ISCTE IUL
Instituto Universitário de Lisboa

Departamento de Ciências e Tecnologias de Informação

Advanced Transmitters and Receivers in Future Wireless Networks

João André Correia Batista Conduto

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Orientador:
Professor Doutor Nuno Manuel Branco Souto,
Professor Auxiliar, ISCTE - IUL

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Resumo

O objectivo desta dissertação é aprofundar o estudo de tecnologias que permitam atingir comunicações mais eficientes e fiáveis nas futuras redes sem fios. Uma das tecnologias estudadas nesta dissertação e que ainda não existem muitos estudos é o *Complex Rotation Matrix* (CRM). Esta tecnologia é bastante útil em sistemas que usem multi-portadoras como o *Orthogonal Frequency Division Multiplexing* (OFDM) pois permite dividir a informação pelas várias sub-portadoras. Caso este sistema use também a tecnologia MIMO ainda permitirá a divisão da informação por várias antenas. As constelações hierárquicas são outro dos temas abordados nesta dissertação e são um método eficiente de entregar o mesmo conteúdo a diferentes utilizadores. Esta técnica poderá ser bastante útil tanto em sistemas de uma portadora como multi-portadoras. O *Single Carrier* (SC) é outra das tecnologias abordadas nesta dissertação.

Um dos standards em que poderia ser utilizado tanto o OFDM com o SC é no *Digital Video Broadcasting – Satellite services to Handhelds* (DVB-SH). Este esquema de comunicação tem com propósito a entrega de conteúdos multimédia aos terminais móveis via comunicação com estações base ou por satélite. O uso de o OFDM no *downlink* (DL) e do SC no *uplink* (UL) no mesmo standard/protocolo teria repercussões também ao nível dos terminais móveis pois permitiria uma melhor eficiência na duração das baterias.

Os resultados obtidos nesta tese visam sobretudo o estudo do CRM, estimação de canal e constelações hierárquicas. Para a obtenção de resultados foram efectuadas simulações com o método de Monte Carlo e Turbo Códigos. Os simuladores foram desenvolvidos em Matlab.

Palavras-chave: CRM, OFDM, constelações hierárquicas, SC e DVB-SH.

Abstract

The main purpose of this dissertation is the study of technologies that allow achieving more reliable and efficient communications in wireless systems. One of the technologies studied in this dissertation and practically new is the Complex Rotation Matrix (CRM). This technology is useful in systems that use multi-carrier as the Orthogonal Frequency Division Multiplexing (OFDM). The hierarchical constellations are other theme approached in this dissertation and it purpose efficiently is to deliver the same content to different users. Another technology studied in this dissertation was the Single Carrier (SC) with Frequency Division Equalization. The SC is a well-know technology and is used in several telecommunications systems. The goal is the future wireless communications adopt the two technologies in the same system and use one of them depending of the situation.

The Digital Video Broadcasting – Satellite services to Handhelds (DVB-SH) is one standard that can take advantage of the using of the OFDM and SC in the same system. The main goal of the DVB-SH is deliver multimedia content via satellite communications or communications with base stations to mobile terminals. The mobile terminals can achieve a more efficiency in their batteries whether in a standard/protocol that uses OFDM in DL and SC in UL.

The results obtained with this thesis have the purpose to study the CRM, channel estimation and hierarchical constellation. The simulators were developed in Matlab platform and Turbo Codes are the codification used, channel estimation is also used and all the simulations were made with the Monte Carlo method.

Key-words: CRM, OFDM, hierarchical constellations, SC and DVB-SH.

Dedication

The first person I would like to thank you to Professor Doctor Nuno Souto for help me in this journey since the thesis beginning until the last day. He really made an effort to the success of this study. Thank you.

I would like to thank you to my parents and all my family for the support over these years. It was a long journey but now we can see the outcomes. Next I want to thank to my special friends Genádio Martins, Rui Batalha, Catarina Cruz, João Teixeira and Alexander Machado. My family and my friends always support me and help me during this thesis, the degree and the life. Thank you!

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Acronyms List

0G	Zero Generation
1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ABS	Advanced Base Station
AMPS	Advanced Mobile Phone System
AMS	Advanced Mobile Station
AMTS	Advanced Mobile Telephone System
ASN	Access Service Network
ASN-GW	ASN Gateway
ATM	Asynchronous Transfer Mode
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
CGC	Complementary Ground Component
COFDM	Coded OFDM
CoMP	Coordinate Multipoint
CRM	Complex Rotation Matrix
CSN	Connectivity Service Network
DFE	Decision Feedback Equalization
DFT	Discrete Fourier Transform
DL	Downlink
DSL	Digital Subscriber Line
DTT	Digital Terrestrial Television
DVB-SH	Digital Video Broadcasting – Satellite services to Handhelds
DVB-T	Digital Video Broadcasting – Terrestrial
EDGE	Enhanced Data rates for GSM Evolution

ETACS	European TACS
ETSI	European Telecommunication Standards Institute
FDD	Frequency Division Duplex
FDE	Frequency Domain Equalization
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	*Groupe Spécial Mobile*
HM	Hadamard Matrix
HPA	High Power Amplifier
HPSK	Hierarchical PSK
HQAM	Hierarchical QAM
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
IB	Iteration Block
IDFT	Inverse DFT
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse FFT
IP	Internet Protocol
IPDC	IP Datacast
ISI	Inter-symbol Interference
LAN	Local Area Network
LDPC	Low-Density Parity-Check
LLR	Log-likelihood Ratio
LTE	Long Term Evolution
MAC	Media Access Control
MBMS	Multimedia Broadcast Multicast Service
MIMO	Multiple-input Multiple-output
MISO	Multiple-input Single-output

MLSO	Maximum Likelihood Soft Output
MMSE	Minimum MSE
MSE	Mean Square Error
MU	Multi-user
NCRM	Non-orthogonal CRM
OCRM	Orthogonal CRM
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open Systems Interconnections
P/S	Parallel to Serial
PAPR	Peak to Average Power Ratio
PCCC	Parallel Concatenated Convolutional Code
PDF	Probability Density Function
PHY	Physical Layer
PSAM	Pilot Symbol Assisted Modulation
PSK	Phase Shift Keying
PtM	Point to Multipoint
PtP	Point to Point
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RRM	Real Rotation Matrix
S/P	Serial to Parallel
SAE	System Architecture Evolution
SC	Single Carrier
SIMO	Single-input Multiple-output
SISO	Single-input Single-output
SNR	Signal to Noise Ratio
TACS	Total Access Communication System
TDD	Time Division Duplex
TDM	Time Division Multiplexing
TV	Television
UE	User Equipment

UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRA	Universal Terrestrial Radio Access
W-CDMA	Wireless Code Division Multiple Access
WiMAX	Worldwide Interoperability for Microwaves Access

Chapter 1 – Introduction

Introduction

In our society, communication is extremely important. All kinds of communications are important, people talking with each other, newspapers, television, phones, internet and other kinds of communications. The internet has taken a relevant place in our society. Nowadays is usual to see people using social networks in their mobile phones. They have access to the internet in their mobile phones. Using your mobile phones to make a call or even access the internet fifty years ago were something impossible and unthinkable (fifty years ago the concept of internet was something unthinkable as well). So in our society to get access to 'the world' is a piece vital in everything, in people well-being, economy, military, etc.

Alexander Bell and Charles Tainter made the first wireless conversation using a telephone in 1880. They used a telephone that conducted wireless communications over a modulated light beams - which are narrow projections of electromagnetic waves. Good weather was required to perform the communication.

Another important step in wireless communication happened eight years after the experience of Alexander Bell and Charles Tainter. Heinrich Hertz demonstrated the theory of electromagnetic waves. Hertz (based on research developed by James Maxwell and Michael Faraday) demonstrated that electromagnetic waves could be transmitted and transmitted an electromagnetic wave through space at straight lines and that they were able to be received.

In 1901, Marconi (the inventor of the radio telegraph) established a wireless communication over the Atlantic Ocean. The distance between the transmitter and receiver was about 3,500 kilometers.

As we can see, wireless communications started in the end of the XIX century and suffered a tremendous evolution since those days. Nowadays cellular networks are one of the most important networks for the human kind.

The zero generation (0G) of mobile communications started with the Advanced Mobile Telephone System (AMTS) in Japan.

The first generation (1G) of mobile communication took place in 1983. The standard used was Advanced Mobile Phone System (AMPS) and is an analog mobile phone system developed by Bell Labs [1]. This standard was used in Americas, Israel and Australia. In Europe the standard used was Total Access Communication System (TACS). The TACS is a mostly-obsolete variant of AMPS and in Europe is known as ETACS, in Japan is known as JTACHong Kong also adopted the TACS.

The main standard of the second generation (2G) was the *Groupe Spécial Mobile* (GSM) known in English as Global System for Mobile Communications. This standard was developed by the European Telecommunication Standards Institute (ETSI). The GSM was developed to replace the 1G analog cellular networks. After a while the GSM was expanded to include a first circuit switched data transport (initial design for circuit switched network for full duplex voice telephony) and after it, a packet data transport via General Packet Radio Service (GPRS) was adopted. The GPRS is known in the telecommunication world as 2.5G.

The third generation (3G) is the well-known Universal Mobile Telecommunication System (UMTS). The UMTS was developed by the 3rd Generation Partnership Project (3GPP) and employs wideband code division multiplexing (W-CDMA) radio access to achieve good spectral efficiency and bandwidth to the mobile operators.

The Enhanced Data rates for GSM Evolution (EDGE) were developed to improve the data transmission rates in GSM and the High Speed Packet Access (HSPA) improves the performance of the W-CDMA protocol existing in UMTS. The Long Term Evolution (LTE) is a set of enhancements of the UMTS. This standard is known as the 3.75G and was also developed by the 3GPP. The LTE is the latest standard in mobile communications that produce GSM/EDGE and UMTS/HSPA network technologies.

The Worldwide Interoperability for Microwave Access (WiMAX) is another famous telecommunications protocol of the 3.5G. The purpose of WiMAX is to provide fixed and mobile Internet access and is described as a standard enabled to deliver wireless broadband access as an alternative to cable and Digital Subscriber Line (DSL). The standard of the 3.75G is the most advanced that we have in the market in these days.

The 4G is based in the LTE Advanced and the WiMAX-Advanced. Both standards are evolutions of previously protocols LTE and WiMAX respectively. The standards of the 4G are the last developed to these days.

The wireless communications are not only about cellular networks. The Global Positioning System (GPS) is used in several different contexts like airplane industry, military and other industries/situations. The purpose is always the same to know the location in real-time of an object. In GPS the communication is by satellite and was developed by the United State government.

The same device can communicate with different networks. For example a mobile phone can communicate with a cellular network (2G or 3G mainly), wireless network only to provide Internet (Local Area network – LAN) and/or communication with satellite to have GPS services.

It is expected that the wireless communication continue to evolve. These communications are important because of their importance in our society. So it is important to continue investing in this sector. It is guaranteed that mobile phones will continue to have more different services and will continue to improve over the years.

Motivation

Nowadays the technologies took a huge control over our lives. The mobile phone is like a wallet. Everybody owns one and carry it everywhere. It is important to deliver to the mobile phone all kind of content. The mobile is no longer a gadget to make phone calls. You can use them to send/receive e-mails, use the internet, update your social network profile, etc. Basically it is a little laptop. So it is extremely important to deliver multimedia content to them with the need to have a great experience to the users. For example, the digital TV is here and is important to deliver the best quality of image as we can to the mobile phones.

Wireless communications have a few issues. The download velocity is extremely important if we want to deliver interactive content or watch live events. The fading effects are other of the biggest problems of wireless communications. Fading effect is explained in the following figure:

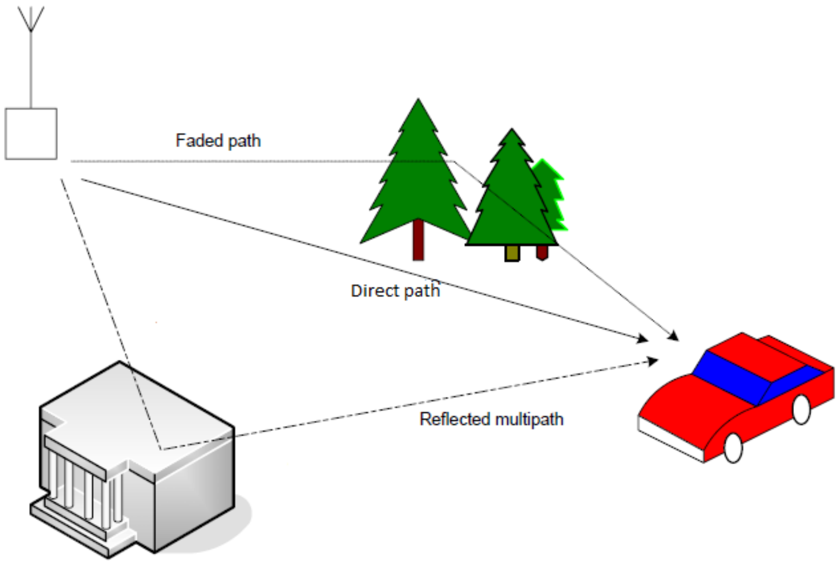

Figure 1 – Fading Effect [17]

This effect only appears when the path from the transmitter to the receiver either has reflections or obstructions. The signal reaches the receiver from many different routes, each being a copy of the original (multipath effect). The slightly difference are delay and gain. The time delays result in phase shifts which added to main signal component causes the signal to be degraded. This causes the Rayleigh fading. The Rayleigh fading effects assume that the magnitude of the signal has passed through a transmission medium and will vary randomly. Rayleigh fading is most applicable when is no dominant along a line of sight between the transmitter and receiver. Another issue in wireless communications is the poor channel estimation or imperfect channel estimation.

Sometimes the data information has errors that must be recovered at the receiver.

The study of Complex Rotation Matrix (CRM) and Multiple-input Multiple-output (MIMO) in the same system is not deeper. It is expect that both technologies working together can achieve a great performance in wireless communications. It should be introduces techniques with the purpose of reduce this effects.

State of the Art

The Orthogonal Frequency Division Multiplexing (OFDM) appeared for the first time in 1966 [4]. Over the years the OFDM evolved and nowadays is a well-known technology used mostly in wireless communications [5]. The Universal Terrestrial Radio Access (UTRA) Long-Term Evolution (LTE) was the first technology to mobile communication who adopted the OFDM [6]. The UTRA LTE has a service which is specialized in delivering Multimedia content to the mobile terminals. The service is called Multimedia Broadcast Multicast Service (MBMS) and includes two types of transmission modes: point-to-point (PtP) and point-to-multipoint (PtM).

Voice and video signals information are scalable and to permit reliable and efficient broadcast communication using these kind of signals in mobile technologies we can use hierarchical constellations with different protection bit error in broadcast transmissions[7][8].

Hierarchical constellations [15][16] had already been incorporated into Digital Video Broadcasting – Terrestrial (DVB-T) [10]. DVB-T is a standard for broadcast transmission of digital terrestrial television (DTT). It was published in 1997 and the first broadcast was in the United Kingdom in 1998 [11]. The modulations used in DVB-T were 16 and 64 Quadrature Amplitude Modulation (QAM). This technology uses OFDM. The hierarchical constellations are being considered for the UTRA LTE [6].

Another technology for the delivery of multimedia content to mobile terminals is the Digital Video Broadcasting – Satellite services to Handhelds (DVB-SH). The DVB Project published this standard in February 2007 [9]. The DVB-SH was designed for frequencies below 3 GHz and proposes was to support the televisions bands UHF, S and L.

The Complex Rotation Matrix (CRM) is a technique capable of achieving performance gains in fading channels using OFDM transmission [12]. The CRM is based in spreading the information over a large number of subcarriers of the OFDM signal.

Multiple-input and multiple-output (MIMO) schemes have emerged as a promising method for improving the capacity of wireless communication systems [13][14][16]. This technique consists in the use of multiple antennas at both transmitter and receiver to improve communication performance.

Objectives

The purpose of this dissertation is to study technologies that can improve the quality of signal in the receiver and improve communication reliability. The Complex Rotation Matrix (CRM) is a technique that can improve the quality of the experience especially when used in a multi-carrier system as Orthogonal Frequency Division Multiplexing (OFDM).

The hierarchical constellation is other technique of doing that improvement. This technique has the capacity of adapting to the conditions of the channel. The key of hierarchical constellation is the different error protection between the symbols. A more detail information about hierarchical constellation in the chapter 3.

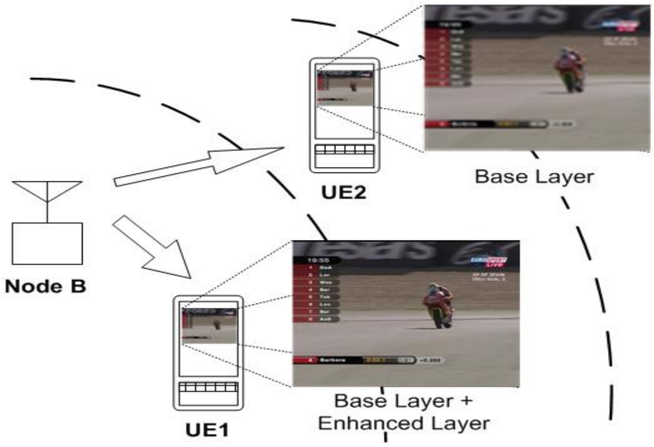

Figure 2 - The same signal to different mobile terminals [18]

One technology that can absorb these two techniques (CRM and hierarchical constellation) is the Digital Video Broadcasting – Satellite services for Handhelds (DVB-SH). This standard is already using the OFDM for deliver information to the mobile terminals. The Long Term Evolution (LTE) use OFDM with the same purpose. The 3G can easily adopt both the CRM and the hierarchical constellation as well.

The combination of the OFDM with the Single Carrier (SC) in the same system can be really useful for the life of batteries if the OFDM is used in downlink and SC in uplink. We can use both models with the purpose of concentrate the processing signal in a place where the battery is not really important.

Chapter 2 – Block Transmission Techniques

OFDM

The OFDM (Orthogonal Frequency Division Multiplexing) is a transmission technique with the purpose of improving the spectrally efficiency and to combat the effects of multipath conditions. It is a one of the most famous techniques which uses a multicarrier solution [19]. The main idea in OFDM technique is the orthogonality of the sub-carriers. Since the carriers signals are all sine or cosine waves, the area under one period of the wave is zero [17]. This is shown is the next image.

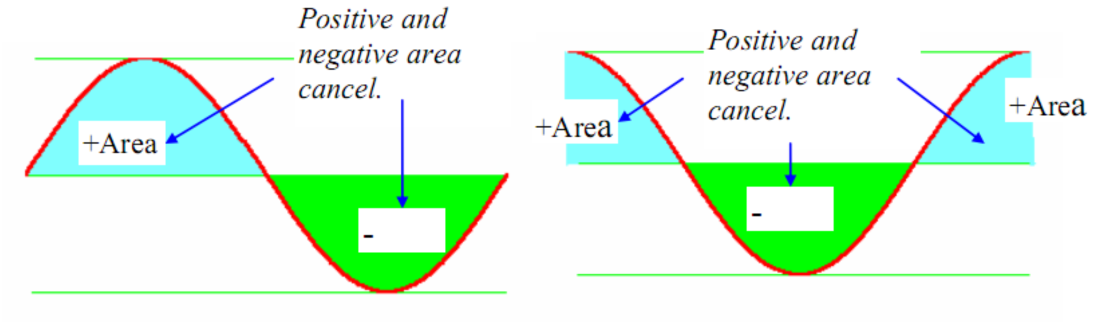

Figure 3 - The area under a sine or cosine wave is always zero (in the same period) [17]

The area under the product is represented by $\sin mwt \times \sin nwt$. With a simple trigonometric relationship, this is equal to a sum of two sinusoids of frequencies $(n - m)$ and $(n + m)$. So the area under the sinusoid is given by $\int_0^{2\pi} \left[\frac{1}{2}\cos(m-n)\,wt\right] - \int_0^{2\pi} \left[\frac{1}{2}\cos(m+n)\,wt\right] = 0$ [17].

