Norwegian University of
Science and Technology

Bachelor's Thesis

Paula Ballester Palacios

Channel Estimation in a MIMO Spread Spectrum System with Frequency-Selective Rayleigh Channel

Bachelor's Thesis in Telecommunication
Technologies and Services Engineering with
specialisation in Telecommunication Systems
Supervisor: Prof. Kimmo Kansanen
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Abstract

This thesis deals with the analysis of channel estimation in MIMO (Multiple-Input Multiple-Output) systems with a Frequency Selective Rayleigh Channel, under the condition of having employed Direct Sequence Spread Spectrum techniques and have maintained the orthogonality of the codes by using Zadoff-Chu sequences as well as employing Cyclic Prefix. One problem in this scenario is that to estimate the channel coefficients we must choose an appropriate preamble configuration. Choices such as where to place the preamble as well as the length of the preamble are necessary to obtain accurate results.

The first scheme is based on a 2x1 MIMO System with an initial preamble which length has been changed throughout the thesis to examine the behaviour of the system for different preamble lengths. It is also proposed and analysed the impact of varying the preamble length in a higher diversity order scheme, 4x2 MIMO, since the poor quality of a 2x1 MIMO presents unreliable results. In order to study how to improve the quality of the system, that is, increase the diversity order, without changing the number of transmit and/or receive antennas, a third scheme is proposed. It is based on a 4x2 MIMO in which the impact of varying the number of taps on system quality and estimation accuracy has been analysed.

We examine the accuracy of the estimation in terms of MSE (Mean Square Error) and the performance in terms of BER (Bit Error Rate). It is studied if increasing the number of transmit and/or receive antennas provides better system quality for transmitting than increasing the number of channel taps. Moreover, after analysing the impact of varying the preamble length, it can be seen that it is not always better to increase the length of the preamble because the longer the preamble, the more power is needed to transmit pilot symbols and therefore the less power is available to transmit data.

All the schemes assume time invariant channel to simplify the LS channel estimation so we can assume that the coefficients estimated at a precise instant, in this case in the initial preamble, will be practically unchanged throughout the whole communication.

Preface

This thesis finalises a bachelor's degree in Telecommunication Technologies and Services Engineering with specialisation in Telecommunication Systems at the Polytechnic University of Valencia (UPV) having spent the last year as an exchange student at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The thesis specialises in Signal Processing and Communication and was done during the autumn semester of 2021. The design of the task is mainly made by the supervisor Kimmo Kansanen.

I wish to thank Prof. Kansanen for his noticeable support throughout the development of the project.

Lastly, I would like to thank friends and family for their support, love and encouragement during these four years of study.

List of Acronyms

AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BPS	Bits Per Symbol
BPSK	Binary Phase-Shift keying
CDMA	Code-Division Multiple Access
W-CDMA	Wideband Code -Division Multiple Access
DSSS	Direct-Sequence Spread Spectrum.
MIMO	Multiple-Input Multiple-Output
PN	Pseudorandom Noise
SISO	Single-Input Single-Output
SNR	Signal-to-Noise Ratio
STBC	Space-Time Block Coding
ZC	Zadoff-Chu
LS	Least Squares
MMSE	Minimum Mean Square Error
MSE	Mean Square Error
SU-MIMO	Single-User MIMO
MU-MIMO	Multi-User MIMO
LOS	Line Of Sight

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1 Introduction

1.1 Context

The very first use of radio transmitted coded information was a result of the works of Maxwell and Hertz with their pioneering experiments using electromagnetic waves. Tesla described the very first papers detailing radio communication systems in the late 1800’s.

Around the same time, Marconi patented the telegraph and demonstrated the use of mobile communications with ships crossing the English Channel.

These technologies continued to develop for more than a hundred years, when the intricacies of telecommunications began to unravel. The next breakthrough came during World War II, when military research was driven by radar and remote sensing, and from these technologies came television broadcasting in the 1940s.

In the 1970s, AT&T's Bell Labs devised cellular systems and continued to drive the advancement of technologies.

The enormous growth of the consumer sectors during the 1980s and 1990s led to the modern mobile wireless services we know today.

From then until now, much progress has been made in the telecommunications sector as consumers demand faster and more reliable connectivity. The development from 1G to 4G, to LTE and beyond to 5G and 6G has accelerated the pace of progress in most technologies.

Obtaining reliable transmissions can concern several challenges. Two of the most important ones are:

1. Minimizing the error probability when the signal is affected by random noise and fading.
2. Preventing the signal from being detected and jammed by any enemy forces.

More reliable transmissions can be obtained through multiple-input multiple-output (MIMO) communications. Before the 1990s, multiple antennas at one end of the link, called single-input multiple-output (SIMO), were used to estimate the direction of arrival of the signal. However, the new spatial dimension gave rise to new possibilities, such as beamforming and spatial diversity. The concept of using multiple antennas in both ends of the link was introduced in 1995 by A.J Paulraj and T. Kailath. Later, in 1998, Alamouti presented a transmit diversity scheme, using transmit precoding that exploited the multipath channel properties when the transmitter does not have channel knowledge to make transmission more robust to random fading.

In addition, spread spectrum communication is designed to make the signal more robust to enemy detection and jamming, what was a natural result of the Second World War for electronic supremacy. The major development in spread spectrum technology results from improvements in hardware, and the technology is still widely used today, for instance in code-division multiple access (CDMA). CDMA employs spread spectrum technology and a special coding scheme (where each transmitter is assigned a unique code) allowing several users to share the same bandwidth and being able to send information simultaneously over a single communication channel. It offers some advantages such as:

1. Low probability of interception
2. Resistance to jamming
3. Resistance to fading

1.2 Background

The basis of this thesis will be several papers as well as Marius Grønby Kristoffersen master's thesis. His thesis is mainly based on C. D'Amours and J-Y. Chouinard paper that presents a new technique for CDMA/MIMO systems that employ multiple spreading codes.

