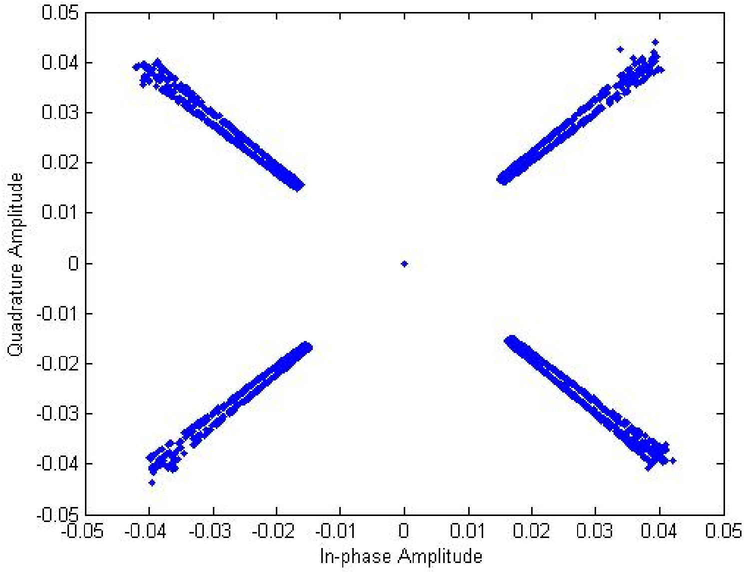

Figure 5.18: QPSK signal before the Normalize block

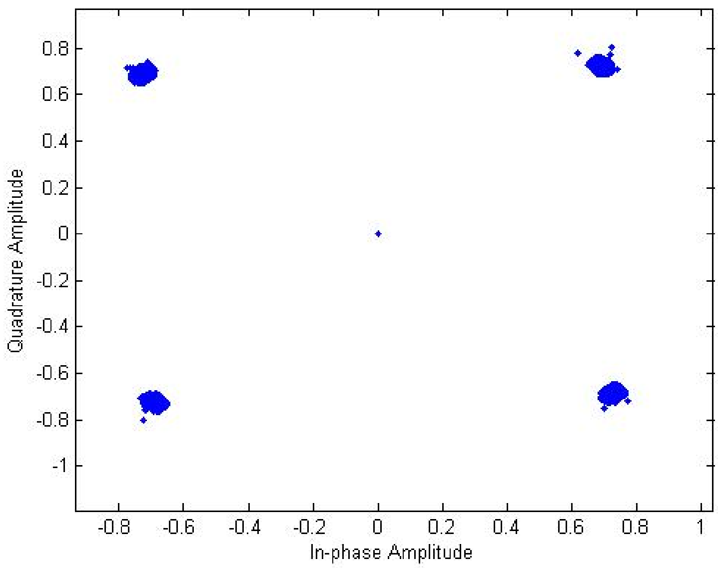

Figure 5.19: QPSK signal after the Normalize block

It can be concluded that by varying the amplitude of the signal, it remains unchanged which demonstrates that the Normalize block can correct the magnitude of the signal and also that the equation 5.3 is verified.