The orthogonality allows simultaneous transmissions on a lot of sub-carriers in a tight frequency space without interference from each other [17]. This is the great advantages of the OFDM and with this technique we can improve the use of the bandwidth.

First we modulate all sub-carriers separately. After the modulation the sub-carriers go through an IFFT (Inverse Fast Fourier Transform) to create the OFDM signal. We can describe the IFFT process as $\sum_{n=1}^{N} m_n(t)\sin(2\pi nt)$ where N is the number (number or frequency) of sub-carriers, n is the actual sub-carrier and $m_n(t)$ is the sub-carrier signal. The IFFT converts the signal from the frequency domain to time domain by successively multiplying it by a range of sinusoids [17]. The equation for IFFT is

$$X(n) = \sum_{n=0}^{N-1} x(k) \sin\left(\frac{2\pi kn}{N}\right) - j \sum_{n=0}^{N-1} x(k) \cos\left(\frac{2\pi kn}{N}\right) \quad (1)$$

Where k is the index of the frequencies over the N frequencies and n is the time index. $x(k)$ is the value of the spectrum for the k_{th} frequency [17]. One of the main purposes of the IFFT block is to change the domain of the signal.

The extraction of the sub-carriers at the receiver is done by applying the FFT (Fast Fourier Transform) operation. The result of the FFT block in common understanding is a frequency domain signal. We can write the FFT as

$$x(k) = \sum_{n=0}^{N-1} x(n) \sin\left(\frac{2\pi kn}{N}\right) + j \sum_{n=0}^{N-1} x(n) \cos\left(\frac{2\pi kn}{N}\right) \quad (2)$$

Where $x(n)$ are the coefficients of the sines and cosines of frequency $\frac{2\pi kn}{N}$, k is the index of the frequencies over the N frequencies and n is the time index. The coefficients by convention are defined as time domain samples $x(k)$ for the FFT and $X(n)$ frequency bin values for the IFFT [17].

After the IFFT block, the system adds a cyclic prefix. The cyclic prefix is a repetition of the last data symbols in a block. The purpose of the cyclic prefix is to mitigate the ISI (Inter-Symbol Interference) and the fading effects. The cyclic prefix is discarded at the receiver because its only purpose is to mitigate the referred last two effects. ISI is a form of distortion of a signal in which one symbol interferes with the nearest symbols. In wireless communications, ISI is usually caused by multipath propagation. The presence of ISI in systems can introduce errors in the decision device at the receiver.

We can get fading effects when the path from the transmitter to the receiver has reflections or obstructions [17]. This type of effect is common in wireless communications. The problem arises when the signal reach the receiver from many different paths and each signal is a copy of the original signal having a different delay and gain. The degradation of the signal appears due to the sum of the time delays. The reflected signals that are delayed cause either gains in the signal strength or deep fades and by deep fades we mean that the signal is practically wiped out [17]. The delay spread is the maximum time delay that occurs in a certain environment.

Sometimes the environment cause fading in several frequencies, this type of fading is called deep fades frequencies. This happens to some frequencies in the band. The channel does not allow any information to go through in this frequencies and it does not occur uniformly across the band.

You can see these frequencies in the next image:

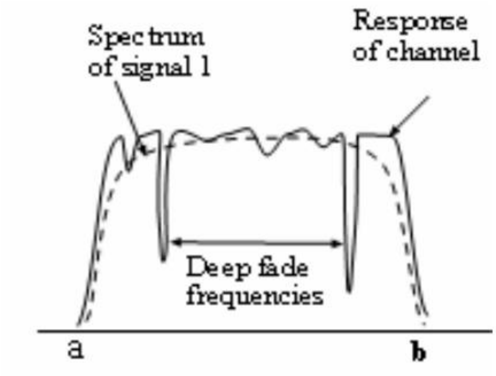

Figure 4 - A fading channel has frequencies that do not allow anything to pass. Data is lost sporadically. ‘a’ and ‘b’ are frequencies [17]

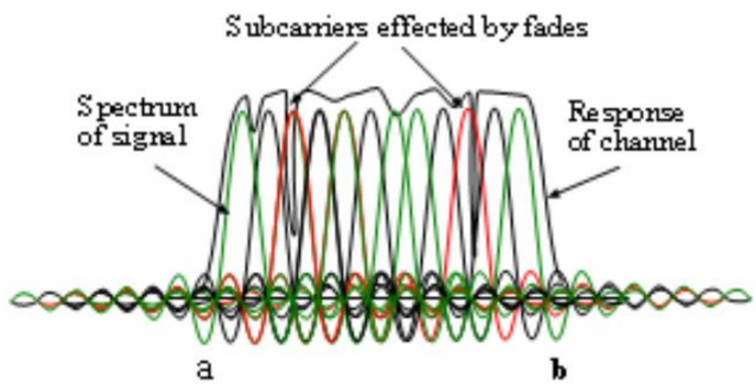

Figure 5 - In an OFDM signal, only a small sub-set of the data is lost due to fading [17]

As we can see in the Figure 9, in this case, only two sub-carriers are affected by the fading. With a proper coding this can be recovered.

To use the perfect delay spread we have to move the symbols further away from the region of delay spread, this will help to mitigate the noise at the front of the symbol. This noise happens due to the multipath and the symbols that arrived at the receiver (copies of the main signal). If we are moving the symbols further from each others, blank spaces can appear in the signals. We cannot have blank spaces in signals because it won't work for the hardware which likes to crank out signals continuously. To resolve this problem we extend the symbol into the empty space, so the actual symbol is more than one cycle. But now the start of the symbol is still in the danger zone (zone which copies of the main signal can arrive to the receiver). The start is the most important about our symbol since the slicer needs it in order to make a decision about the bit [17]. To avoid the situation where the first part of the symbol falls in this danger zone, we can slide the symbol backwards and then fill this area with a copy of what turns out to be the tail end of the symbol.

The addition of the cyclic prefix results in an extension of the original symbol. The symbol source is continuous so all we are doing is adjusting the starting phase and making the symbol period longer [17].

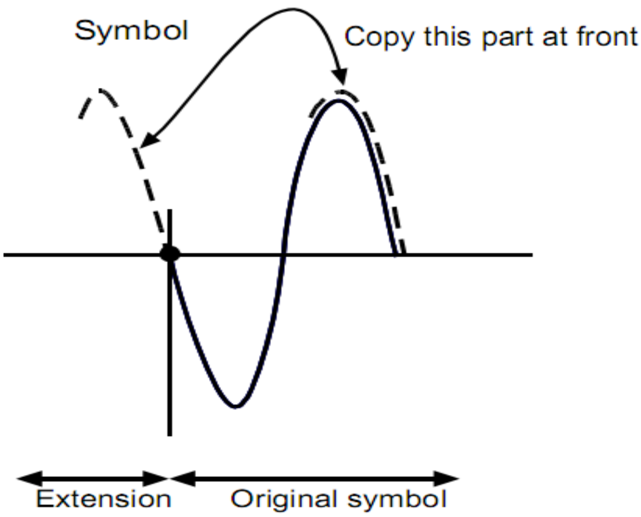

Figure 6 - Cyclic prefix adding

Since OFDM has a lot of carriers, instead of doing this to all carriers, we add the cyclic prefix to the OFDM signal (with all carriers). The cyclic prefix produces the appearance of circular convolution which is essential to the proper function of the FFT operation [19].

We add the cyclic prefix after applying the IFFT. When the signal arrives at the receiver, the first thing to do is to remove the cyclic prefix to get the perfectly periodic signal and a FFT is applied to get back the symbols on each carrier. You can see a typical OFDM transmitter and receiver diagram in the next image.

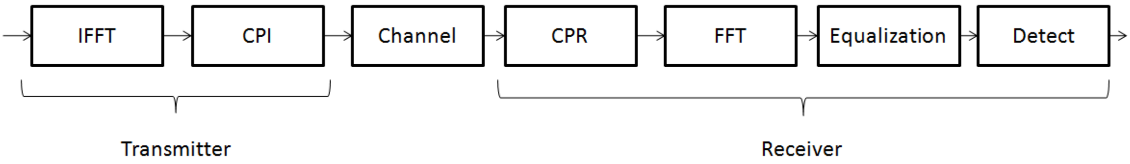

Figure 7 – OFDM system representation

The disadvantage of using the OFDM is that OFDM has a high PAPR (peak-to-average ratio). This ratio exists because the transmitted OFDM signal is a sum of a large number of modulated sub-carriers. This situation means that the power amplifier in an OFDM system generally must be backed off by several dB to remain linear over the range of signal envelope peaks that must be faithfully reproduced [19].

SC-FDE

Single Carrier (SC) is a frequency division multiple access scheme. It is a scheme of sending data. SC is used with equalization. There are two types of equalization: Frequency Domain Equalization (FDE) and Time Domain Equalization (TDE). In this thesis we used the FDE. FDE has better performance than TDE and the low signal processing is lower as in OFDM. The major SC-FDE advantage over OFDM is the less sensitive to radio-frequency impairments such as power amplifier nonlinearities [19]. As Sari [38] [39] pointed out that when combined Fast Fourier Transform (FFT) processing with SC- FDE, the system can achieved performance and low complexity as an OFDM system.

As the name SC says this technique has just one carrier which is modulated at a high symbol rate. To understand the SC-FDE, we consider an SC-based block transmission with N useful modulation symbols per block $\{s_n; n = 0,1, \dots, N-1\}$. This results from a direct mapping of the original data into a selected signal constellation [37]. To complete the SC-FDE signal it is necessary to add the cyclic prefix (as in the OFDM signal). The receiver scheme can have the representation of Figure 13, where it is assumed that the signal is sampled and S/P (Serial to Parallel) converted, the cyclic prefix samples removed, resulting in time-domain samples $\{y_n; n = 0,1, \dots, N-1\}$. These samples are converted to the frequency domain by a FFT (Fast Fourier Transform), leading to frequency domain samples $\{Y_k; k = 0,1, \dots, N-1\}$.

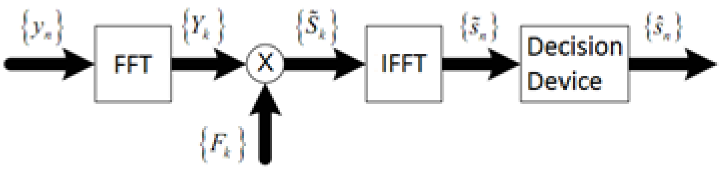

Figure 8 - SC-FDE receiver structure with no space diversity (a) and with an ***L*** order space diversity [37]

Sometimes the channel has a lot of noise enhancement effects caused by deep notches in the channel frequency response. To minimize the channel noise and ISI effects, the equalized samples $\{\tilde{S}_k; k = 0,1, \dots, N-1\}$ are obtained with the coefficients $\{F_k; k = 0,1, \dots, N-1\}$ usually optimized under the MMSE (Minimum Mean Square Error) technique [37]. The MSE (Mean Square Error) can be expressed as (in time domain)

$$\Theta(\mathrm{k}) = \frac{1}{N^2}\sum_{k=0}^{N-1}\Theta_\mathrm{k} \tag{3}$$

and

$$\Theta_k = E\left[\left|\tilde{S}_k - S_k\right|^2\right] = E[|Y_k F_k - S_k|^2]\,. \tag{4}$$

To minimize the MSE, we can minimize Θ_k in order to F_k, for each k separately, i.e.

$$min_{F_k}(E[|Y_k F_k - S_k|^2]), k = 0,1,\dots,N-1 \tag{5}$$

which leads to the set of optimized FDE coefficients

$$F_k = \frac{H_k^*}{\beta + |H_k|^2}, k = 0,1,\dots,N-1 \tag{6}$$

where β is the inverse of the SNR (Signal-to-Noise Ratio), given by

$$\beta = \frac{\sigma_N^2}{\sigma_S^2} \tag{7}$$

with

$$\sigma_N^2 = \frac{E[|N_k|^2]}{2} \tag{8}$$

and

$$\sigma_S^2 = \frac{E[|S_k|^2]}{2}. \tag{9}$$

In SC modulations the data contents are transmitted in the time domain, the equalized samples $\{\tilde{S}_k; k = 0,1,\dots,N-1\}$ are converted back to the time domain by an IFFT operation leading to the time domain samples. These samples are equalized $\{\tilde{s}_n; n = 0,1,\dots,N-1\}$ then will be used to make decisions on the transmitted symbols.

The attractive features of processing the FFT of the received signal in the frequency domain are:

- The OFDM has a high PAPR (peak-to-average ratio) and the SC modulation reduced that PAPR. This allows using less costly power amplifiers.
- The performance of the two systems (OFDM and SC) when the equalization of SC modulation is in the frequency domain are similar and codification is used in OFDM. Even for a very long channel delay spread.

- To achieve reliable results in OFDM, coding is a requirement which does not happen on SC-FDE. In spite of that both technologies are usually combined with coding.
- The SC modulation systems are a well proven technology in many existing wireless systems.

To obtain better performances than the linear equalization we can use a DFE (Decision Feedback Equalization) in a frequency selective radio channels. The goal of this technique is to remove the interference effect from subsequently detected symbols. It is achieved when symbol-by-symbol data symbol decisions are made, filtered and immediately fed back [19]. Due to the inherent delay of the FFT signal processing, this cannot be done in a frequency domain. To avoid the feedback delay problem, the approach is a hybrid time-frequency domain DFE to filtering only for the forward filter part of the DFE and a conventional transversal filtering for the feedback part [19]. Due to multiplications only on data symbols, this kind of filter is relatively simple.

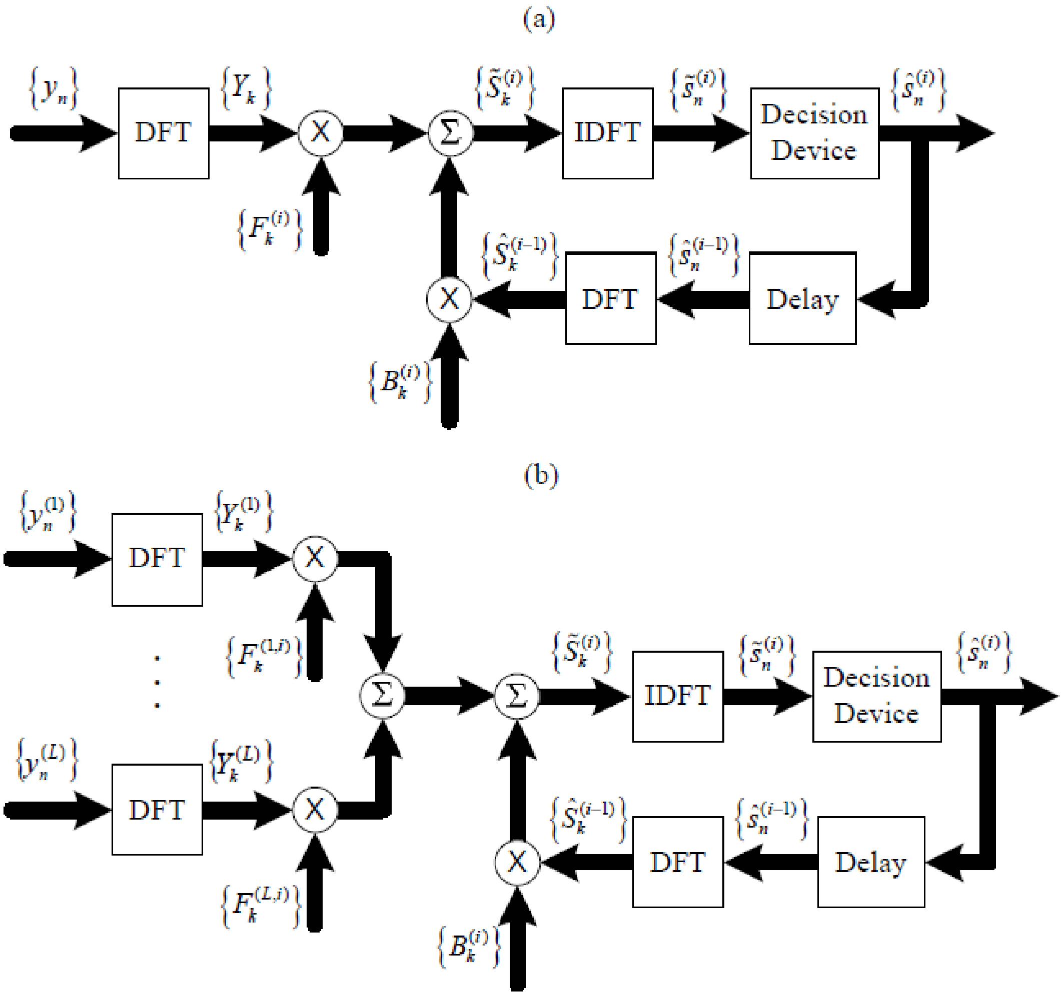

Figure 9 – IB-DFE receiver structure with no diversity (a) and with L-branch space diversity (b)

Once per block, the M FFT output coefficients (R_l) are multiplied by the complex-valued M forward equalizer coefficients (F_k). This multiplication has the purpose to compensate the frequency-selective channel's variations of amplitude and phase with frequency. An IFFT is applied to the M weight-equalized complex-valued samples and the resulting time domain sequence is passed to a data symbol decision device. In the case of the DFE, the estimated ISI due to previously detected symbols is computed using B feedback taps (B_k) and subtracted off symbol-by-symbol [37].

MIMO

Multiple-Input Multiple-Output (MIMO) is a scheme of multiple antennas transmitting or receiving the signal. The purpose of this scheme is to reduce the bit error rate (BER) and increase the transmission ratio. To achieve a higher data throughput and link range, there are no needs to increase the bandwidth or the transmitter power. This technology allows a higher spectral efficiency. The antennas, at the transmitter and at the receiver, must have sufficient distance to ensure an adequate decorrelation of the signals. There are plenty of combinations between the antennas in transmitter or at the receiver, as shown below

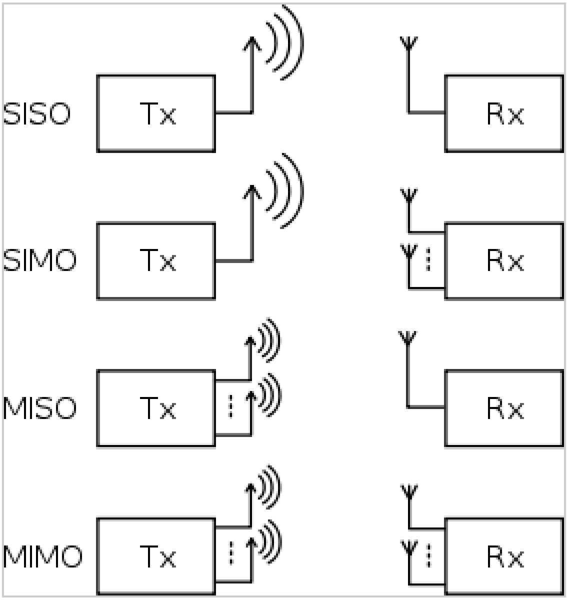

Figure 10 – SISO, SIMO, MISO and MIMO techniques [44]

Single-Input Single-Out (SISO) corresponds to one antenna transmitting and one receiving. Single-Input Multiple-Output (SIMO) means one antenna transmitting and multiple antennas receiving and Multiple-Input Single-Output (MISO) is the opposite of SIMO. A protocol can combine between these four schemes.