This bachelor's thesis is a continuation of his master's thesis which aims to improve his study by assuming that the channel is not known to the receiver, facing a scenario closer to reality, and therefore must be estimated.

1.3 Problem Definition and Objective of the Thesis

The information in a MIMO System, since it is a Wireless Communication System, is transmitted through a radio channel. For conventional, coherent receivers, the effect of the channel on the transmitted signal must be estimated to recover the transmitted information.

There exist many well-known techniques that can be used to estimate the channel coefficients, such as Least Square (LS) Technique or MMSE (Minimum Mean Square Error) Technique. Therefore, to estimate the channel some important aspects need to be considered.

The aim of this thesis is to obtain a highly accurate estimation that allows us to reliably transmit information without wasting the available resources by using as basis the DSSS MIMO scheme using permutation spreading with Zadoff-Chu sequences presented in Marius Grønby Kristoffersen master's thesis. To achieve this, the following issues need to be addressed:

1. Select the appropriate channel estimation technique
2. Decide how to allocate the pilot symbols in the preamble
3. Decide where to allocate the preamble
4. Discuss how to obtain the channel coefficients for the symbols transmitted out of the preamble
5. Discuss how many different channels should be generated to obtain reliable results
6. Analyse how varying the length of the preamble affect the performance of our MIMO System
7. Select an appropriate preamble length for our scenario
8. Analyse how varying the number of taps affect the performance of our MIMO System
9. Analyse whether the estimation provides sufficient accuracy
10. Discuss which technique is better to obtain more reliable transmissions

2 Background Theory

2.1 Communication Channel

The communication system is a model that describes the communication between two stations, the transmitter, and the receiver. A simple scheme of a communication system is shown in Fig.1.

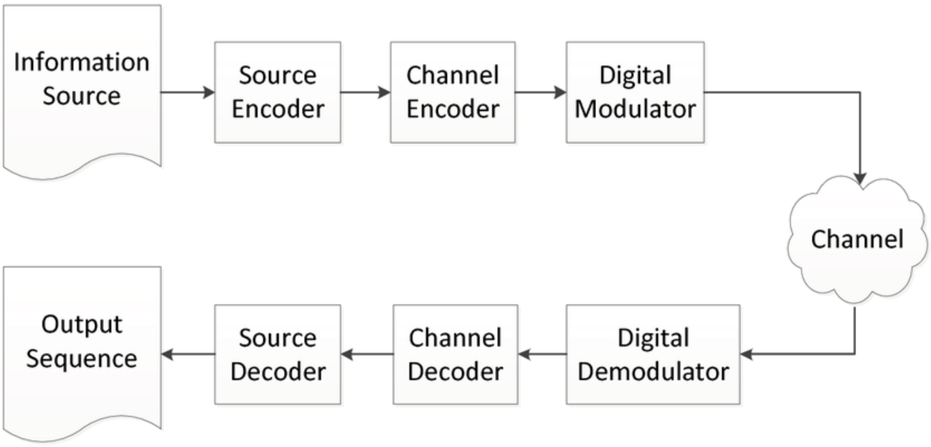

Figure 1. Scheme of a digital communication system

The information wanted to be sent by the transmitter is encoded into bits. Then, we do channel encoding, that is, we add redundancy bits to be able to detect and decode with a smaller number of errors. From there, the bits are digitally modulated into symbols before being sent by the transmitting antenna/s through the communications channel.

Finally, on the receiver side we have the reverse process to properly detect and decode the symbols.

2.1.1 Multipath Propagation: Fading

Multipath propagation refers to the phenomenon that transmitted symbols reach the receiver through many paths (two or more paths) and their relative strengths and phases vary. This happens because of the reflections from objects such as buildings, ground, water, etc. that the signal suffers.

Besides, fading refers to the distortion that the modulated signal suffers when being propagated through the channel. In wireless systems, fading is due to multipath propagation.

The changes in the relative path lengths could result either the transmitter or receiver moving, or any of the objects that provides a reflective surface moving. Implying that the phases of the signals received change, and, in turn, this will result in the signal strength varying as a result of the different way in which the signals will sum together. It is this what causes the fading that is present on many signals.

Multipath fading is a feature that needs to be considered when designing a wireless communication system because it may cause distortion to the radio signal. As the various paths through which the signal is transmitted vary in length, the signal transmitted at a particular time will arrive at the receiver over a spread of times causing issues with phase distortion and Inter-Symbol Interference (ISI) (see Fig.2).

Hence, it might be necessary to incorporate some features within the communication system to minimise these effects.

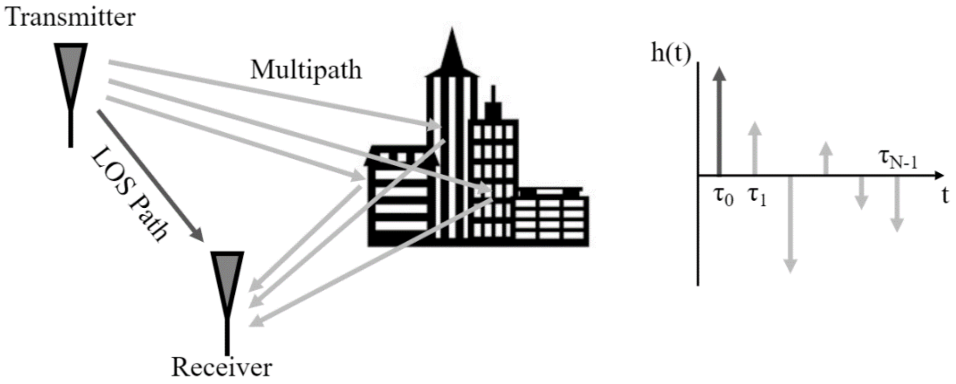

Figure 2. Illustration of multipath propagation

An important definition is the *delay spread* (T_d), it can be defined as the time difference between the earliest significant multipath component and the last one. It will be used to describe characteristics of the different types of fading that exist.