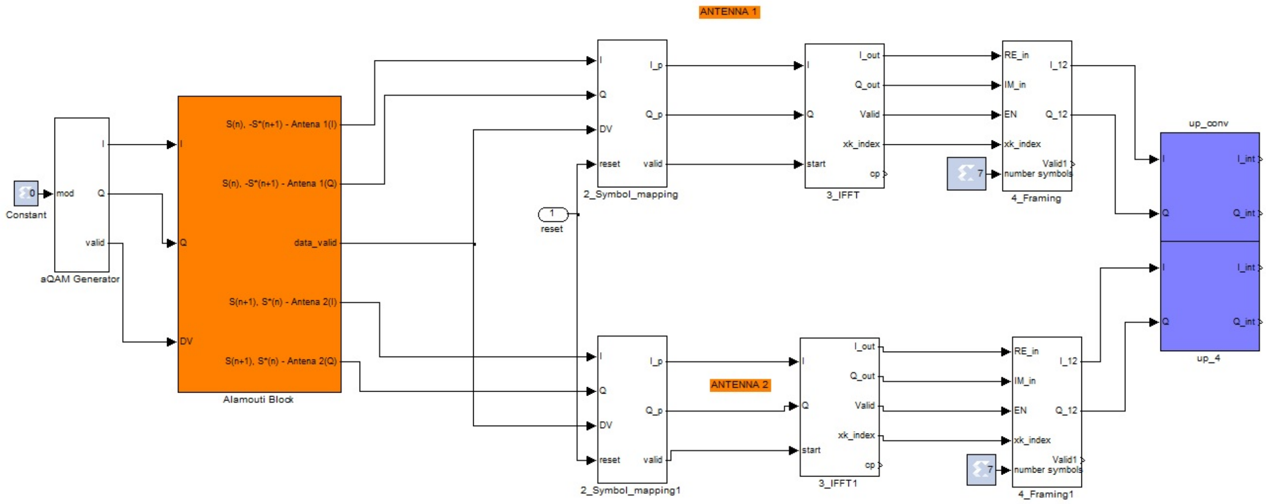

Figure 5.20: MISO chain with inclusion of the encoder

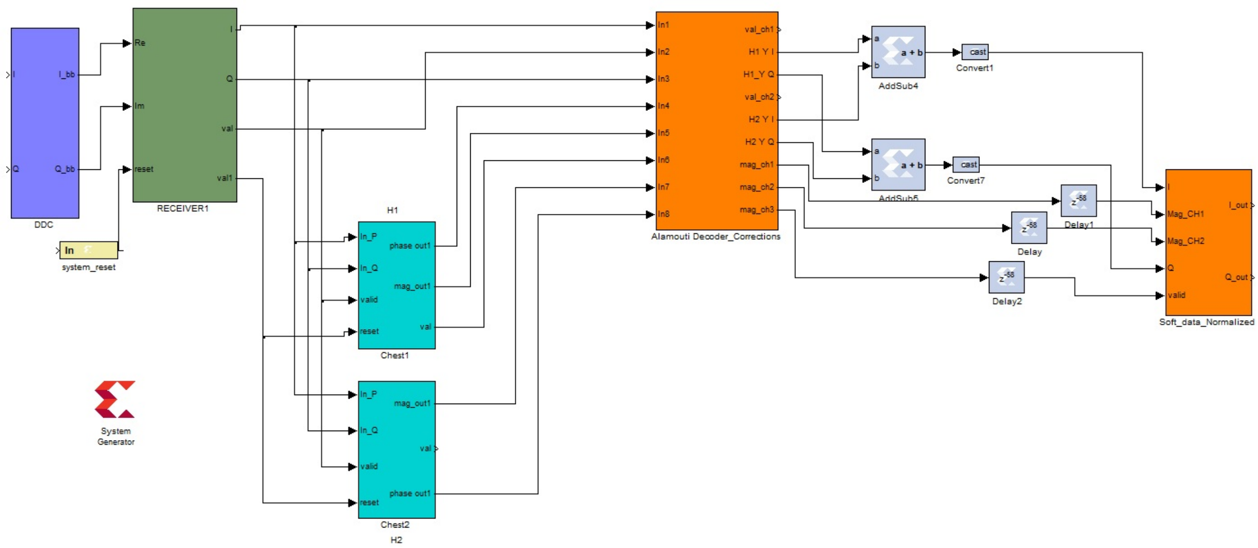

Figure 5.21: MISO chain with inclusion of the decoder

Chapter 6

Conclusions and Future Work

In this work we proposed an Alamouti encoder/decoder that follows closely the LTE physical layer specifications. In order to test the blocks they were included in two different chains, given that off the obtained results in each of them, one can conclude with certainty that the blocks work properly since they are able to encode/decode a QPSK signal. In order to correct the magnitude of the signal, we developed a Normalize block according to the equation (5.3).

The developed blocks will be implement in a FPGA so as to be used on a wireless tested, specifically on a developing MISO chain.

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