Channel estimation

Channel estimation processing is required for accomplishing coherent detection at the receiver [40]. This channel estimation is important for the system to work reliably. These estimates can be obtained with the help of training symbols that are multiplexed with the data. These training symbols are called pilots. It is desirable to reduce the overheads required for channel estimation because this approach can result in an inefficient use of bandwidth. There are two methods of pilot symbols transmission: the data multiplexed method or the implicit method.

The data multiplexed pilots technique consists in the insertion of pilot symbols into to the modulated symbols sequence. In the scheme the pilot symbols are randomly introduced with data symbols in the same structure.

The implicit pilots technique relies on the idea of pilot embedding where a pilot sequence is summed to the data sequence and both are transmitted at the same time. This technique demands that some power to be spent on the pilot sequence but allows to increase the pilots' density without sacrificing the system capacity [40]. The biggest problem on the technique of implicit pilots transmission relies on the interference that can occur between data and pilots which might be high, especially when employing multiple antennas schemes since each pilot symbol will be affected by interference of several data symbols simultaneously [40]. The pilots can interfere with the data symbol as well. This can lead to substantial performance degradation and to irreducible noise.

For both methods, the transmitter chain is the same like we show in figure 16.

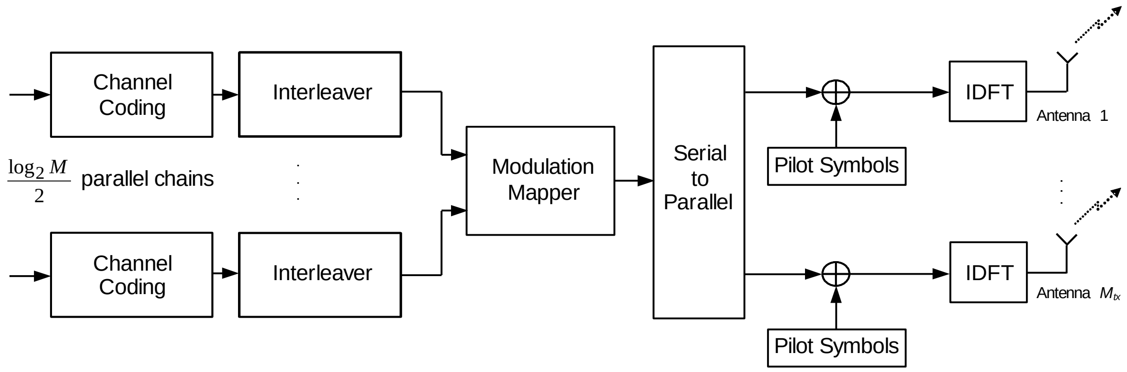

Figure 11 – Transmitter chain [40]

The input streams depend of the modulation that we are using. There are $\frac{1}{2}\log_2 M$ parallel chains. The parallel chains are used in Hierarchical Constellations (chapter 3). Each stream is encoded, interleaved and mapped into the constellation symbols. After the modulation, the pilots are inserted. The insertion of the pilots depends of the technique we are using (data multiplexed pilots or implicit pilots). We can see the difference next. The insertions of the pilots are followed by an IDFT (Inverse Discrete Fourier Transform) with the purpose of converting the signal to time domain. Finally the resulting stream is split into several smaller streams that are transmitted by M_{tx} antennas.

Data Multiplexed Pilots

The Data Multiplexed Pilots method consists in the insertion of pilots into the data stream. The frame structure is shown below.

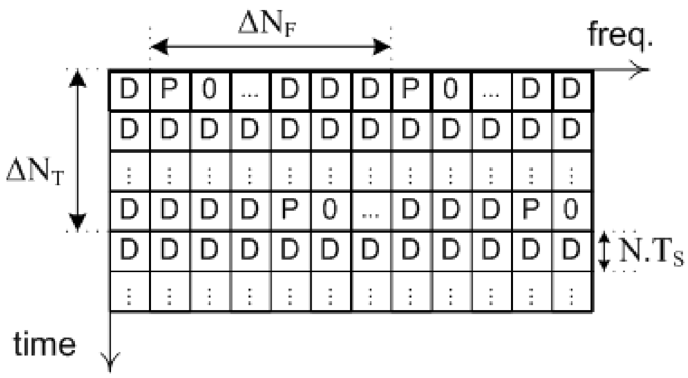

Figure 12 - Data Multiplexed Pilot frame structure (P – pilot symbol; D – data symbol; T_s – symbol duration; N – number of carriers;) [40]

If the scheme adopted is a MIMO, to mitigate the interference between pilots of different transmitting antennas, the pilots are multiplexed in FDM (Frequency Division Multiplexing). This means that all pilot symbols have a different sub-carrier. Data symbols are not transmitted on reserved sub-carriers for pilots in any antenna.

Before being transmitted, the sequences of symbols are converted to the time domain through $\{x_{i,l}^{m}, i = 0,1, \dots, N-1\} = IDFT\{S_{k,l}^{m}, k = 0,1, \dots, N-1\}$, where $S_{k,l}^{m}$ is the symbol transmitted by the k^{th} sub-carrier of the l^{th} OFDM block using antenna m. The transmitted OFDM signals are then expressed as

$$x^{m}(t) = \sum_{l} \sum_{i=-N_G}^{N-1} x_{i,l}^{m}\, h_T(t - iT_s) \quad (10)$$

Where T_s is the symbol duration, N_G is the number of samples at the cyclic prefix using OFDM and $h_T(t)$ is the adopted pulse shaping filter [40].

<u>Implicit Pilots</u>

The frame structure for the implicit pilots is different than the last one. The image below shows the frame structure.

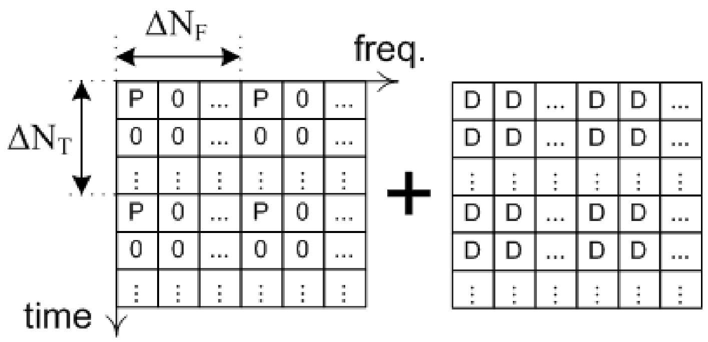

Figure 13 - Implicit Pilot frame structure (P – Pilot symbol; D – Data symbol) [40]

The implicit pilots are generated using a grid with a spacing of ΔN_T symbols in the time domain and ΔN_F symbols in the frequency domain. As we can see in the image above, the pilot symbols and the data symbols are not multiplexed. Similarly to the data multiplexed pilot method, the pilot symbols in different antennas are not transmitted over the same sub-carrier. FDM is employed to avoid interference between the pilot symbols in different antennas. Transmitted sequences are given by $X_{k,l}^{m} = S_{k,l}^{m} + S_{k,l}^{m,Pilot}$, where $S_{k,l}^{m,Pilot}$ is the implicit pilot transmitted over the k^{th} sub-carrier in the l^{th} OFDM block using antenna m. Before being transmitted, the sequence is converted to time domain through the process $\{x_{i,l}^m, i = 0,1,\dots,N-1\} = IDFT\{X_{k,l}^m, k = 0,1,\dots,N-1\}$. The transmitted OFDM signal is expressed in the same format as for the data multiplexed pilot, $x^m(t) = \sum_l \sum_{i=-N_G}^{N-1} x_{i,l}^m \, h_T(t - iT_s)$.

Turbo codes

The turbo codes are a class of forward error correction[1] (FEC) codes. The turbo codes were designed to achieve reliable communication over a limited bandwidth or latency in the presence of a channel with a high noise. Turbo codes have been used in satellite communications and in UMTS where the noise is high. The main characteristic of the turbo codes is that they almost take full advantage of the channel capacity and they were the first does it.

Next we will briefly describe the turbo encoder and decoder.

<u>Turbo Encoder</u>

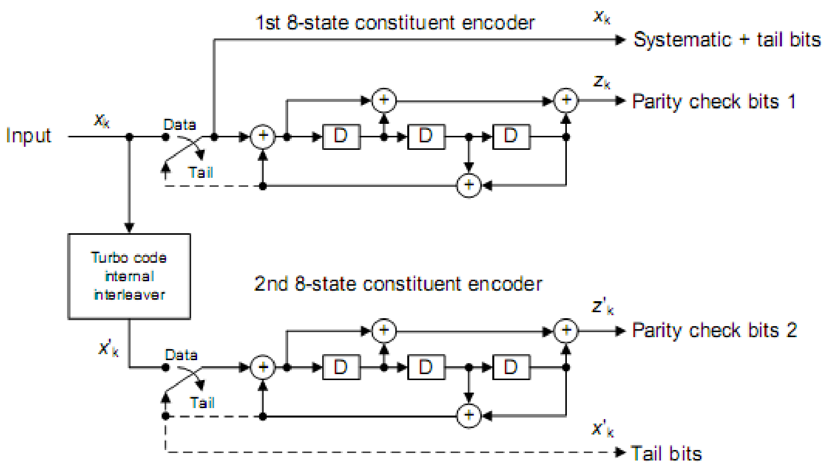

Figure 14 - Turbo Encoder structure for the rate of 1/3. D is the encoders shift registers [41]. 3GPP specified.

The image above represents the structure of a Turbo Encoder block with a rate of 1/3. The rate means the percentage of bits that are original data. The other 2/3 is redundant data to help the receiver to detect and correct a possible error. The structure consists in two 8-state constituent encoders and an internal interleaver. This specific system produces a recursive Parallel Concatenated Convolutional Code (PCCC). Each constituent has a shift register of

[1] FEC is a system of controlling the error in a data transmission. Usually in this kind of system, the transmitter generates redundant data to its messages. The redundant data is known as checksum and in FEC systems are useful and desired because it helps the error detection and correction at the receiver. The detection and correction of the errors is limited to a certain number of errors.

length 3 that can represent 8 different states. Each of the eight states depends on the input bits. In the first constituent encoder receives input bits directly and the other constituent encoder receives input bits from the interleaver. For each input, three outputs are generated. This rate can be altered depending on the puncturing [2]of bits and tail bits from the second constituent encoder. This system is recursive so one error in a bit will result in several error in the parity check bits.

Turbo Decoder

The purpose of the Turbo Decoder is to reestablish the transmitted data from the original bit stream even if the received bit stream is corrupted. The turbo decoder structure is shown below:

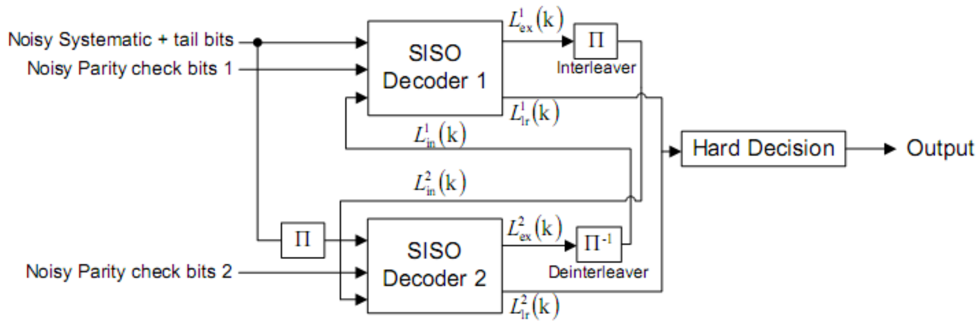

Figure 15 - Turbo Decoder structure where the two decoders are soft-input soft-output (SISO) [41]

There are three types of inputs in the SISO Decoders blocks: systematic bits, parity check bits 1 and 2. Each of the parity check bits are for the different SISO Decoders blocks. The SISO Decoder 1 block use the systematic bits, the parity check bit 1 and information from the SISO Decoder 2 block to estimate a bit sequence. These inputs results in two outputs: extrinsic information L_{ex}^1 and log-likelihood ratio (LLR) L_{Ir}^1. The extrinsic information is an input in the SISO Decoder 2 such as systematic bits and parity check bits 2 but the extrinsic information and the systematic bits are both interleaved before the SISO Decoder 2 block. The outputs of the SISO Decoder 2 block are extrinsic information L_{ex}^2 and a LLR L_{Ir}^2. The L_{ex}^2 is de-interleaved and used as an input in the SISO Decoder 1 block. This L_{ex}^2 in the SISO Decoder 1 block represents the beginning of the second iteration of the decoding. The two LLRs from the SISO Decoder 1 and 2 blocks are used to make a hard decision on the bit sequence. The

[2] Puncturing is a technique based on channel properties to add and remove parity bits. The reasons of using puncturing in turbo coding are to the number of coded bits fit the available bits in the channel and to make different redundancy versions, adding more parity bits.

hard decision consists in assigning the value 0 or 1 to the LLRs. The number of iterations to provide a good estimation of the bit sequence depends on the type of the encoder that was used.

LTE

The Long Term Evolution (LTE) is known as 3.75G of mobile telecommunications networks. The LTE is a project of the 3^{rd} Generation Partnership Project (3GPP) and provides an uplink speed of up 50 Mbps and downlink speed of up to 100 Mbps. The LTE was designed to carrier needs of high-speed and data and media transport as well as high-capacity voice support. When we compare LTE with previous technologies, the LTE introduced several new improvement techniques. The technologies in LTE that permit the system to operate more efficiently are:

- Orthogonal Frequency Division Multiplexing (OFDM).
- Multiple-Input Multiple-Output (MIMO).
- System Architecture Evolution (SAE).

The OFDM is explained in the beginning of this chapter and is incorporated into LTE with the purpose of enabling high data bandwidths. LTE uses different access schemes between the downlink and the uplink. The downlink uses OFDM Access (OFDMA) while Single Carrier with Frequency Division Multiple Access (SC-FDMA) is used in uplink. The main goal of using the SC-FDMA in LTE is to improve the battery life of the mobile handsets because the peak to average power ratio (PAPR) is small in SC-FDMA and the more constant power enables high radio-frequency (RF) power amplifier efficiency in the mobile terminal. The choice of the bandwidth is a key parameter associated to the OFDM in LTE. The bandwidth influences the number of carriers available that can be accommodated in the OFDM signal. The channel capacity achieves the best performance when the bandwidth is the biggest available.

The MIMO is the capacity to send and receive data from multiple antennas. This technology was developed to mitigate the problem of previous telecommunications systems has encountered multiple signals arising from the many reflections. Using MIMO, these additional signal paths can be used to advantage and are able to be used to increase the throughput [22]. To distinguish the different paths it is necessary to use multiple antennas. The schemes available in LTE are showed in table 1. The mobile handset introduces a limitation because the number of antennas should be placed at least a half wavelength apart (to not interfere with each others). The baseline of the downlink in LTE is two antennas at the transmitter and two at receiver but configurations with 4x4 schemes are also being considered. In uplink is applied a scheme called Multi-User MIMO (MU-MIMO). The MU-MIMO exploits the availability of multiple independent radio terminals in order to enhance the communication capabilities of each individual terminal [23].

To improve the LTE performance when compared with previous systems, it was necessary to evolve the system architecture. The most important change was that a number of functions previously handled by the core network have been transferred out to the periphery [22]. With this change latency times were reduced and data can be routed more directly to the destination.

Table 1 - LTE specification overview [20][22]

Peak downlink speed 64-QAM (Mbps)	100 (SISO), 172 (2x2 MIMO), 326 (4x4 MIMO)
Peak uplink speeds (Mbps)	50 (QPSK), 57 (16QAM), 86 (64QAM)
Data type	All packet switched data (voice and data).
Channel bandwidth (MHz)	1.4, 3, 5, 10, 15, 20
Duplex schemes	FDD and TDD
Mobility	0 – 15 km/h (optimized) 15 – 120 km/h (high performance)
Latency	Idle to active less than 100 ms Small packets ~10 ms
Spectral efficiency	Downlink: 3 – 4 times Rel 6 HSDPA Uplink: 2 – 3 times Real 6 HSUPA
Access schemes	Downlink: OFDMA Uplink: SC-FDMA
Modulation types supported	QPSK, 16-QAM, 64-QAM (Downlink and uplink)
Antenna configuration supported	Downlink: 4x4, 4x2, 2x2, 1x2, 1x1 Uplink: 1x2, 1x1
Coverage	Full performance up to 5 km Slight degradation 5 km – 30 km Operation up to 100 km should not be precluded by standard

The schemes employed in this standard vary slightly between the uplink and the downlink. The reason is to keep the terminal cost low and the complex signal processing should be far away from the terminals as well.

The LTE is prepared to use Frequency Division Duplex (FDD) or Time Division Duplex (TDD) with the purpose communicating in both directions simultaneously.

LTE Advanced

The LTE Advanced is a standard which is an evolution of LTE. This new standard belongs to the fourth generation (4G). LTE Advanced arose to keep the pace of cellular networks constant evolution. The main headlines of the LTE are:

- Speed data rate: downlink – 1 Gbps; uplink – 500 Mbps.
- Spectrum efficiency: 3 times greater than LTE.
- Peak spectrum efficiency: downlink – 30 bps/Hz; uplink – 15 bps/Hz.
- Spectrum use: the ability to support scalable bandwidth use and spectrum aggregation where non-contiguous spectrum needs to be used.
- Latency: from Idle to connected in less than 50 ms and then shorter than 5 ms one way for individual packet transmission.
- Cell edge user throughput to be twice that of LTE.
- Average user throughput to be 3 times that of LTE.
- Compatibility: LTE Advanced shall be capable of interworking with LTE and 3GPP legacy systems [24].
- Hybrid OFDMA and SC-FDMA in uplink.
- Coordinated multipoint (CoMP) transmission and reception.
- UE Dual TX antenna solutions for SU-MIMO and diversity MIMO [27].

The three main technologies to achieve the required high data throughput are OFDM, SC-FDMA and MIMO such as in LTE. The number of antennas used in LTE MIMO increased. With the number of antennas increasing, techniques such as beamforming[3] may be used to enable the antenna coverage to be focused where it is needed. The core network has to change

[3] Beamforming is a signal processing technique used in sensor arrays for directional signal transmission or reception.

and the objective is to bring the network closer to the user by adding low power nodes such as picocells[4] and femtocells[5]. The network will become optimized and heterogeneous.

To achieve higher data rates than in the first release of LTE, the method adopted is carrier aggregations or sometimes channel aggregation. With this method, it is possible to utilize several carriers and increase the overall transmission bandwidth with it. Using carrier aggregation means that several carrier will be aggregated on the physical layer to achieve the required bandwidth.