A. *Flat and Selective Fading*

The terms of flat and selective fading are related with the coherence bandwidth of the channel (W_c), that is, the minimum separation in frequency after which two signals will experience uncorrelated fading. It is defined as follows:

$$W_c = 1/T_d$$

- *Flat fading:* the coherence bandwidth of the channel is larger than the bandwidth of the signal, implying that all frequency components of the signal will experience the same magnitude of fading. It can also be interpreted from the time domain view, being the symbol period T_s larger than the delay spread.

$$W_c > W_s \leftrightarrow T_s > T_d$$

Where the signal bandwidth is $W_s = 1/T_s$.

- *Frequency-Selective fading:* the coherence bandwidth of the channel is smaller than the bandwidth of the signal, meaning that the amplitudes and phases of the signal will vary across the channel during the period of use. Since different frequency components of the signal are affected independently, it is highly unlikely that all parts of the signal are simultaneously affected by a deep fade.

$$W_c < W_s \leftrightarrow T_s < T_d$$

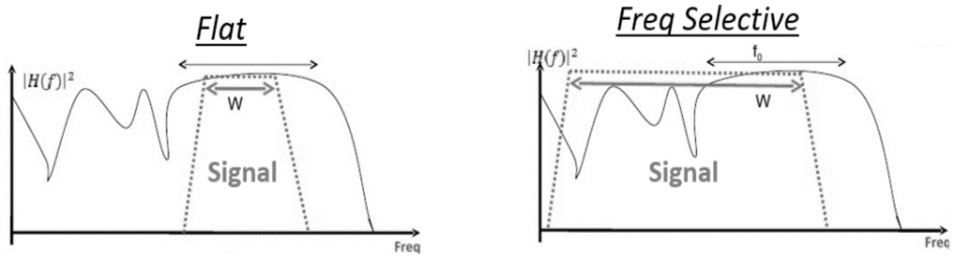

Figure 3. Flat vs Frequency Selective Fading

B. *Slow and Fast Fading*

The terms of slow and fast fading refer to the rate at which the magnitude and phase change imposed by the channel on the signal changes. To understand this phenomenon, we must introduce the coherence time (T_c), being it the time duration over which the channel impulse response is considered not to vary.

- *Slow fading:* when the coherence time of the channel is large relative to the delay constraint of the channel. If this occurs, the changes in amplitude and phase can be considered constant over the period of use.

- *Fast fading:* when the coherence time of the channel is small relative to the delay constraint of the channel. If this occurs, the changes in amplitude and phase vary considerably over the period of use.

In a fast-fading channel, the transmitter may take advantage of the variations in the channel conditions using time diversity to help increase robustness of the communication to a temporary deep fade.

In general, we say that time coherence is inverse proportional to Doppler spread. Being the Doppler Spread a measure of the spectral broadening caused by the rate of time shift of the mobile radio channel. It can be defined as the frequency range in which the received Doppler spectrum is essentially non-zero.

$$Tc = \frac{K}{Ds}$$

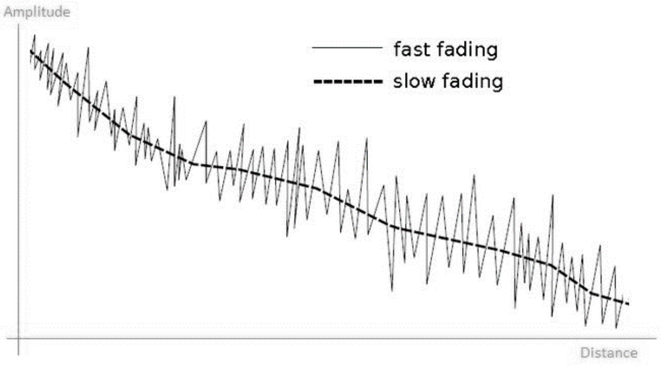

Figure 4. Fast vs Slow fading

2.1.2 MIMO Narrowband and Wideband Channel

In a MIMO system we can find different types of channels depending on the bandwidth of the transmitted signal and the coherence bandwidth. Concretely, regarding what explained in 2.1.1, a narrowband channel or a flat fading channel is a channel whose signal bandwidth is within the coherence bandwidth of a frequency channel, that is $W_s < W_c$. In other words, narrowband systems are those that carry signals in a narrow band of frequencies.

Besides, a wideband channel or a frequency selective channel refers to broadband communications that use a wide range of frequencies, implying that $W_s > W_c$.

They present several differences in the following fields.

A. *Data Rate*
   The signals in a narrowband channel are about 100KHz or smaller whereas in a wideband channel the data rate supported is relatively higher. More bandwidth is translated into higher data rates, in terms of transmitted and received signal information.

B. *Architecture*
   In the narrowband architecture, the total frequency spectrum is divided into as many channels as the technology allows. But, in the wideband architecture, either the entire

frequency spectrum is available or a significant portion of it is used by each carrier.