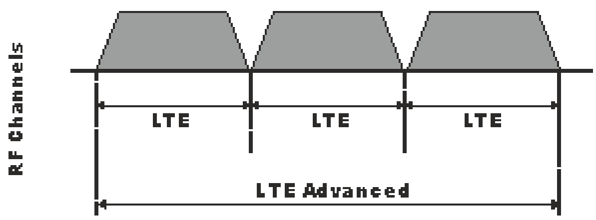

Figure 16 - LTE Carrier Aggregation [9]

A system that supports LTE Advanced must support LTE first release so in LTE each component appears as an LTE carrier but in LTE Advanced is processed as an aggregate.

The Coordinated Multipoint (CoMP) is a technology that is being developed to incorporate the LTE Advanced. This technology consists in transmitting or receiving data from several base stations. When using CoMP the throughput values are higher than no CoMP is used.

Higher data rates are easy to maintain close to the base station (BS), the problem emerges when the user is near the edge of the cell. The issue is not only the far distance to the base station but also the interference of the other BSs. The CoMP requires close coordination between the BSs. The BSs dynamically coordinate themselves to provide joint scheduling and processing of the received signals.

[4] A picocell is a small cellular base station typically covering a small area, such as in-building (offices, shopping malls, train stations, etc.), or more recently in-aircraft. In cellular networks, picocells are typically used to extend coverage to indoor areas where outdoor signals do not reach well, or to add network capacity in areas with very dense phone usage, such as train stations [25].

[5] Femtocell is a small cellular base station, typically designed for use in a home or small business. It connects to the service provider’s network via broadband [26].

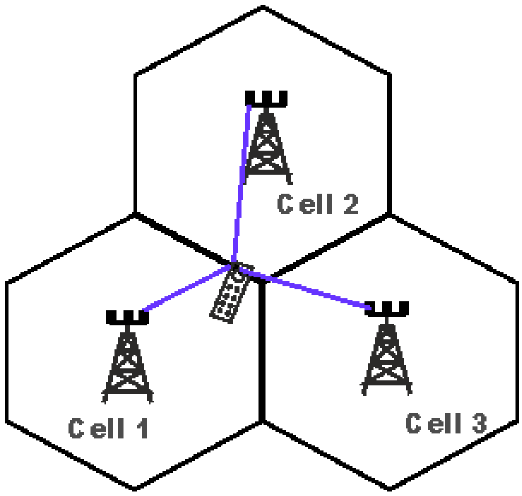

Figure 17 - LTE Advanced CoMP

In the Figure 4 we can see an example of the CoMP being used by a mobile terminal. The mobile terminal is transmitting/receiving data from three BSs to increase the throughput and the signal transmission/reception.

Relay is being considered in LTE Advanced to ensure that an excellent performance is achieved to enable the expectations of the users. The relay is another technology to mitigate the issues of the users in the edge of the cell. Relay consists in receiving the signal, demodulating, decoding the data (apply any error correction) and re-transmit the signal. This is much better than repeaters because relays can reduce the signal-noise ratio compared with the repeaters. There are two types of relaying in LTE Advanced:

- Type 1 – These LTE relays control their cells with their own identity including the transmission of their own synchronization channels and reference symbols. This ensures backward compatibility.
- Type 2 – These LTE relaying nodes do not have their own cell identity and look like the mail cells.

DVB-SH

The Digital Video Broadcasting for Satellite services to Handhelds (DVB-SH) is a system for delivering IP multimedia content to handheld terminals. Handheld terminals can be mobile phones, PDAs, etc. The content can be delivered via satellite or a cellular network in the S or L band which are below the 3 GHz of frequency. The DVB-SH is a complement to the Digital Video Broadcasting – Handhelds (DVB-H) physical layer standard. The DVB-H is a technical specification of bringing mobile TV to mobile handsets [30]. Both, DVB-SH and DVB-H are based on DVB IP Datacast (IPDC) deliver (which are in broadcast), electronic service guides and service purchase and protection standards.

Below is an image of the entire DVB-SH scheme:

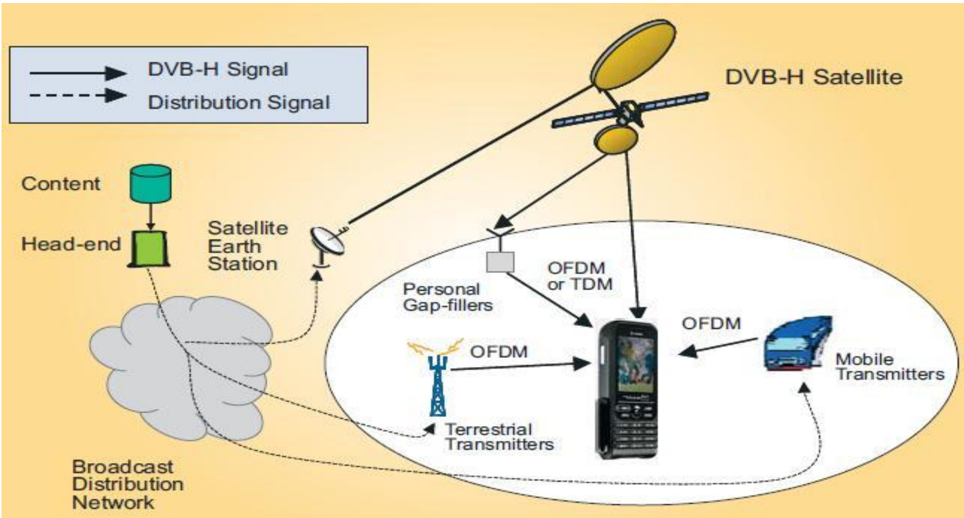

Figure 18 - DVB-SH system [32]

There are three kinds of terrestrial repeaters:

- Terrestrial Transmitters – are broadcast infrastructures transmitters and have the purpose to reach area where the satellite reception is difficult. They may be collocated with mobile cell site or standalone [33].
- Personal Gap-fillers – the typical application is indoor enhancement under satellite coverage. These repeaters have limited coverage providing in local on-frequency retransmission and/or frequency conversion.

- Mobile transmitters – are mobile broadcast infrastructure transmitters creating a moving complementary infrastructure. The typical use is for trains, commercial ships or other environment where the coverage of the satellite transmission and the terrestrial transmission are not guaranteed.

The DVB-SH ensures a wide area covered by the satellite communication known as Satellite Component and combined with a Complementary Ground Component (CGC). The Satellite Component ensures a global coverage while the CGC provides a cellular coverage. There are two operation modes in this system:

- SH-A – use Coded Orthogonal Frequency Division Multiplexing (COFDM) modulation in satellite and terrestrial links with the possibility of single frequency network;
- SH-B – use Time Division Multiplexing (TDM) in the satellite link and COFDM in the terrestrial communication.

Two main classes of satellite payloads may be considered:

- Single DVB-SH physical layer multiplex per high power amplifier (HPA).
- Multiple DVB-SH physical layer multiplex per high power amplifier. This is the case with multibeam satellite with re-configurable antenna architecture based on large size reflectors fed by arrays [33].

In the single DVB-SH, the SH-A requires that satellite transponders operated in quasi-linear mode while the SH-B takes advantage of satellite transponders operated in full saturation. For the second case, the SH-B provides little or no performance advantage over SH-A.

A choose has to be made between physical layer or link layer techniques to combat long interruptions of the line of sight typical in satellite receptions with mobile terminals. The choice is dictated by the cost and required footprint of the memory to implement long interleaver at physical layer. The combination of a short physical interleaver with a long link layer interleaver could be advantageous, especially for handheld terminals (battery life). The long interleaver at physical layer might be better in difficult reception, especially with no battery life restrictions.

Considering spectrum allocation, SH-B needs a dedicated sub-band for satellite transmission, completed with a part of the sub-band available for the terrestrial local component to reenforce reception of the satellite programs [33]. The SH-A allows on terrestrial repetition of the satellite content in the same sub-band. All the remaining sub-bands are available for terrestrial transmission.

WiMAX

The Worldwide Interoperability for Microwaves Access (WiMAX) is a telecommunications protocol that provides fixed and mobile Internet access. The first WiMax release provides up 40 Mbit/s of download speed. The WiMax Forum is the creator and this technology which is based on 802.16 IEEE (Institute of Electrical and Electronics Engineers) standards for the physical and Media Access Control (MAC) layer.

WiMAX uses Orthogonal Frequency Division Multiplexing (OFDM) and the signal incorporates multiples of 128 carriers in a bandwidth from 1.25 MHz to 20 MHz. To maintain orthogonality between the individual carriers the symbol period must be the reciprocal of the carrier spacing [35]. As a result of the narrow bandwidth, the WiMAX technology has a longer symbol period. This longer symbols period is an advantage that helps to mitigate the problem of the multipath interference.

Such as in Long Term Evolution (LTE), the WiMAX adopted Multiple Input Multiple Output (MIMO) techniques to improve the quality of the system. MIMO provides benefits in coverage, power consumption, frequency re-use and bandwidth efficiency.

WiMAX modulation and coding is adaptive, enabling it to vary these parameters according to prevailing conditions. Channel quality feedback indicator is used to determine the modulation and coding to be used. WiMAX is particularly flexible in channel bandwidth, modulation and coding schemes, these three factors can significantly vary the data rates that can be achieved.

Table 2 – Modulation and coding used in WiMAX

Parameter	**Downlink**	**Uplink**
Modulation	BPSK, QPSK, 16 QAM, 64 QAM; BPSK optional for OFDMA-PHY	BPSK, 16 QAM; 64 QAM optional
Coding	**Mandatory:** convolutional codes at rate 1/2, 2/3, 3/4, 5/6 **Optional:** convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6;	**Mandatory:** convolutional codes at rate 1/2, 2/3, 3/4, 5/6 **Optional:** convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6; repetition

	repetition codes at rate 1/2, 1/3, 1/6, LDPC, RS-Codes for OFDM-PHY	codes at rate 1/2, 1/3, 1/6, LDPC

Time Division Duplex (TDD) is the most common in WiMAX systems but Frequency Division Duplex (FDD) is used as well. TDD allows greater efficiency in the use of the spectrum.

Multiple frequencies can be used to transmit in WiMAX. The lower the frequency the lower is the signal attenuation and therefore the multiple frequencies can improve range and better coverage within buildings.

The MAC layer is an essential element within the overall WiMAX software stack. The MAC layer is a sub-layer of the Data Link Layer. This is based in the Open Systems Interconnections architecture (OSI) level 2. The MAC layer provides addressing and channel access control mechanisms that make it possible for several terminals or network nodes to communicate within multi-point network [35].

WiMAX Release 2

The WiMAX Release 2 has several improvements to the previous release. Core enhancement is supported for the Wireless Man-Advanced air interface and the air interface capacity is the double of the previous release. The objective of the WiMAX for the release 2 was to achieve better performances without increase the cost of the network. It is important to upgrade the core network elements but with the aim of spending the less possible.

The upgrading to the Release 2 has two phases. In the first phase, new network elements are introduced: the Advanced Mobile Station (AMS) and the Advanced Base Station (ABS). The second phase consists in the upgrading of the other network elements.

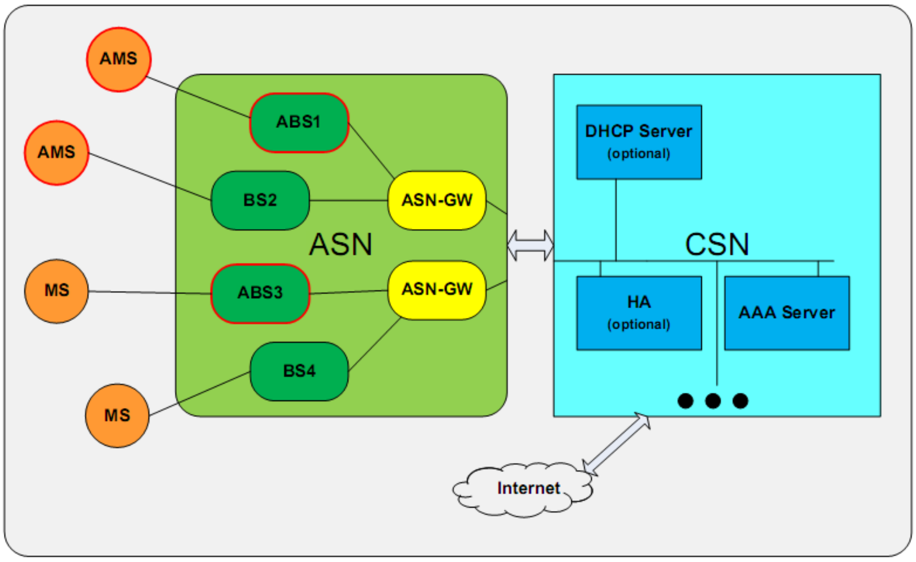

Figure 19 – WiMAX Phase 1 upgrade [36]

The red bordered elements are the two new elements on the WiMAX Release 2. The other elements migrated from the older release.

The ABSs operates in a mixed mode:

- An LZone implementing the legacy 802.16e air interface.
- An MZone implementing the new 802.16m air interface.

The 802.16e/802.16m mixed mode enables a smooth evolution of the network. The 802.16e is basically the use of OFDMA, adaptive modulation and coding and MIMO on the physical layer (PHY). The MAC consists on the Ethernet, Asynchronous Transfer Mode (ATM) and IP encapsulated on the air interface – Convergence Sublayers.

The benefits of this phase 1 are the double throughput in the ABS sector coverage. A new advanced air interface features that are transparent to ASN-GW and CSN.

The phase 2 is the phase to upgrade the others network elements. Upgrading the ASN-GWs provides the ability to offer additional WiMAX 2 services such as identity hiding for AMSs, improve their power management, multiple IP address allocation and improvement of other services such as roaming [36].

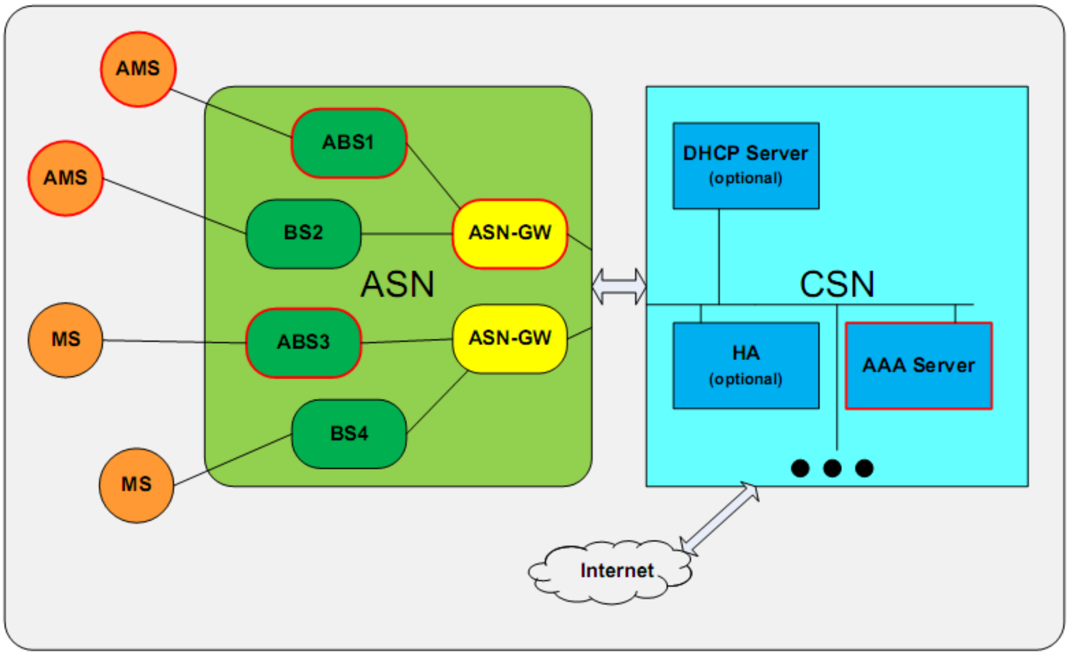

Figure 20 – WiMAX Phase 2 Upgrade supporting Release 2 functionality [36]

The Phase 2 benefits are AMS identity privacy, MS deep power save support with context retention, faster IP address location and optimized mobility management.

Chapter 3 – Enhancement Techniques

Hierarchical Constellations

Hierarchical constellations are a simple technique for achieving multi-resolution in a wireless system [37]. This means than employing hierarchical constellations, we can deliver the same content to several users in a cell. In this study we used two modulations. The modulations were M-ary Phase Shift Keying (M-PSK) and Multilevel Hierarchical Quadrature Amplitude Modulation (M-HQAM). This technique must be used when the information is scalable (video signals) [40]. The different streams of information can be mapped using this type of constellations which use several classes of bits with different error protection. A given user can attempt to demodulate only the more protected bits or also the least protected bits. The least protected bits carry the additional information and the demodulation depends on the propagation conditions.

In a traditional constellation the distance between adjacent symbols is always the same. In this case we call it a uniform constellation otherwise it is called non uniform.

<u>Constellations Design</u>

As was said above, in hierarchical constellations there are two or more classes of bits with different error protection levels onto which different streams of information can be mapped [37]. It is possible to modify the different error protection levels when the distances along the I or Q axis between adjacent symbols are not the same. An example of a hierarchical constellation is showed in figure 21.

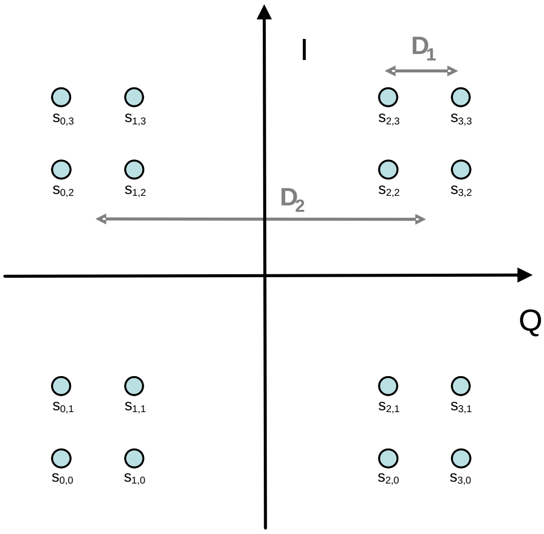

Figure 21 - Signal Constellation for a 16-QAM hierarchical modulation [37]

Taking the 16-HQAM as an example and as in a regular 16-QAM constellation, four bits are required for selecting a symbol. Two bits select one of the four inner QPSK or quadrant while the other two bits select the symbol inside that inner QPSK constellation. In this case there are two classes of bits with different error protection. If the channel conditions are good the receiver can see the constellation as a 16-QAM otherwise it will be seen as a QPSK. If the channel conditions are not good enough to view the 16-QAM constellation, the received bit rate is reduced to half. Each symbol *s* of figure 21 can be written as

$$s = \left(\pm\frac{D_2}{2}\pm\frac{D_1}{2}\right) + \left(\pm\frac{D_2}{2}\pm\frac{D_1}{2}\right)i. \quad (11)$$

Instead of defining a hierarchical constellation through the inner constellation distances it is usually more convenient to characterize it using ratios between these distances [37]. For example, the 16-HQAM constellation of figure 21 can be defined using $k_1 = {}^{D_1}/_{D_2}$ $(0 < k_1)$. Changing k_1 is equivalent to changing the distance D_1 and D_2 modifying the degree of protection of the different bits. A 16-QAM uniform constellation corresponds to $k_1 = 0.5$. This approach can be easily extended to any square M-QAM constellation resulting the following general expression for a symbol

$$s = \sum_{l=1}^{\frac{1}{2}log_2 M}\left(\pm\frac{D_l}{2}\right) + \sum_{l=1}^{\frac{1}{2}log_2 M}\left(\pm\frac{D_l}{2}\right)i, \quad (12)$$

where the number of possible classes of bits with different error protection is $\frac{1}{2}log_2M$. These constellations can be characterized by ratios between the distances of the inner nested constellations as

$$k_i = \frac{D_i}{D_{i+1}}, i = 1, \ldots, \frac{1}{2}log_2M - 1. \quad (13)$$

The previous explanation is adequate for square constellations. However we can also employ rectangular constellations. We can obtain a rectangular constellation when the inner distances along the axis are different or when number of bits mapped to the I and Q branches is not the same. In both cases the number of different error protection levels becomes log_2M.

The expression to build M-QAM constellation is

$$\begin{cases} k_i^I = \frac{D_i^I}{D_{i+1}^I}, i = 1, \ldots, log_2M_{PAM}^I - 1 \\ k_j^Q = \frac{D_j^Q}{D_{j+1}^Q}, j = 1, \ldots, log_2M_{PAM}^Q - 1 \end{cases} \quad (14)$$

with the symbols expressed as

$$s = \sum_{l=1}^{log_2M_{PAM}^I}\left(\pm\frac{D_l^I}{2}\right) + \sum_{l=1}^{log_2M_{PAM}^Q}\left(\pm\frac{D_l^Q}{2}\right)i, \quad (15)$$

Where M_{PAM}^I and M_{PAM}^Q are the number of projected symbols onto the I and Q axis of the constellation, i.e., the sizes of the equivalent PAM (Pulse Amplitude Modulation) constellations. To achieve a square constellation we must have $M_{PAM}^I = M_{PAM}^Q = \sqrt{M}$. Computing the corresponding distances D_i^I and D_i^Q we can build the constellation with specified average symbol energy E_s. The symbol energy is obtained with the following expression

$$E_s = E\left[|s|^2\right] = \frac{4}{M}\sum_{l=1}^{M/4}|s_l|^2 \quad (16)$$

$$= \frac{2}{M_{PAM}^I}\sum_{l=1}^{M_{PAM}^I/2}\left(s_l^I\right)^2 + \frac{2}{M_{PAM}^Q}\sum_{l=1}^{M_{PAM}^Q/2}\left(s_l^Q\right)^2 \quad (17)$$

$$= \frac{2}{M_{PAM}^I}\sum_{l=1}^{M_{PAM}^I/2}\left(\sum_{i=1}^{\log_2 M_{PAM}^I}\left(\pm\frac{D_i^I}{2}\right)\right)^2 + \frac{2}{M_{PAM}^Q}\sum_{l=1}^{M_{PAM}^Q/2}\left(\sum_{i=1}^{\log_2 M_{PAM}^Q}\left(\pm\frac{D_i^Q}{2}\right)\right)^2 \quad (18)$$

$$= \frac{1}{2M_{PAM}^{I}}\left[\sum_{l=1}^{M_{PAM}^{I}/2}\sum_{i=1}^{\log_2 M_{PAM}^{I}}\left(D_i^I\right)^2 + \sum_{l=1}^{M_{PAM}^{I}/2}\sum_{k=1}^{\log_2 M_{PAM}^{I}}\sum_{i=1}^{\log_2 M_{PAM}^{I}}\left(\pm D_k^I\right)\left(\pm D_i^I\right)\right]$$
$$+ \frac{1}{2M_{PAM}^{Q}}\left[\sum_{l=1}^{M_{PAM}^{Q}/2}\sum_{i=1}^{\log_2 M_{PAM}^{Q}}\left(D_i^Q\right)^2 + \sum_{l=1}^{M_{PAM}^{Q}/2}\sum_{k=1}^{\log_2 M_{PAM}^{Q}}\sum_{i=1}^{\log_2 M_{PAM}^{Q}}\left(\pm D_k^Q\right)\left(\pm D_i^Q\right)\right] \quad (19)$$

$$= \frac{1}{4}\left[\sum_{i=1}^{\log_2 M_{PAM}^{I}}\left(D_i^I\right)^2 + \sum_{i=1}^{\log_2 M_{PAM}^{Q}}\left(D_i^Q\right)^2\right] \quad (20)$$

We can combine this last definition of the symbol energy with the definition of the non-uniformity ratios (14) and obtain an expression that only depends on one of the distances on each axis:

$$E_s = \frac{1}{4}\left[\left(D_{\log_2 M_{PAM}^{I}}^{I}\right)^2 + \sum_{i=1}^{\log_2 M_{PAM}^{I}-1}\left(D_{\log_2 M_{PAM}^{I}}^{I}\prod_{j=i}^{\log_2 M_{PAM}^{I}-1}k_j^I\right)^2 + \left(D_{1/2\cdot\log_2 M_{PAM}^{Q}}^{Q}\right)^2 + \sum_{i=1}^{\log_2 M_{PAM}^{Q}-1}\left(D_{\log_2 M_{PAM}^{Q}}^{Q}\prod_{j=i}^{\log_2 M_{PAM}^{Q}-1}k_j^Q\right)^2\right] \quad (21)$$

The first two terms correspond to the average symbol energy in the I branch while the other two refer to the average symbol energy in the Q branch. So we can write

$$E_S = E_S^I + E_S^Q \quad (22)$$

with

$$E_S^{I/Q} = \frac{\left(D_{log_2 M_{PAM}^{I/Q}}^{I/Q}\right)^2}{4}\left[1 + \sum_{i=1}^{log_2 M_{PAM}^{I/Q}-1}\prod_{j=i}^{log_2 M_{PAM}^{I/Q}-1}\left(k_j^{I/Q}\right)^2\right]. \quad (23)$$

The desired distances can then be easily computed using

$$\begin{cases} D_{\log_2 M_{PAM}^{I/Q}}^{I/Q} = \sqrt{\dfrac{4E_s^{I/Q}}{1+\sum\limits_{l=1}^{\log_2 M_{PAM}^{I/Q}-1}\prod\limits_{j=l}^{\log_2 M_{PAM}^{I/Q}-1}\left(k_j^{I/Q}\right)^2}} \\ D_i^{I/Q} = D_{\log_2 M_{PAM}^{I/Q}}^{I/Q}\prod\limits_{j=i}^{\log_2 M_{PAM}^{I/Q}-1}k_j^{I/Q}, \qquad i < \log_2 M_{PAM}^{I/Q} \end{cases} \quad (24)$$

In the following we will show how to apply a similar construction approach and obtain a hierarchical PSK (Phase Shift Keying). The PSK symbols lie on the same circumference on the complex plan, only the phases differ between them. A few signal constellation are showed in figure 22.

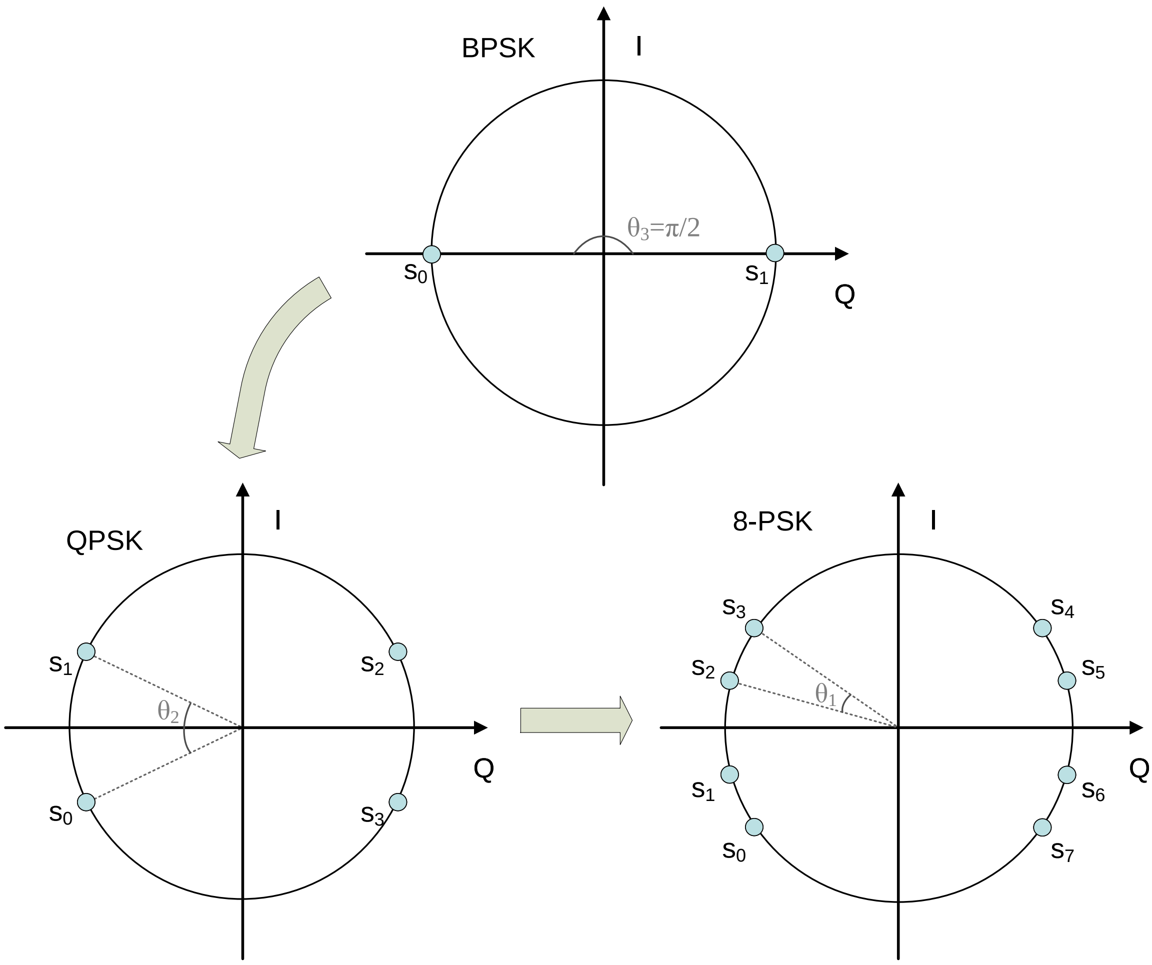

Figure 22 - Signal Constellation construction for an 8-PSK hierarchical modulation [37]

A complex 8-HPSK constellation symbol can be written as

$$s = \sqrt{E_s}\exp\left[\boldsymbol{i}\left(\frac{\pi}{2} \pm \frac{\pi}{2} \pm \frac{\theta_2}{2} \pm \frac{\theta_1}{2}\right)\right] \tag{25}$$

with the non-uniformity ratios defined as $k_1 = {}^{\theta_1}/_{\theta_2}$ and $k_2 = {}^{\theta_2}/_{\theta_3}$. Typically a constellation is defined with $\theta_3 = {}^{\pi}/_{2}$ to minimize the error probability for the most protected bit. We can write any M-HPSK symbol as

$$s = \sqrt{E_s}\exp\left[\boldsymbol{i}\left(\frac{\pi}{2} + \sum_{l=1}^{\log_2 M}\left(\pm\frac{\theta_l}{2}\right)\right)\right] \tag{26}$$

$$= \sqrt{E_s}\exp\left[\boldsymbol{i}\left(\frac{\pi}{2} \pm \frac{\pi}{2} + \sum_{l=1}^{\log_2 M - 1}\left(\pm\frac{\theta_l}{2}\right)\right)\right] \tag{27}$$

with

$$k_i = \frac{\theta_i}{\theta_{i+1}}, \quad i = 1, \ldots, 1/2 \cdot \log_2 M - 1. \tag{28}$$

<u>Transmitter and Receiver Structure</u>

The transmitter chain applied when Hierarchical Constellations are used is shown bellow.

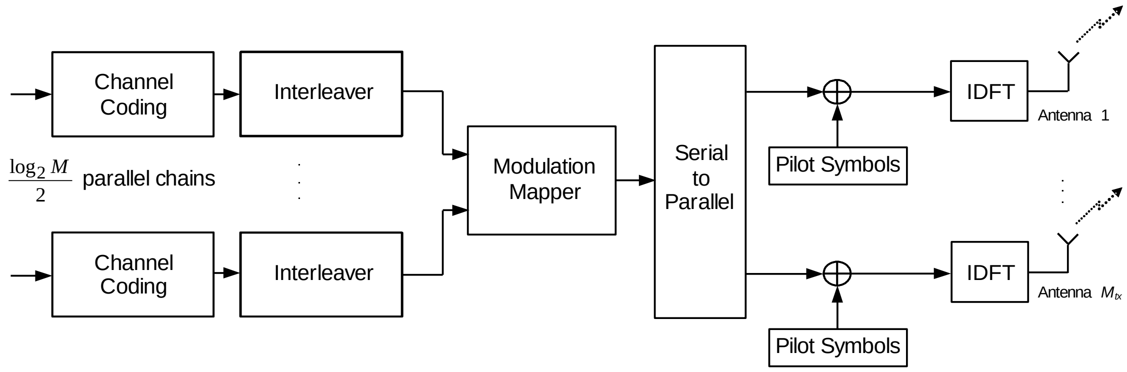

Figure 23 – Transmitter chain for a MIMO-OFDM [40]

The number of parallel chains depends of the constellation. First we start with a Channel Coding block followed by the Interleaver block. The modulation mapper has the purpose of mapping each stream to constellation symbols. The pilots are inserted before the IDFT block. The information can be spread for several antennas.

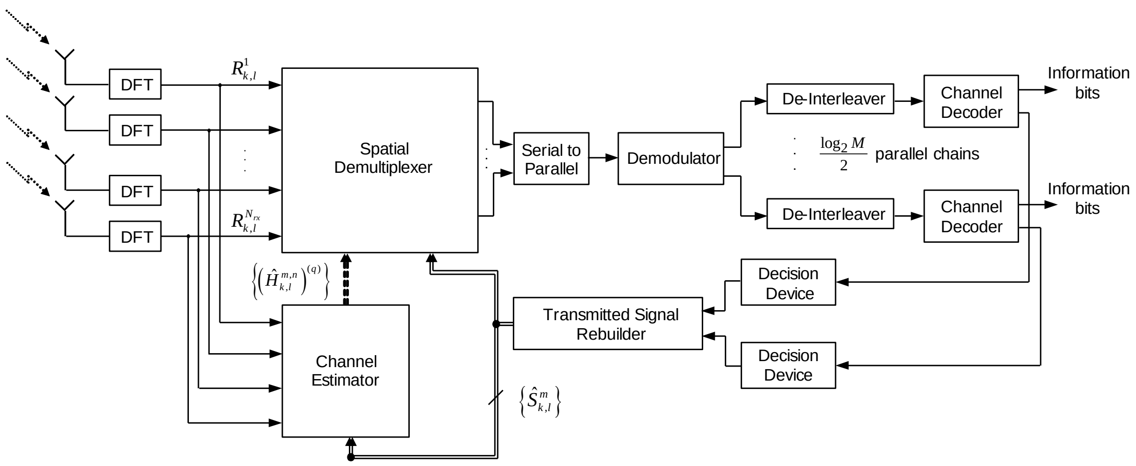

Figure 24 – Iterative receiver structure for data multiplexed pilots [40]

The receiver structure for data multiplexed pilots starts with a DFT block. The Spatial Demultiplexer separates the streams transmitted simultaneously by the multiple antennas. The equalization used in this step can be Minimum Mean Squared Error (MMSE) or Maximum

Likelihood Soft Output (MLSO). Demodulation, De-Interleaver and Channel Decoder are the following blocks. This channel decoder has two outputs. The Channel Estimator input is the log-likelihood (LLR) estimated for the code symbols and the Transmitter Signal Rebuilder performs an interleaving, modulation and a conversion of S/P (the same of the transmitter operation). The reconstructed symbol sequences are used for refinement of the channel estimation and for improvement of the spatial demultiplexing.

To obtain the frequency channel estimation, the receiver applies the following steps in each iteration:

1. The channel estimation between transmit antenna m and receive antenna n for each pilot symbol is simply processed as $\widetilde{H}_{k,l}^{m,n} = \frac{(S_{k,l}^{m,Pilot})^*}{\left|S_{k,l}^{m,Pilot}\right|^2} R_{k,l}^n$ where $S_{k,l}^{m,Pilot}$ corresponds to a pilot symbol transmitted in the k^{th} sub-carrier of the l^{th} OFDM block using antenna m. Obviously not all indexes k and l will correspond to a pilot symbol since $\Delta N_T > 1$ and $\Delta N_F > 1$.
2. The interpolation using a finite impulse response (FIR) filter with length W results in a channel estimates for the same sub-carrier $k,$ transmit antenna m and receive antenna n (time domain positions – index l) that do not carry a pilot symbol, $\widehat{H}_{k,l+t}^{m,n} = \sum_{j=-\lfloor (W-1)/2 \rfloor}^{\lfloor W/2 \rfloor} h_t^j \; \widetilde{H}_{k,l+j\Delta N_T}^{m,n}$, where t is the OFDM block index relative to the last one carrying a pilot (which is block with the index l) and h_t^j is the interpolation coefficients of the estimation filter which depends on the channel estimation algorithm employed (Weiner filter or Low Pass Sinc Interpolator).
3. The channel estimates are computed as (after the first iteration the data estimates can also be used as pilots for channel estimation refinement) $(\widehat{H}_{k,l}^{m,n})^q = \frac{R_{k,l}^n (\hat{S}_{k,l}^m)^{(q-1)^*}}{\left|(\hat{S}_{k,l}^m)^{(q-1)}\right|^2}$. R is the number of iterations in the receiver.

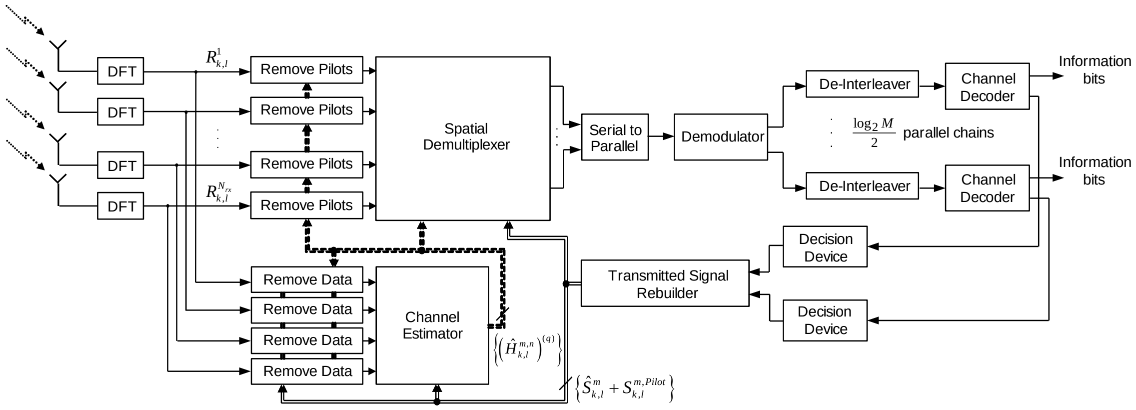

Figure 25 – Iterative receiver structure for implicit pilots [40]

The main difference between the receiver of figure 24 and the implicit pilots receiver (figure 25) relies in the Remove Pilots and Remove Data blocks.