C. *Fading Model*
Narrowband channels are often called flat fading channels because they usually pass all spectral components with equal gain and phase to each other. Wideband channels, on the other hand, are called selective fading or frequency selective channels because different parts of the signal will be affected by different frequencies.

D. *Interference*
In a narrowband channel, the probability of overlap with an interfering signal is lower but may suffer loss due to selective fading. However, in a wideband channel, the probability of suffering interference from other transmitters increases linearly with bandwidth.

E. *Signal Power*
Regarding the signal power, in a narrowband channel lower transmit signal power is needed because the paths are added together vectorially.
On the other hand, in a wideband channel the paths are added algebraically, and the received paths are isolated by the correlation properties of the signal. Thus, higher transmit signal power is needed in this second type of channels.

F. *Applications*
Since narrowband systems require less operating power, they are more suitable for shorter-range, fixed-location wireless applications with shorter distances. Nevertheless, wideband is a low-power technology that is used in applications such as connected cars, IoT devices, 5G wireless communications, etc.

2.2 Diversity

MIMO aims to improve the reliability of communications by using diversity, like in fast-fading channels where it is used as a strategy for mitigating the effects of multipath fading.

Wireless communications suffer from fading, in which the quality of the communication degrades causing an increase in the probability of bit error, i.e., reducing the reliability of the link, as explained in 2.1.1.

Diversity means transmitting different copies of the same signal through the different channels in such a way that each of them undergoes an independent fading. The probability that all replicas are degraded at the same time is reduced as more replicas are transmitted.

Three important forms of diversity are *spatial*, *frequency,* and *time diversity*.

- *Spatial diversity:* exploits the fact that when several antennas are sufficiently separated the fading experienced at the receiver by each antenna is independent. The required separation distance depends on the propagation environment details.
  Some advantages are that it can be achieved without bandwidth expansion of coding and that it does not require additional signal processing. Hence, considering *Nr* receive

antennas, since we obtain the same symbol transmitted over *Nr* different channel coefficients, we say that we have *Nr*th diversity order.

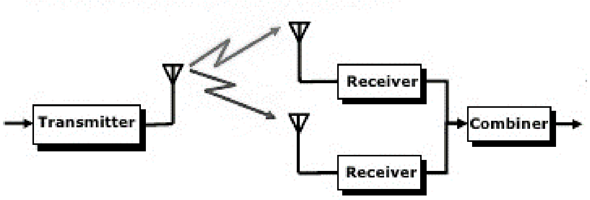

Figure 5. Spatial diversity

- *Frequency diversity:* exploits the frequency-selective nature of multipath fading channels, and in particular, the fact that the fading correlation at two different frequencies tends towards zero as the frequency separation increases. Frequency diversity can be exploited by using spread-spectrum modulation and Rake receiver, combining OFDM and coding, etc.

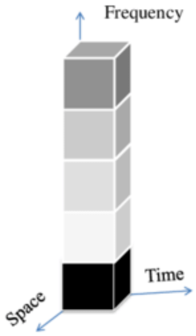

Figure 6. Frequency diversity

- *Time diversity:* exploits the time-varying nature of the fading channel. It is achieved by sending the same signal several times and with a separation between symbols such that the fading of each symbol is independent of the others. However, time diversity is not always the best option due to the latency that could be added when using time diversity in static environments or in a slowly varying channel.

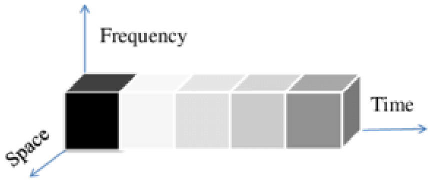

Figure 7. Time diversity

2.3 Direct-Sequence Spread Spectrum

Direct-Sequence Spread Spectrum (DSSS) is a spread-spectrum modulation technique commonly used to minimise signal interference. DSSS makes the transmitted signal wider in bandwidth than the original transmitted signal bandwidth by using chips that represent binary 0s or 1s. The ratio of chips to data is known as the spreading ratio, meaning that the higher the ratio, the more interference reduction will be because if some part of the transmitted signal presents errors it can still be recovered from the remaining part of the chipping code.

After the dispreading or removal of the direct-sequence modulation in the receiver, the information bandwidth is restored, while the unintentional and intentional interference is substantially reduced.

There exist several methods to spread the spectrum, however DSSS provides greater rates of transmission than other methods such as Frequency Hopping Spread Spectrum (FHSS) or Time Hopping Spread Spectrum (THSS).

Besides, since spreading spectrum techniques make the bandwidth wider it is also more vulnerable to interference from devices operating in the same frequency range.

2.3.1 Spreading Sequence: Zadoff-Chu Sequence

For this thesis, a Zdoff-Chu sequence will be used to obtain a spread spectrum because of its beneficial characteristics for this work.

A Zadoff-Chu (ZC) sequence is a complex-valued mathematical sequence which, when applied to a signal, provides a new signal that presents constant amplitude. Hence, a ZC sequence can be expressed mathematically as follows:

$$Z_u(k) = e^{-j\pi uk(k+1)/N_c}, k \in M \qquad (1)$$

Where N_c is the code length, $M = \{0,1,\ldots,N_c-1\}$ and u is chosen such that,

$$0 < u < N_c \; and \; \gcd(N_c, u) = 1 \qquad (2)$$

Thus, ZC sequences are periodic with period N_c if N_c is odd.

This type of sequences have been used as synchronization sequences in modern wireless communication systems, replacing the conventional pseudo-random noise (PN) sequences because of their perfect autocorrelation properties.

Then, the reason for choosing ZC sequences is because they have a couple of special properties that can be very useful for our environment.