To achieve reliable channel estimation when employing implicit pilots, the receiver must apply the following steps in each iteration and for each pair of antennas:

1. Data symbols are removed from the pilots using $\left(\tilde{R}^n_{k,l}\right) = R^n_{k,l} - \sum_{m'=1}^{M_{tx}} \left(\hat{S}^{m'}_{k,l}\right)^{(q-1)} \left(\hat{H}^{m,n}_{k,l}\right)^{(q-1)}$, where $\left(\hat{S}^{m'}_{k,l}\right)^{(q-1)}$ and $\left(\hat{H}^{m,n}_{k,l}\right)^{(q-1)}$ are the data and channel response estimates of the previous iteration. This step can only be applied after the first iteration (1). In the first iteration the $\left(\tilde{R}^n_{k,l}\right)^1 = R^n_{k,l}$;
2. The receiver uses a moving average with size W to process the channel frequency response estimate as follows $\left(\hat{H}^{m,n}_{k,l}\right)^{(q)} = \frac{1}{W} \sum_{l'=l-\lfloor W/2 \rfloor}^{l+\lceil W/2 \rceil - 1} \frac{\left(\tilde{R}^n_{k,l'}\right)^{(q-1)}}{S^{m,Pilot}_{k,l'}}$;
3. After the first iteration if a fully dense pilot distribution is not employed (i.e. $\Delta N_F \neq 1 \cup \Delta N_T \neq 1$) then the data estimates can also be used as pilots for channel estimation refinement.

CRM

The Complex Rotation Matrix (CRM) is a technique for achieving signal space diversity where the goal is to improve the performance in band-limited wireless communication system. This technique can be used in an Orthogonal Frequency Division Multiplexing (OFDM)/ Orthogonal Frequency Division Multiplexing Access (OFDMA) and take advantage of the typical frequency response channel in mobile communication environments. Turbo or Low-Density Parity-Check (LDPC) codes can be combined with the signal space diversity provided by CRM.

When powerful channel coding schemes are employed, the OFDM can have a brilliant performance. However the required code rate must be low reducing the system's spectral efficiency, [43]. The performance of an OFDM system decreases whether we use an uncoded system or when high coding rates are employed. In this case, to take advantage of the diversity effects inherent to a severely frequency selective channel, we can associate a specific symbol to different subcarriers. To do this we use a simple technique called RRM (Real Rotation Matrix). The RRM technique allows significant gains. Unfortunately, the RRM technique has a flaw since it was designed to spread a symbol over only two subcarriers. To overcome the RRM flaw we can adopt the *Hadamard* Matrix (HM). The HM technique allows spreading the symbol over a large number of subcarriers. This technique is used in fully multicarrier code division multiplexing schemes. In this thesis, we choose to study CRM because it has more potential do achieve better performance than HM.

<u>Transmitter</u>

The next figure shows the block diagram of an OFDM-MIMO transmitter with CRM incorporated.

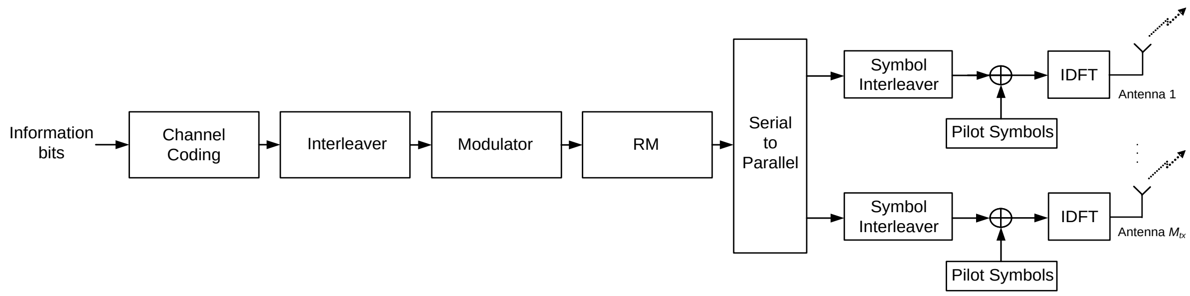

Figure 26 - Transmitter block diagram [43]

An information block is encoded, interleaved, mapped according the constellation symbols and after these three process we apply a Rotation Matrix (RM) by grouping the symbols and multiplying them by rotation matrix $A_{M_{CRM}}$. The matrix $A_{M_{CRM}}$ belongs to the family of the orthonormal (OCRM) or non-orthonormal (NCRM) complex matrices, which are defined as

$$\mathbf{A}_{M_{OCRM}} = \begin{cases} \begin{bmatrix} e^{j\varphi} & je^{-j\varphi} \\ -je^{j\varphi} & e^{-j\varphi} \end{bmatrix} / \left|\mathbf{A}_2\right|^{1/2}, M_{OCRM} = 2 \\ \left|\mathbf{A}_2\right| = \det(A_2) = 2 \\ \begin{bmatrix} \mathbf{A}_{M_{OCRM}/2} & \mathbf{A}_{M_{OCRM}/2} \\ \mathbf{A}_{M_{OCRM}/2} & -\mathbf{A}_{M_{OCRM}/2} \end{bmatrix} / \left|\mathbf{A}_{M_{OCRM}}\right|^{1/M_{OCRM}}, M_{OCRM} > 2 \end{cases}$$

$$\mathbf{A}_{M_{NCRM}} = \begin{cases} \begin{bmatrix} e^{j\varphi} & e^{-j\varphi} \\ -e^{-j\varphi} & e^{j\varphi} \end{bmatrix} / \left|\mathbf{A}_2\right|^{1/2}, M_{NCRM} = 2 \\ \left|\mathbf{A}_2\right| = \det(A_2) = 2\cos(\varphi) \\ \begin{bmatrix} \mathbf{A}_{M_{NCRM}/2} & \mathbf{A}_{M_{NCRM}/2} \\ \mathbf{A}_{M_{NCRM}/2} & -\mathbf{A}_{M_{NCRM}/2} \end{bmatrix} / \left|\mathbf{A}_{M_{CRM}}\right|^{1/M_{NCRM}}, M_{NCRM} > 2 \end{cases} \quad (29)$$

when $M_{OCRM} = M_{NCRM} = M_{CRM} = 2^2$ $(n \geq 2)$ and with $|A_2| = \det(A_2)$, $\left|A_{M_{CRM}}\right| = \det(A_{M_{CRM}})$ and φ being the rotation angle [43]

To obtain a rotated super-symbol we have to apply this formula $X = A_{M_{CRM}}.\ S$, where S is a set of all modulated symbols present in the information composing the super-symbol. As we can observe in the figure 26 the resulting sequence is split into M_{tx} parallel streams which after the split are interleaved. This interleaving has the purpose of explore the OFDM transmission characteristics in a severe time-dispersive environment. Due to these characteristics the channel frequency response can change significantly between different subcarriers of the OFDM signal.

The samples are split in different antennas so the interleaver insures that samples of a super-symbol transmitted in the same antenna are mapped to distant subcarriers and take advantage of the diversity in the frequency domain. Finally we convert the signal to the time domain with an IDFT (Inverse Discrete Fourier Transform) before being transmitted by the respective antennas. The pilot symbols are inserted in the signal before the IDFT block.

<u>Receiver</u>

Figure 27 below represents the receiver block diagram for a MIMO standard with N_{rx} receiving antennas.

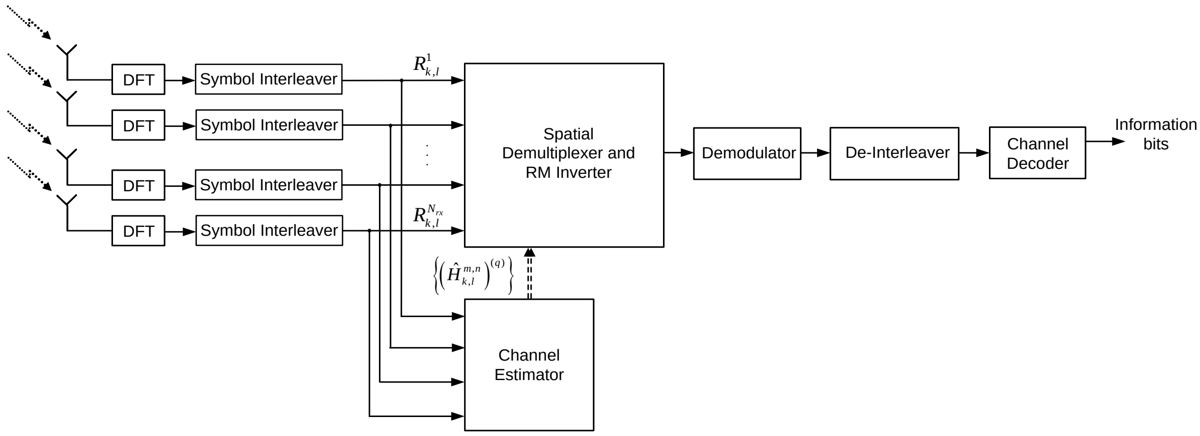

Figure 27 - Receiver Structure [43]

The sampled signal (with the cyclic prefix removed) is converted to the frequency domain through a DFT (Discrete Fourier Transform) block, with one DFT used in each receiving antenna. After the DFT the symbols are de-interleaved. Assuming that the cyclic prefix is longer than the overall channel impulse response, each received super-symbol can be represented using the following matrix notation $R = H.X + N$, where H is the frequency response channel matrix [43]. Matrix H can be defined as a block wise diagonal matrix as

$$\mathbf{H} = \begin{bmatrix} \mathbf{H}_1 & & \mathbf{0} \\ & \ddots & \\ \mathbf{0} & & \mathbf{H}_{M_{CRM}/M_{tx}} \end{bmatrix} \tag{30}$$

with,

$$\mathbf{H}_k = \begin{bmatrix} H_k^{1,1} & \cdots & H_k^{1,M_{tx}} \\ \vdots & \ddots & \vdots \\ H_k^{N_{rx},1} & \cdots & H_k^{N_{rx},M_{tx}} \end{bmatrix}, \quad k = 1,\ldots,M_{CRM}/M_{tx} \tag{31}$$

Index k represents a sub-carrier position. Due to the symbol interleaver and de-interleaver the sub-carrier denoted by k may not be necessarily adjacent. To simplify we will assume M_{CRM} is a multiple of the number of transmitting antennas M_{tx}. Finally N is a vector containing Additive White Gaussian Noise (AWGN) samples.

The super-symbol's samples enter in the Spatial Demultiplexer and CRM Inverter block which has the purpose of separating the streams transmitted simultaneously by the multiple antennas and invert the rotation applied at the transmitter. Two alternative methods are employed in this thesis, MMSE equalizer and the MLSO detector.

The MMSE criterion is applied to each individual sub-carrier using

$$\hat{X}_k = (H_k)^H.[H_k(H_k)^H + \sigma^2 l]^{-1} R_k \tag{32}$$

where $\hat{X}_k$ is the $M_{tx}\ x\ 1$ vector with the estimated subset of coordinates from the super-symbol mapped to a sub-carrier k. R_k is the $N_{rx}\ x\ 1$ received signal vector in the sub-carrier k with one different receive antenna in each position and σ^2 is the noise variance [43]. The component symbol estimates are computed through

$$\hat{S} = \left(A_{M_{CRM}}\right)^{-1}.\hat{X}. \tag{33}$$

The MLSO criterion is applied to each symbol and computed as

$$\widehat{S_l} = E[S_l|R] \tag{34}$$

$$= \sum_{S_i \in \Lambda} s_i.P(S_l = s_i|R) \tag{35}$$

$$= \sum_{s_i \in \Lambda} s_i.\frac{P(S_l=s_i)}{p\ (R)} p(R|S_l = s_i), \tag{36}$$

where $p(.)$ is a PDF (probability density function), $P(.)$ is a discrete probability, $E[.]$ is an expected value and s_i is a constellation symbol from the modulation alphabet Λ. If the symbols has the same probability of appear, we have $P(S_l = s_i) = {}^1/_M$, where M is the constellation size. The PDF values can be computed as

$$p(R|S_l = s_i) = \frac{1}{M^{M_{CRM}-1}} \sum_{S_l^{compl} \in \Lambda^{M_{CRM}-1}} p\left(R|S_l = s_i, S_l^{compl}\right) \tag{37}$$

with

$$p\left(R|S_l = s_i, S_l^{compl}\right) = \frac{1}{(2\pi\sigma^2)^{N_{rx}{}^{M_{CRM}}/_{M_{tx}}}} exp\left[\sum_{n=1}^{N_{rx}{}^{M_{CRM}}/_{M_{tx}}} - \frac{\left|R_n - H(n,:).A_{M_{CRM}}.s\right|^2}{2\sigma^2}\right], \tag{38}$$

where S_l^{compl} is a $(M_{CRM} - 1)x1$ vector representing a possible combination of symbols transmitted together with S_l in the same super-symbol, s is a $M_{CRM}x1$ vector comprising S_l^{compl} and s_i, R_n is the n^{th} received sample in $R = H.X + N$ and $H(n,:)$ is the n^{th} line of channel matrix H [43].

After we apply one of these two methods, each symbol is serialized, demodulated and de-interleaved before entering the channel decoder block which produces the final estimate of the information.

Chapter 4 – Experimental Results

The chapter 4 contains the results of the study. These results were obtained in OFDM and SC-FDE systems and the purpose was to study the techniques previously discussed – CRM, hierarchical constellation and channel estimation.

Simulation Results

The parameters used in these simulations are from LTE standard but the conclusion will be the same for WiMAX or DVB-SH. For these results were used two simulators, a Single Carrier with Frequency Division Equalization (SC-FDE) and Orthogonal Frequency Division Multiplexing (OFDM) simulator. The simulators were implemented in Matlab tool/programming language. Monte Carlo method was applied in all simulation and perfect synchronism was assumed.

The scope of this thesis was the development and study of hierarchical constellation for QAM and PSK modulations as well as CRM. The development of hierarchical constellation and CRM was done in the OFDM simulator. Turbo Codes was developed for the SC-FDE simulator

The results are shown below:

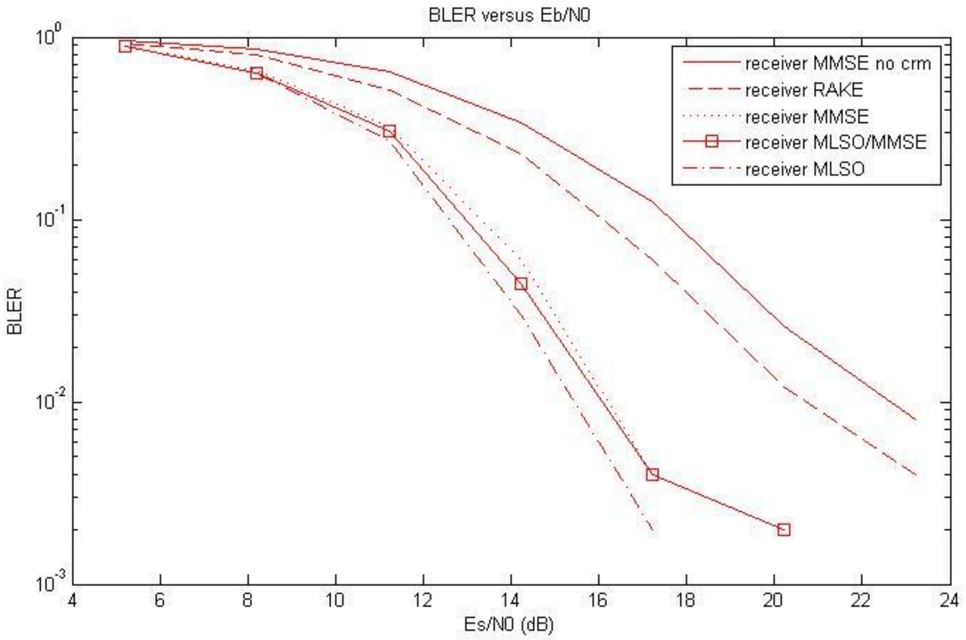

Figure 28 – Difference between the several receivers. QPSK and SISO simulation. OFDM system

Table 3 – Simulation parameters

CRM angle	$\frac{\pi}{6}$
CRM size	2 (MMSE and no CRM) and 4
Channel estimation	PSAM (perfect estimation)
Bits per block	6662
Coding	Turbo coding (12 turbo iterations)
Coding Rate	5/6

Figure 28 shows us the performances of different receiver types. The MLSO/MMSE is an iterative receiver that applies the MMSE receiver first followed by a MLSO. The MMSE is applied to each super-symbol component. There were two simulations for the Minimum Mean Square Error (MMSE) receiver and the difference is whether CRM is used or not. The purpose of this figure is to show that CRM brings a better performance. Of all receivers the one with the worst performance is the MMSE without CRM followed by the RAKE with CRM. The MMSE with CRM, MLSO/MMSE and regular MLSO have similar performances. The one with better performance of these last three receivers is MLSO. The only issue is the complexity of this receiver. The MLSO/MMSE has a slight improvement when comparing with the MMSE with CRM. In the MLSO/MMSE, the complexity is lower when compared with the MLSO.

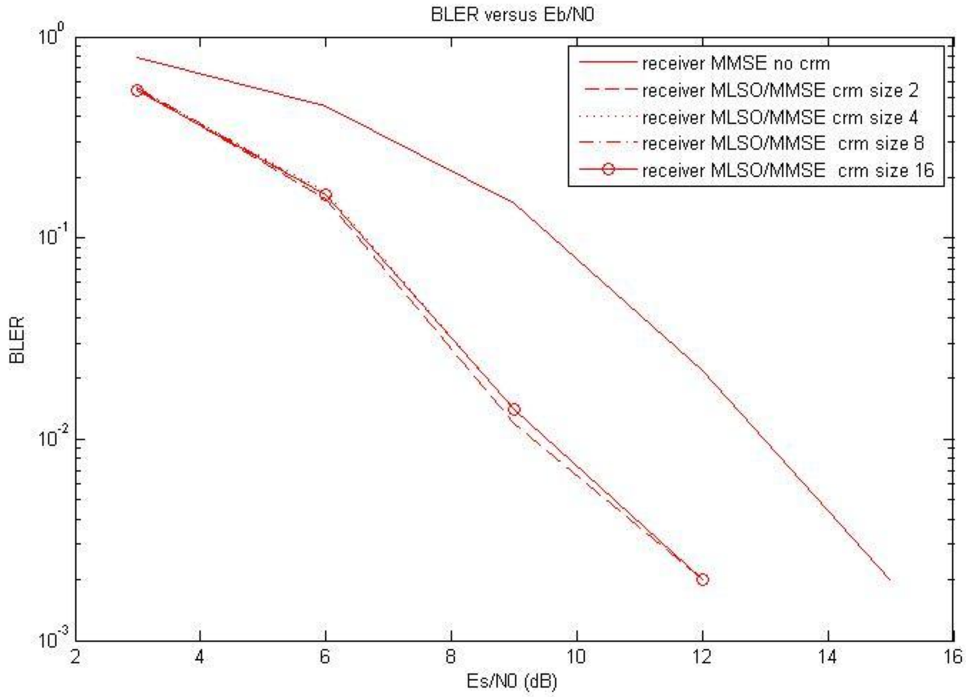

Figure 29 – Figure to show the CRM block size impact (rate ½ - QPSK SISO). OFDM system

Table 4 – Simulation parameters

CRM angle	$\frac{\pi}{6}$
Channel Estimation	PSAM (perfect estimation)
Bits per block	3996
Turbo iterations	4
Receiver iterations	3
Coding rate	1/2

Figure 29 has the purpose to show the difference of the CRM block size. The receiver with a worst performance is MMSE without CRM. This receiver is just to show the difference between the MMSE without CRM and MLSO/MMSE with CRM. The only differences between the others curves are the CRM block size. All of them show a similar performance. In this condition there is no difference between the CRM block sizes but the coding rate is low ½.