- *Constant amplitude:* if we plot the numbers onto a complex plan (Real part - horizontal axis and Imaginary part on vertical axis), all the numbers will lie on the perimeter of a circle. This means that the amplitude of this number is constant.

- *Zero Autocorrelation:* cyclically shifted versions of a ZC sequence root when detected at the receiver are uncorrelated with one another, that is, the correlation is zero. Implying that we can create many orthogonal ZC sequences just by shifting cyclically a ZC root sequence.

Any sequence presenting these two properties, constant amplitude and zero autocorrelation, can also be called CAZAC sequence (Constant Amplitude Zero Autocorrelation waveform).

2.4 Rake Receiver

Due to reflections from obstacles a radio channel can consist of many copies of originally transmitted signals having different amplitudes, phases, and delays since there will be multipath propagation. A Rake receiver is designed to mitigate the effects of multipath fading. Its name indicates that it can be seen as a “rake” that rakes the energy from the multipath propagated signal components.

A Rake receiver is composed of several sub-receivers called “fingers” that have several correlators, one assigned to each multipath component. The intention is to separate the signals so that each finger only sees signals coming from a single path and can decode it.

A. M-fingers Rake receiver

Rake receiver uses the different correlators to detect the M strongest multipath components, being multipath components delayed versions of the original transmitted wave. To take advantage of multipath diversity and approach a better estimation of the transmitted signal, the outputs of the different correlators are weighted. Thus, if the magnitude and phase of each component is computed at the receiver through channel estimation, then all the components can be added coherently to improve the information reliability.
Hence, the demodulation process is based on these weighted outputs of the M correlators.

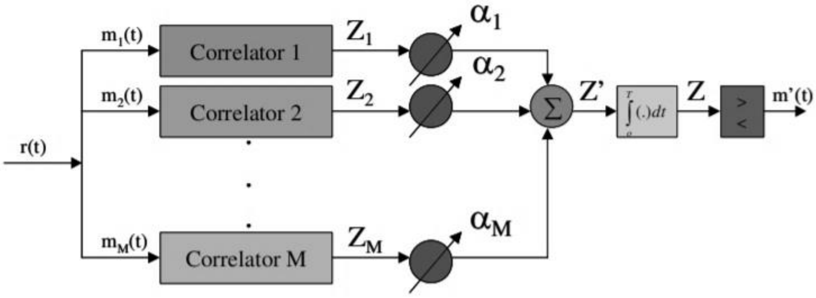

Figure 8. M-Branch Rake receiver implementation

Correlator 1 is synchronized to the strongest multipath *m1*. Multipath component *m2* arrived *t1* later than *m1* but has low correlation with *m1*.

The outputs of the M correlators, denoted as $Z_1, Z_2, \ldots, Z_M$, are weighted with different weighting coefficients, $\alpha_1, \alpha_2, \ldots, \alpha_M$, depending on the SNR of each correlator output. Combining them we arrive to:

$$Z' = \sum_{m=1}^{M} \alpha_m \cdot Z_m \qquad (3)$$

Furthermore, the weighting coefficients must be normalized to the output signal power of the correlator in such a way that the coefficients sum to unity, as in the following equation.

$$\alpha_m = \frac{{Z_m}^2}{\sum_{m=1}^{M} {Z_m}^2} \qquad (4)$$

Indeed, for Rake receiver to work properly the tap weights of the multipath channel model need to be estimated. Throughout this thesis we will explore the possibility of using advanced signal processing algorithms to estimate the channel coefficients and investigate the performance of the RAKE receiver in a realistic mobile environment.

Rake receivers are common in a wide variety of CDMA and W-CDMA radio devices such as mobile phones and wireless LAN equipment.

3 MIMO Communications Description

MIMO is an acronym which stands for Multiple-Input Multiple-Output and refers to the use of multiple antennas at the transmitter and the receiver, enabling, for a given transmitted power, increased spectral efficiency in wireless systems. MIMO exploits multipath propagation, taking advantage of different signals propagating simultaneously through the same channel at the same frequency to increase channel capacity. Therefore, by making use of antenna diversity against multipath fading, we can achieve better transmission conditions without the need for higher bandwidth or higher transmitting power.

3.1 Classes of MIMO Communications

There are two classes of MIMO communications that are used in wireless systems: Point-to-Point MIMO (P2P MIMO) and Multi-User MIMO (MU-MIMO), being the first one the conventional form of the MIMO technology. In this section, each of them will be described in more detail.

3.1.1 Single-User MIMO (SU-MIMO)

This type of MIMO Technology, also known as point-to-point MIMO, is based on a link where there is one transmitting node and one receiving node. The transmitting node consists of an array of N antennas that transmit multiple data streams to a single receiver node which, in turn, consists of another array of antennas, of K dimension in this case.

Therefore, the receiver receives a signal vector where each of the received signals is a linear combination of the transmitted signals. Following Shannon's theory, the best achievable downlink performance is when the channel is known, however, in many cases, the channel is unknown, and a channel estimation is required. Hence, for both downlink and uplink, knowing the channel would simplify the operations and improve performance.

Nevertheless, being able to reach the Shannon’s limit can be considered a major challenge because it would require a great deal of complexity in the systems used.

3.1.2 Multi-User MIMO (MU-MIMO)

Based on Single-User MIMO technology, MU-MIMO differs in the fact that there are several users transmitting to the base station, which, instead of having an array of antennas (of K dimension as in P2P MIMO), is composed of multiple antennas independent of each other as it is illustrated in Fig.9.

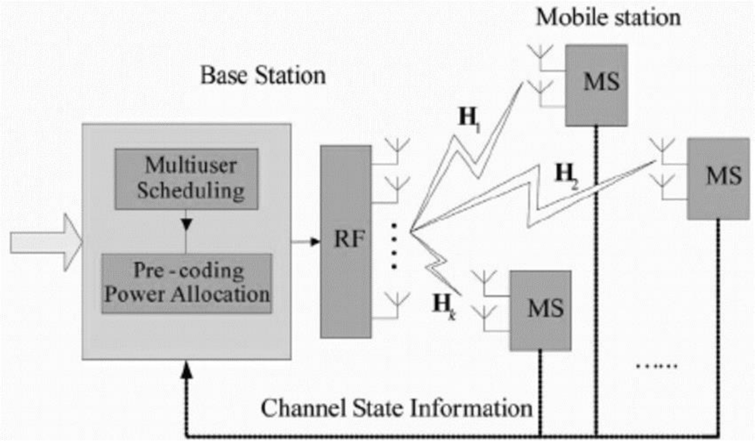

Figure 9. MU-MIMO system diagram

In the case of downlink, the conditions are the same as in P2P MIMO as the base station still needs to know the channel. Even so, for uplink, each user only needs to know its channel, as the channels used by each user are now different and independent.

One of the advantages of MU-MIMO over SU-MIMO is that if we use receivers with a single antenna, we will have a reduction in cost as well as reduced vulnerability to propagation environments, being able to operate under NLOS (No Line of Sight) scenarios. Other benefits are that it helps achieving higher data rates per user and offers an improvement in latency and power consumption requirements for customers.

Besides, there exist some drawbacks to the implementation of a MU-MIMO system because it requires precise beamforming, prior resource allocation to the terminals, more complexity than SU-MIMO owing to the use of multiple antennas, etc.

3.2 MIMO Spread Spectrum

Using spread spectrum (SS) techniques means that the bandwidth used will be higher than the minimum bandwidth needed. It can be approached, as seen in 2.3, by utilizing a spreading code which contains no data, however, which are the beneficial attributes of Spread-Spectrum Systems?

- *Interference suppression*
  The jammer does not know the subset of frequencies used in the transmission, and the noise in the transmission makes it more difficult for the jammer to jam. Therefore, the jammer must choose between attacking each subset of frequencies with low power or attacking fewer subsets of frequencies but using higher power.

- *Energy Density reduction*
  There exist Low Probability of Detection (LPD) systems, which use minimum power and optimum signalling schemes. Having a SS system designed to LPD may also offer low

probability of position fix (LPPF). That is, if the signal is detected the position of the transmitter remains unknown.

- *Fine Time Resolution*
  The distance between the transmitter and the receiver can be calculated by measuring the delay of the pulse trough the channel. The wider the bandwidth, the more accurate the measurement.

- *Multiple Access*
  Spread spectrum can be used to share resources between multiple users. In addition, privacy between users can be provided, as unauthorised users cannot easily monitor the communication.

The three most common spreading techniques are Direct Sequencing (DS), Frequency Hopping (FH) and Time Hopping (TH).

3.3 MIMO System Model

Following the principle explained in section 2.3.1, for this project we have implemented a MIMO System that uses a Zadoff-Chu sequence as a spreading sequence. As we have already seen, this type of sequence is characterised by the fact that, when applied to a signal, it gives rise to a new signal of constant amplitude.

In following sections, the mathematical model of the MIMO System, as well as a description of the transmitter and the receiver schemes will be presented.

3.3.1 Mathematical Model

MIMO Systems are composed by three main elements, the transmitter (*Tx*), the channel (*H*) and the receiver (*Rx*), being located multiple inputs and outputs at the *Tx* and the *Rx*, respectively.

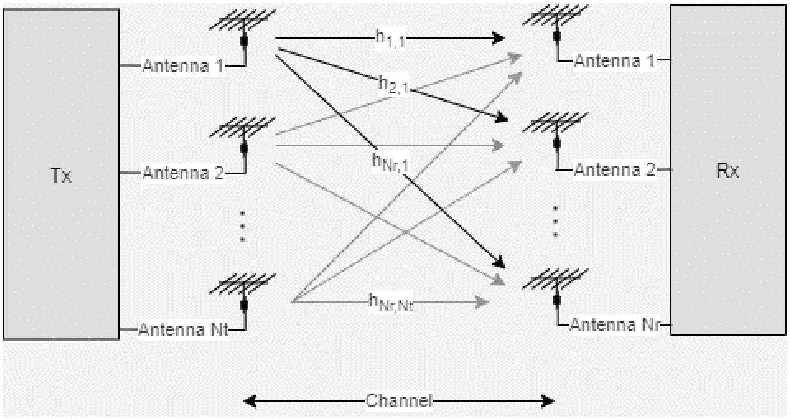

Figure 10. Mathematical model of MIMO system

The spectral efficiency of the system is defined as:

$$\eta = \frac{R \cdot R_S}{W} \qquad (5)$$

Where ***R*** is the data rate (bits/s), R_S is the symbol rate (symbols/s) and ***W*** is the bandwidth (Hz).

On the other hand, to be able to reconstruct the signal, the symbol rate must be lower or equal to the bandwidth. Hence, the spectral efficiency must be lower or equal to the data rate. Meaning that, a lower error probability can be achieved by transmitting data with R≤C, where ***C*** refers to the capacity of the channel.