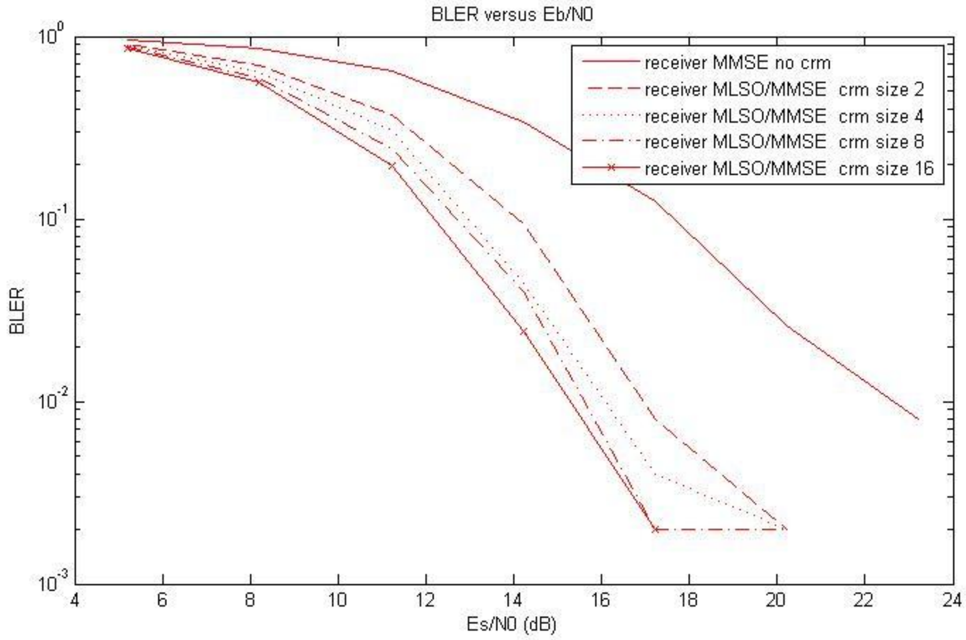

Figure 30 - Figure to show the CRM block size impact (rate 5/6 – QPSK SISO). OFDM system

Table 5 – Simulation parameters

CRM angle	$\frac{\pi}{6}$
Channel estimation	PSAM
Bits per block	6662
Coding rate	5/6
Turbo iteration	4
Receiver iteration	3

In this chart, the MMSE without CRM is shown here as reference. The difference between this figure and figure 29 is the coding rate that in this figure is 5/6. All the MLSO/MMSE simulations achieve a better performance than the MMSE receiver. The one that achieves a better performance is with CRM block size of 16. The larger the block size, better the performance. Of the all MLSO/MMSE simulation, the one with the worst performance is the

CRM block size of 2. The coding rate is higher than in figure 29 which explain the difference. If the coding rate is higher, the error protection decreases. The reduction of the error protection is offset by high coding rates. A better use of the spectrum will be achieved with high code rates. Higher CRM block sizes imply higher processing complexity.

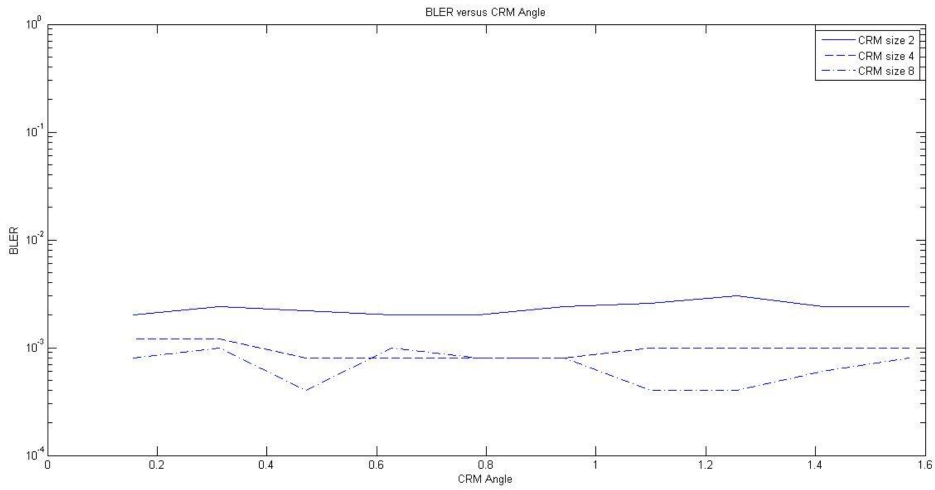

Figure 31 – Figure to show the CRM angle impact (QPSK SISO and OFDM system)

Table 6 – Simulation parameters

Coding rate	5/6
Turbo iterations	4
Reception iterations	3
Bits per block	6662
Channel estimation	PSAM (perfect estimation)

The figure 31 has the purpose to show the impact of the CRM angle rotation. As we can see the CRM angle rotation does not have a big impact in the system. The only slightly improvement seen in figure 31 is for CRM block size of 8 when the CRM angle is 0,5 radians. The lines of CRM size of 2 and 4 are more stable then the CRM size of 8. The CRM size of 4 and 8 are near the BLER of 10^{-3}. The receiver is the MLSO/MMSE.

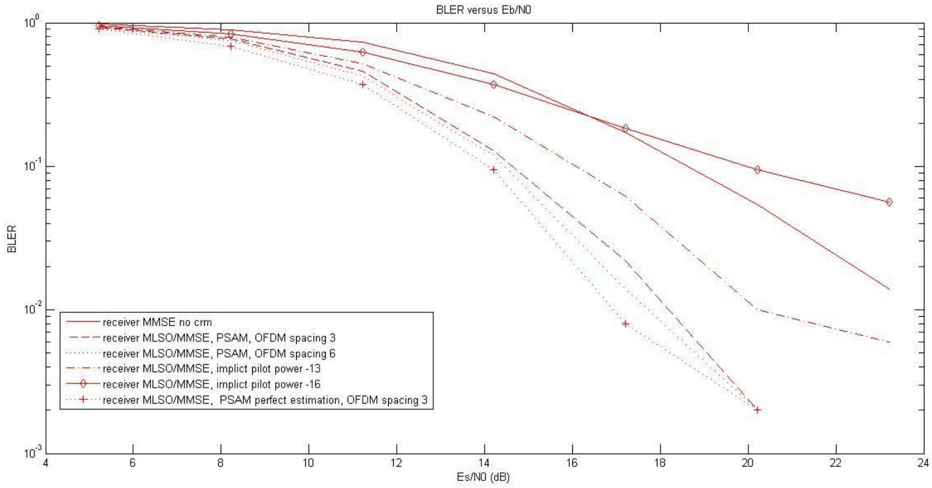

Figure 32 – Figure to show the impact of the channel estimation (QPSK SISO and OFDM system)

Table 7 – General simulation parameters

CRM angle	$\frac{\pi}{6}$
CRM size	2
Bits per block	6662
Coding rate	5/6

Table 8 – Simulation parameters specified for each simulation developed to build the figure 32

Line style	Solid	Dash	Dot	Dash-Dot	Solid with Diamonds
Channel Estimation	PSAM	PSAM	PSAM	Implicit Pilots	Implicit Pilots
Carrier pilot spacing	5	5	5	0	0
OFDM pilot spacing	3	3	6	0	0
Pilot power (dB)	0	0	0	-13	-16
Turbo iterations	12	4	4	4	4

Receiver Iterations	1	3	3	3	3

The figure 32 purpose is to show the possible impact of the channel estimation. This is the first figure which does not have perfect channel estimation. The simulations with PSAM channel estimation achieve better results than with implicit pilots. The simulation with better performance is OFDM pilot spacing of 6 between two consecutives pilot blocks. It is reasonable that the power pilot of -13 dB achieves better performance than -16 dB. The curve with OFDM pilot spacing of 6 is close of the perfect estimation. The PSAM estimation needs more bandwidth because the pilots have position which should belong to data.

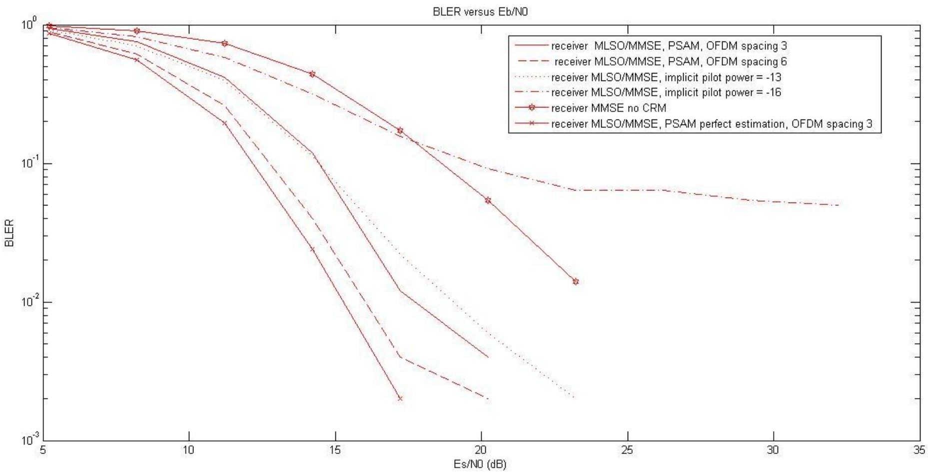

Figure 33 – Figure to show the impact of channel estimation (CRM size of 16 – QPSK SISO). OFDM system

Table 9 – Simulation parameters

CRM size	16
CRM angle	$\frac{\pi}{6}$
Coding rate	5/6
Bits per block	6662

The figure 33 shows the channel estimation for a CRM size of 16. The simulation parameters of the table 8 are the same for this simulation. The conclusions for the figure 33 are basically the same of the figure 32. The simulation of PSAM and OFDM pilot spacing of 6 is very close to the perfect estimation. The worst performance is the one with the implicit pilot power of -16 dB. The implicit pilot power should be higher to improve the performance.

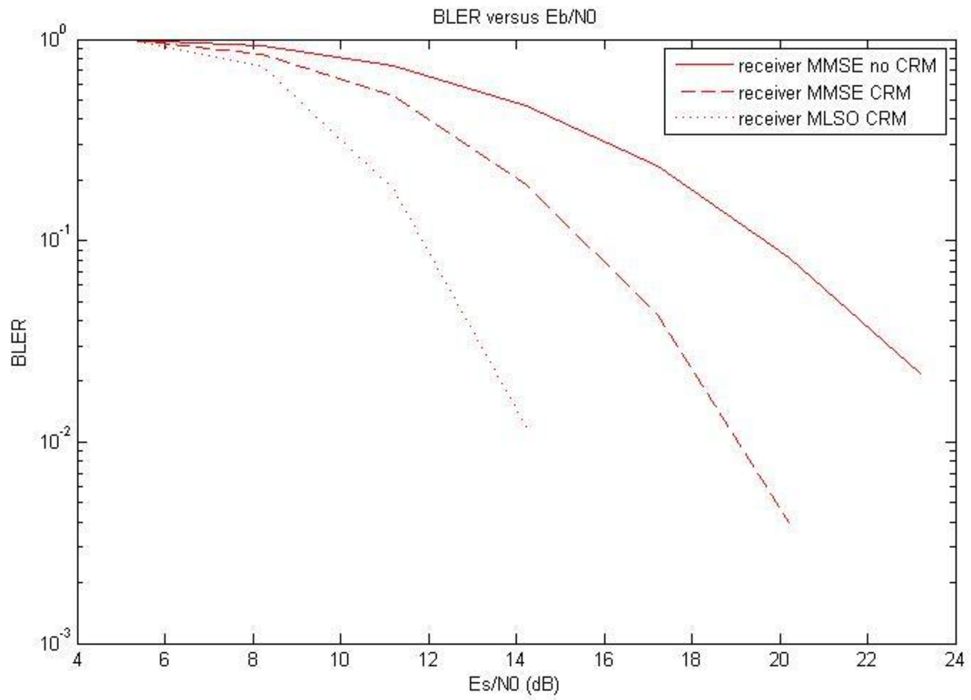

Figure 34 – Different receivers with CRM and without CRM (QPSK MIMO and OFDM system)

Table 10 – Simulation parameters

CRM angle	$\frac{\pi}{6}$
CRM size	2
Channel estimation	PSAM (perfect estimation)
Bits per block	6422
Turbo iterations	12

The figure 34 shows the difference between the MMSE and MLSO receivers. The MMSE receiver without CRM is the simulation that shows a worst performance. On the other hand, the MLSO receiver shows the best performance and between them is the simulation of MMSE receiver with CRM. The CRM block size used in these simulations were 2.

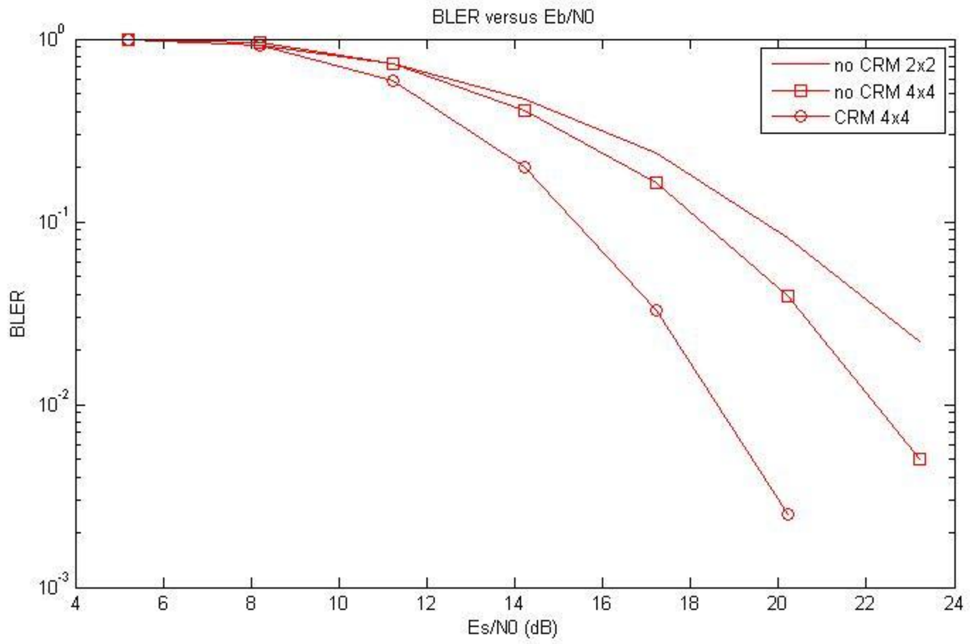

Figure 35 – Figure to show the impact of the number of antennas transmitting/receiving (QPSK MIMO and OFDM system)

Table 11 – Simulation parameters

CRM angle	$\frac{\pi}{6}$
CRM size	2 (no CRM 2x2) and 4
Receiver type	MMSE
Channel estimation	PSAM (perfect estimation)
Turbo iteration	12
Coding rate	5/6
Bits per block	6422 (2x2) and 6102 (4x4)

Figure 35 has the purpose of showing the impact of CRM size and MIMO schemes 2x2 and 4x4. The receiver in these simulations is MMSE. The curve which shows a worst performance is the one with 2 antennas in transmission and reception without CRM. The simulation with a better performance is the one with four antennas for transmission and reception combined with CRM size 4. The MIMO scheme allows the system to increase transmission rate and with CRM achieves better performances. The increase of antennas corresponds to an increase of the complexity of the transmitter and/or receiver. The bits per block used in these simulations were 6422 and 6102 for 2x2 antennas or 4x4 antennas respectively.

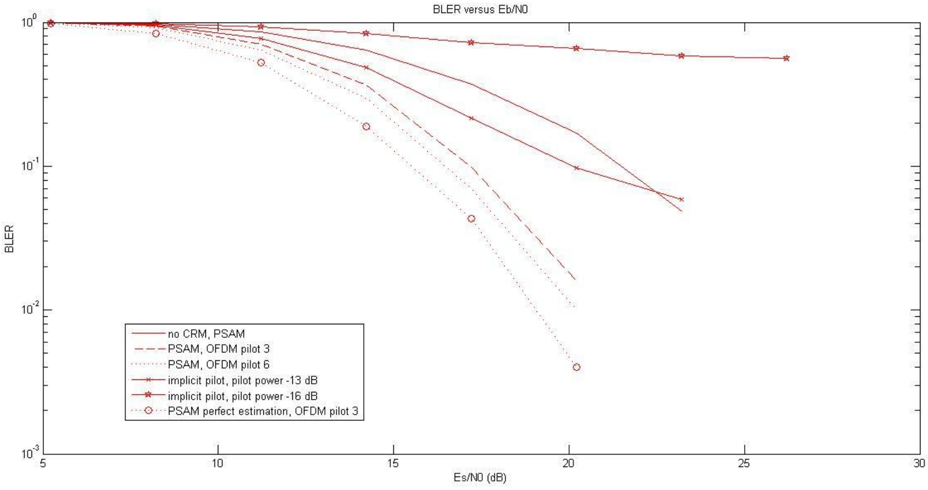

Figure 36 – Figure to show the impact of channel estimation (QPSK MIMO and OFDM system)

Table 12 – General simulation parameters

CRM angle	$\frac{\pi}{6}$
CRM size	2
Bits per block	6422

Table 13 - Simulation parameters specified for each simulation developed to build the figure 36

Line style	Solid	Dash	Dot	Dash-Dot	Solid with Starts
Channel Estimation	PSAM	PSAM	PSAM	Implicit Pilots	Implicit Pilots
Carrier pilot spacing	5	5	5	0	0
OFDM pilot spacing	3	3	6	0	0
Pilot power (dB)	0	0	0	-13	-16
Turbo iterations	12	12	12	3	3

Receiver Iterations	1	1	1	4	4

The purpose of figure 36 is to show the impact of channel estimation in a MIMO system. The BLER is higher than 10^{-1} for a pilot power of -16 dB. The simulation without CRM and PSAM as channel estimation is the second worst until an $\frac{E_S}{N_0}$ of 23 dB when the implicit pilots simulation where the pilot power is -13dB become the worst of these two. The simulations with CRM and PSAM channel estimation have similar performance and the better is the one with OFDM pilot spacing of 6. The PSAM channel estimation with OFDM pilot spacing of 6 has a similar performance to perfect estimation.