In MIMO systems, after removing the CP (Cyclic Prefix), the received vector, ***Y***, can be written as:

$$\boldsymbol{Y} = \boldsymbol{\overline{H}X} + \boldsymbol{N} \qquad (6)$$

Being ***X*** the transmitted vector and ***N*** the noise, assuming it is independent identically distributed (i.i.d) white Gaussian noise with σ = (2×SNR). ***H*** refers to the channel matrix that can be expressed as:

$$\boldsymbol{\overline{H}} = \begin{bmatrix} h_{11} & \cdots & h_{1Nt} \\ \vdots & \ddots & \vdots \\ h_{Nr1} & \cdots & h_{NrNt} \end{bmatrix} \qquad (7)$$

Where h_{ij} describes the channel relationship between the transmit antenna *j* and the receive antenna *i*.

Besides, the capacity C mentioned above refers to Shannon's capacity and its expression is the following:

$$C = log_2(1 + SNR) \qquad (8)$$

Hence, by operating with the equation and assuming the transmitters transmit at equal power and that they are uncorrelated, we obtain:

$$C_{Equal\_Power} \approx \min(N_r, N_t) \cdot constant \qquad (9)$$

Thus, the system capacity increases linearly with the number of antennas used. However, given a high SNR, increasing the number of antennas does not imply a large improvement of the system although it would if the SNR is low.

3.3.2 Proposed Transmission Scheme

The data is transmitted through *Nt* antennas, being divided into *Nt* streams of data such that a ***m = [m_1,…, m_{Nt}]*** is transmitted in each symbol period. Furthermore, each message vector belongs to a coset, M_1,…,M_N. In turn, the different messages are modulated into symbols ***s = [s_1,…, s_{Nt}]*** which are spread with a unique spreading sequence ***q_1,…, q_{Nt}*** determined by the message transmitted.

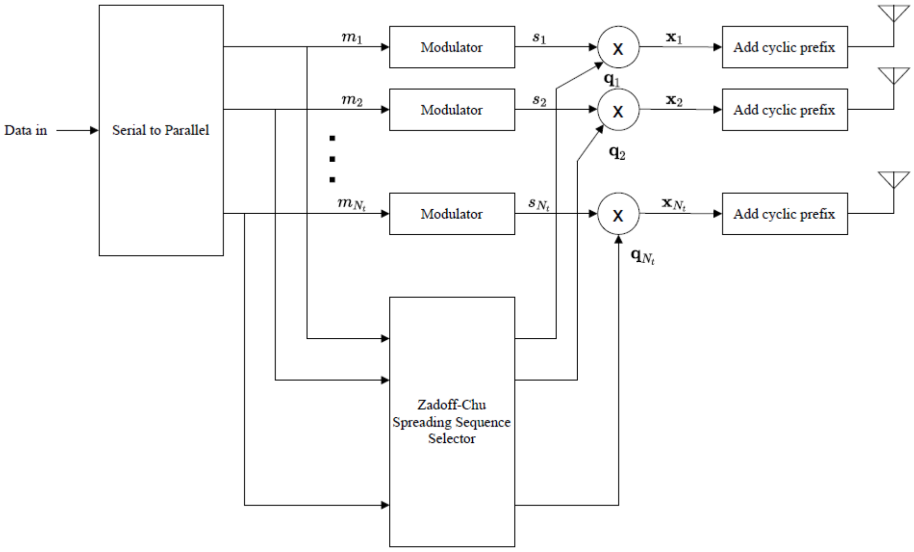

Figure 11. Permutation spreading transmission scheme

For the sequence selector, it is known that all codes ***$c_1,\ldots, c_N$*** are circular shifted versions of a ZC base sequence, also called root sequence. In the Fig.12, ***$a_1,\ldots, a_N$*** are integers that indicate the cyclic shift, a_iT_{cp}, where T_{cp} is the Cyclic Prefix (CP) duration and it has a constant value.

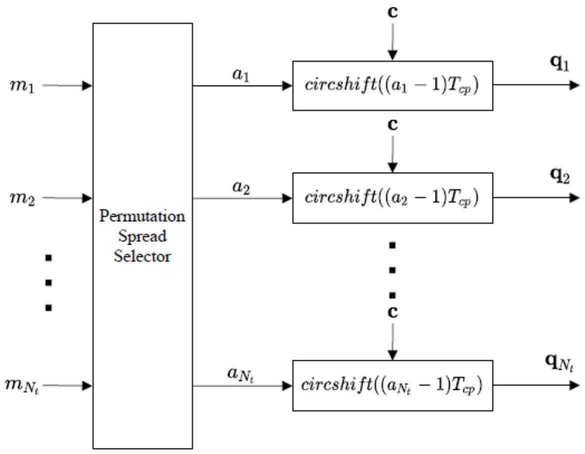

Figure 12. Zadoff-Chu spreading sequence selector scheme

3.3.3 Proposed Reception Scheme

The receiver, first, must remove the CP at antenna *i*, obtaining ***yi*** that goes through a Rake-like receiver that exploits the cyclic channel and correlates the received signal to the *N* different codes and its *L-1* delayed versions from the frequency selective channel. Due to the properties of ZC sequences as cyclic channel and orthogonality, the resulting spreading codes are still orthogonal in the MIMO channel, eliminating self-interference in the system.

Maximum likelihood detection is used to detect which message was transmitted by finding the minimum squared Euclidean distance between the received vector and all the possible received vectors in the absence of noise over all receive antennas, where $\boldsymbol{s}_i$ is the received data vector that depends on the transmitted symbol vector ***s***.