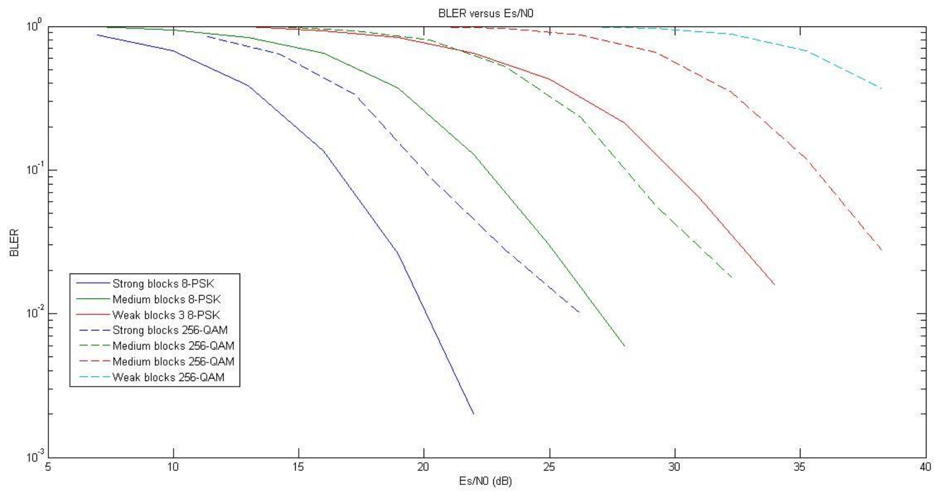

Figure 37 – Comparison between 8-PSK and 256-QAM blocks (OFDM-SISO)

Table 14 – Simulation Parameters

Coding rate	5/6
Turbo iterations	12
Bits per block	6662
Encoders	3 (8-PSK) and 4 (256-QAM)

Figure 37 shows a comparison between the several different protected blocks in 8-PSK and 256-QAM modulations. A direct comparison about the strong blocks, you can see 8-PSK strong blocks has a lower $\frac{E_S}{N_0}$ for the same BLER comparing with the 256-QAM strong blocks. The 256-QAM strong blocks are closer from 8-PSK medium blocks. The 256-QAM (8 bits per symbol) modulation has more bits per symbols than 8-PSK (3 bits per symbol), this means the 8-PSK symbols has a higher difference between them and this leads to a higher protection.

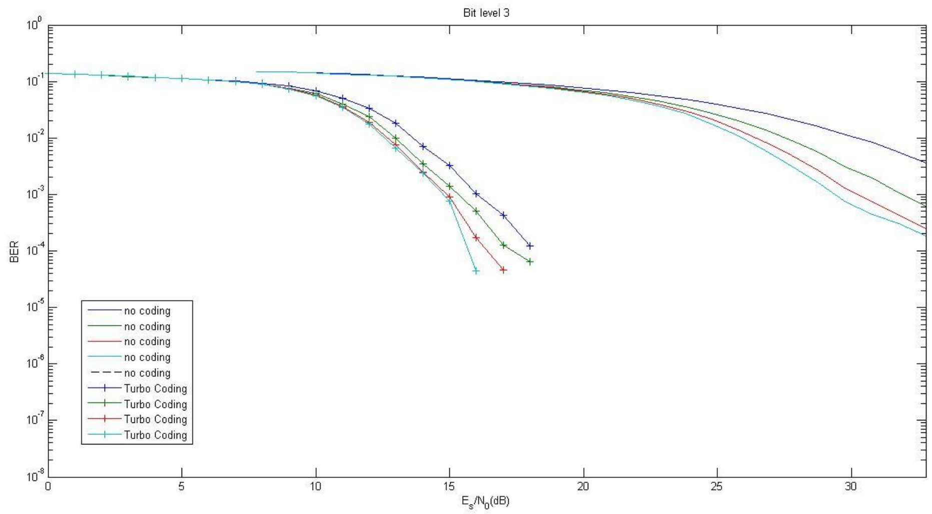

Figure 38 - SC-FDE system. Comparison between coding and no coding (SISO)

Table 15 – Simulation parameters

Bits per block	512
Modulation	64-QAM
Turbo iterations	12
Encoder	1

The goal of figure 38 is to show the difference between simulations with turbo coding in a SC transmission. There are a big difference between the blocks with coding and the other without coding. For the BER, the system with coding has a lower $\frac{E_S}{N_0}$. A system with coding can achieve much better performance. The issue around coding is the complexity of the transmitter and receiver blocks. Each curve represent an IB-DFE iteration.

Chapter 5 – Thesis Conclusions

Conclusions

The first conclusion taken in this study is that the use of CRM can be an advantage. The CRM can lead the future wireless system to better performance. The CRM is complex and that can be a problem to terminals.

The CRM block size is useful when the coding rate is high and high coding rates mean least code protection. If the coding rate is high the efficiency of the spectrum usage will be higher. The CRM combine with higher coding rates can compensate the issue around high code rates, the impairment of the code protection. The performance gain is higher in MIMO system when it is using CRM technique. The advantage of using the MIMO is the higher transmission rate but the system is more complex.

The different protection error bit can take an important impact combining with CRM. You can increase the protection when using CRM. The price to pay is the higher complexity of the system.

The PSAM channel estimation leads to better channel estimation, very close to the perfect estimation when the OFDM pilot spacing is 6. The PSAM needs a higher bandwidth when comparing with the implicit pilots.

Hierarchical constellations can be useful especially for high modulation (M>64 for QAM and M>32 for PSK. These kind of hierarchical constellations are attractive for broadcast transmissions.

The CRM technologies can lead to a new era in wireless communications. Video and Internet are very common in mobile phones. Using CRM can lead to a higher quality of the communications.

Future work

This thesis has in the scope to develop a simulator with the purpose of study the performance of CRM, hierarchical constellations and to study the impact of channel estimation. that allows any kind of modulation. Future studies should be the study of CRM for modulation like M-PSK (M>8) and M-QAM (M>64), to study the impact of CRM in more complex modulation.

Higher CRM block size must be developed because the higher CRM block size the higher can be de performance of the system. The issue is the complexity than higher CRM block size brings.

It would be interesting to develop a receiver with low complexity and a performance similar to the MLSO.

More studies must be done about the possible impact of MIMO system in CRM.

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Appendix A

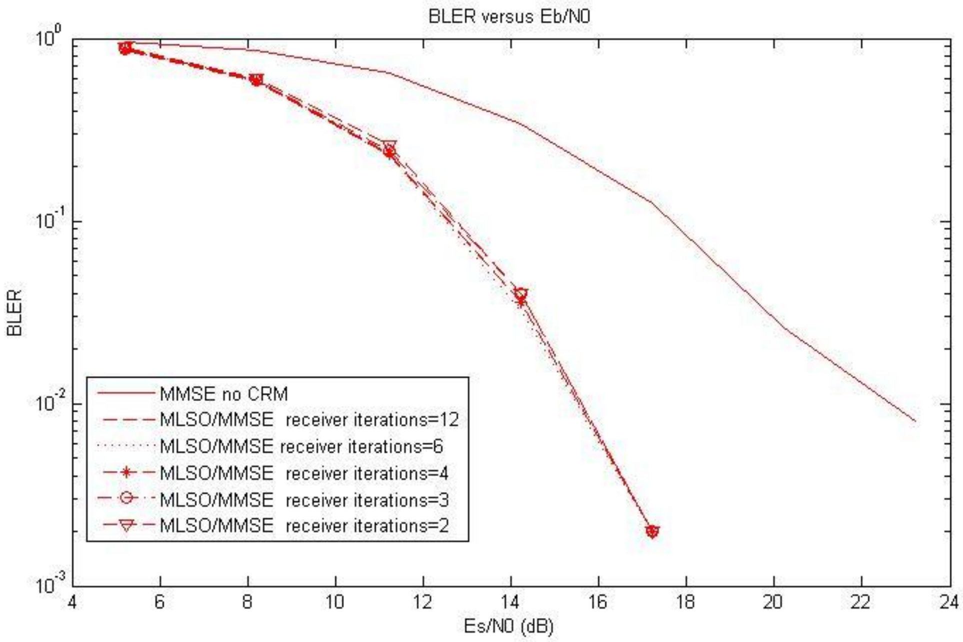

Figure 39 – Figure to show the impact of the reception and turbo iterations

Table 16 – Simulation parameters

CRM size block	8
CRM angle	$\frac{\pi}{6}$
Bits per block	6662
Channel estimation	PSAM (perfect estimation)
Coding rate	5/6

Table 17 – Turbo and receiver iterations correspondence

Turbo iterations	Receiver Iterations
12	1
1	12
2	6
3	4
6	2

The curve representing the MMSE receiver without CRM is the one with the worst performance. All the other simulations have similar performance. The relation between receiver iteration and turbo iterations practically don't affect the performance of the transmission.

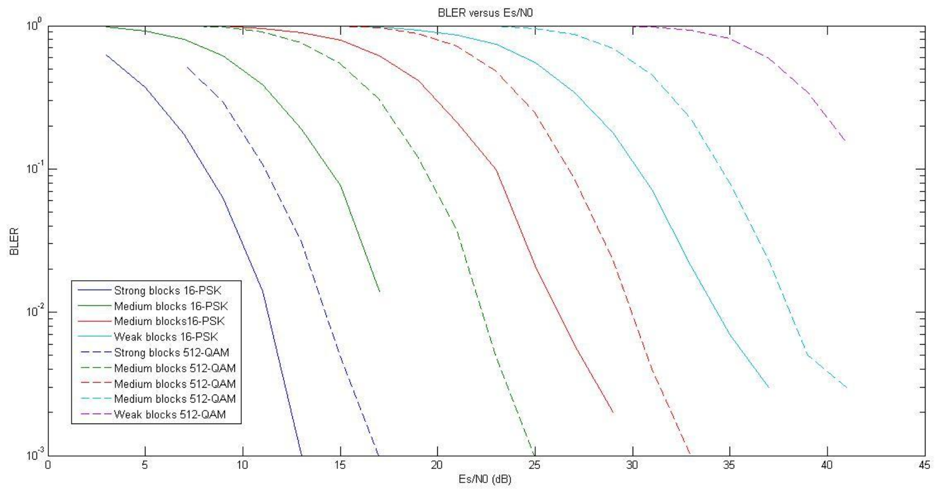

Figure 40 - Comparison between 16-PSK and 512-QAM blocks

Figure 40 shows the comparison between the different kind of blocks in 16-PSK and 512-QAM. The conclusions about this figure are basically the same of the figure 37 in chapter 4.

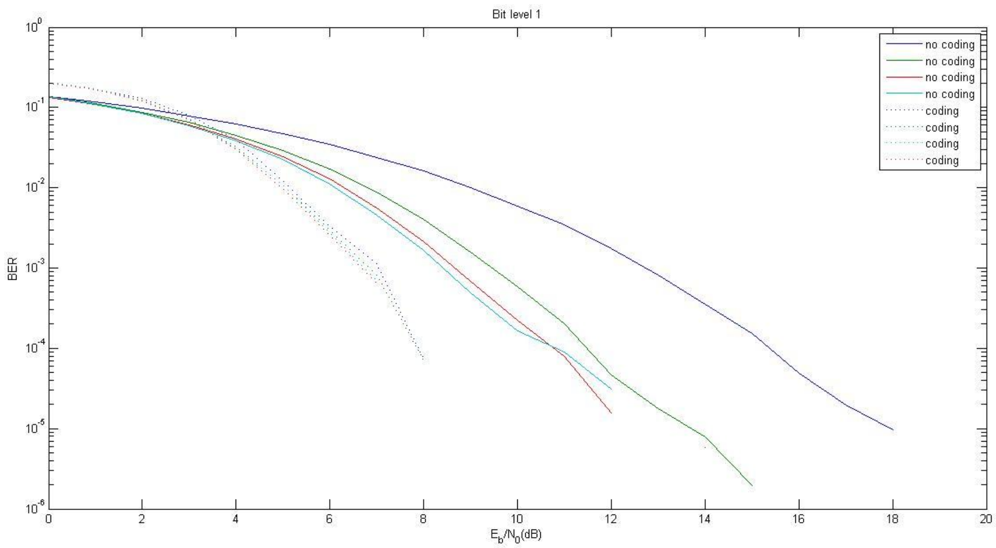

Figure 41 – SC-FDE simulations. Comparison between coding and no coding. QPSK SISO

Table 18 – Simulation Parameters

Bits per block	512
Modulation	QPSK
Turbo iterations	12
Encoder	1

The difference between coding and no coding for a QPSK modulation is not great like was for 64-QAM modulation in figure 38. The coding curves have a slightly better performance than without coding curves.

Appendix B

The OFDM and CRM simulator generate three kind of figures in each simulation. The three kinds of figures are:

- BER versus $\frac{E_s}{N_0}$.
- BLER versus $\frac{E_s}{N_0}$.
- BER evolution.

The first two figures are the BER and BLER versus $\frac{E_s}{N_0}$ respectively. Each of this two figures give information about bit error rate or block error rate, an important indicator about the response of the system. The last figure, known as BER evolution figure, indicates if the simulation has a good number of errors. In the Y axis is the BER and in X axis is the number of Monte-Carlo iterations.

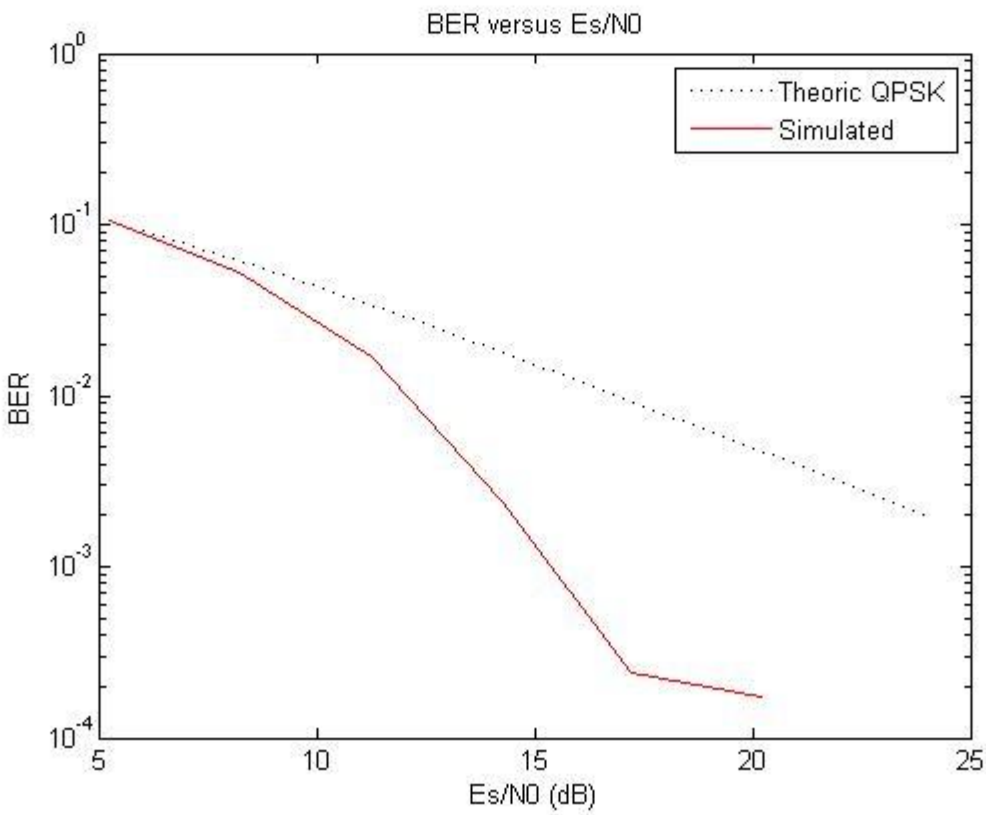

Figure 42 - BER figure example

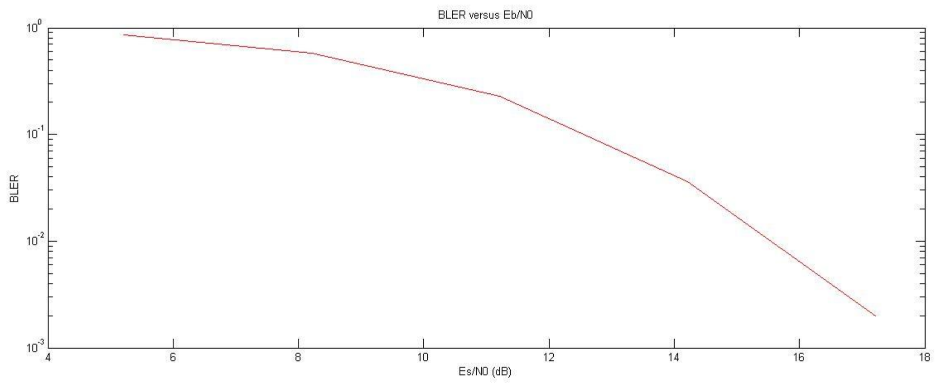

Figure 43 - BLER figure example

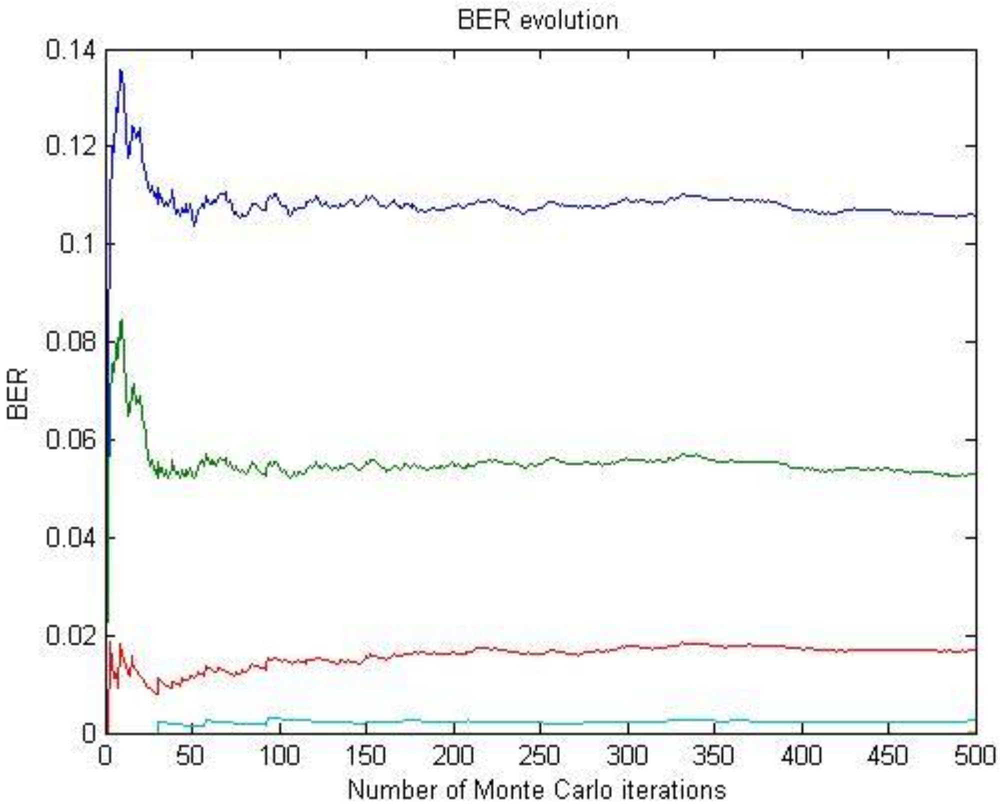

Figure 44 - BLER evolution figure example

Table 19 – Simulation parameters

CRM block size	8
CRM angle	$\frac{\pi}{6}$
Coding rate	5/6
Bits per block	6662

Channel estimation	PSAM (perfect estimation)
Receiver	MLSO/MMSE
Turbo iterations	1
Receiver iterations	12