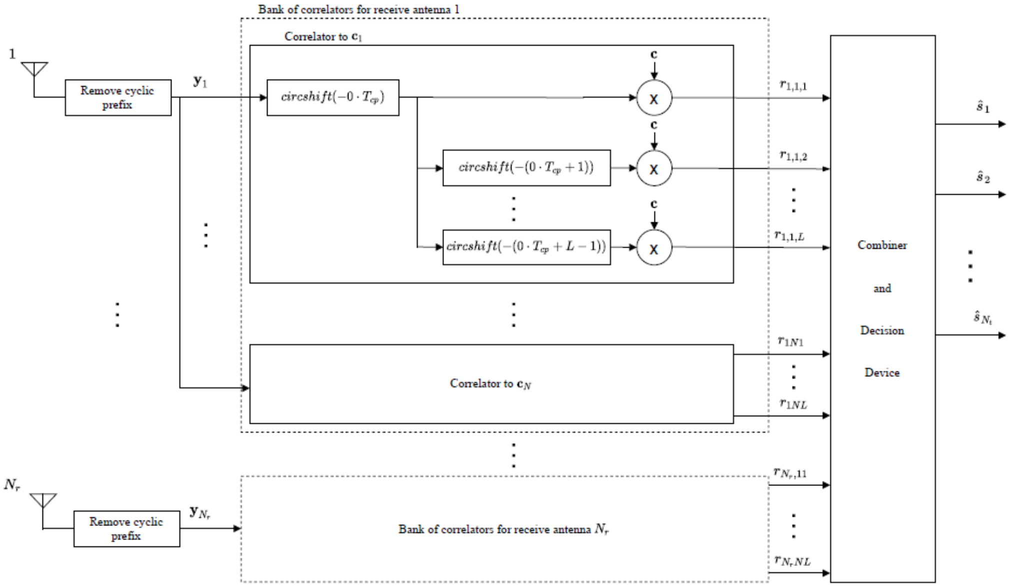

Figure 13. Zadoff-Chu reception scheme

4 Channel Estimation in MIMO Systems

4.1 Impact of Channel Uncertainty

Often channel is considered to be invariant over some symbol intervals but in reality, we face a time-varying channel, in other words, a continuous fading channel. Thus, channel estimation must be periodically conducted to obtain accurate coefficients as the error in the reconstructed data at the receiver will increase the fewer times the channel coefficients are estimated.

Channel estimation can be carried out in several ways, we can mainly differentiate between two types of methods: Training Based, using known training symbols, and Blind-Based that perform channel estimation without knowing any transmitted symbol using statistical techniques.

It is important to be aware of the impact of estimation errors on performance. An interesting question is, what happens as the number of diversity paths L increases? Well, it depends on the diversity scenario.

Coherent detection techniques require the channel information for the symbol detection and such techniques are reported to have better performance than the non-coherent ones. In coherent detection techniques, such as the ones that will be stated in the section below, as L increases, the performance of coherent combining improves and approaches the performance of an AWGN channel. Besides, in non-coherent detection techniques, when L becomes too large, the SNR per branch becomes very poor and by combining them the available diversity cannot be effectively exploit. Hence, it presents a degradation in performance.
But, what methods are available to estimate the channel?

4.2 Theoretical Description of Techniques to Estimate the Channel

Channel estimation is necessary for the Rake receiver and for the non-adaptative equalizers. Generally, channel estimation is done using a training-based method, which, as explained in the above section, means that either there are pilot symbols grouped in a training sequence or in different blocks distributed throughout the data sequence (see Fig.14). In training-based channel estimation algorithms, training symbols or pilot symbols are known to the receiver. Nevertheless, statistical techniques can also be used to estimate the channel coefficients.

The channel estimation should be done periodically, being usually determined by the standard how often it must be re-estimated.

Pilot symbols or training symbols are pseudorandom sequences that consume power. Hence, it is important to decide the number of pilot symbols to be used in relation to the total number of symbols because the power used in pilot symbols is power that is not used to transmit data. Very frequent transmission of pilots is not desirable due to consumption of resources.

There are two main types of pilot arrangement depending on the fading channel. On one hand, for a block fading channel, where there is a constant channel over a few symbols, the pilot symbols are usually transmitted on all subcarriers in periodic intervals (Fig.14 a), this pilot arrangement is called block type arrangement.

On the other hand, for fast fading channel, where the channel changes for adjacent symbols, pilots are always transmitted with an even spacing on the subcarriers, illustrated in Fig.14 b, calling this type of arrangement comb type pilot placement.

In block type pilots, as depicted in the illustration, all the subcarriers are used like pilot symbols. Thus, assuming constant channel over the pilot symbols transmission, there will be no channel estimation error since each subcarrier is transmitting symbols known to the receiver.

The procedure followed consists of performing the estimation by using either LS or MMSE (techniques that are explained below) when the pilot symbols are transmitted, however, to estimate the coefficients when the transmission is of data, the previously estimated coefficients are interpolated.

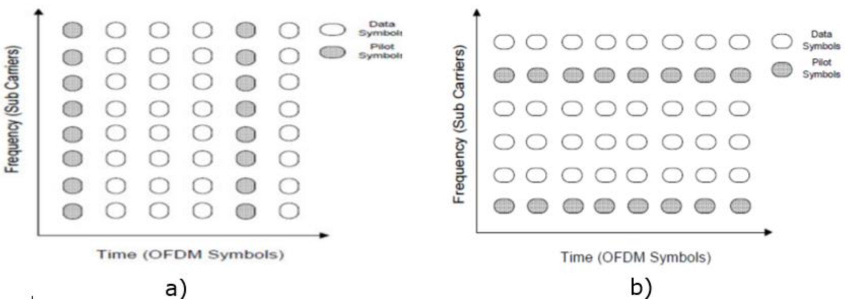

Figure 14. a) Block type pilot symbols arrangement b) Comb type pilot symbols arrangement

A. LS Channel Estimation

In least squares estimation, the estimate of ***H*** is the value that minimizes the squared error between the actual received signal, ***Y***, and the estimated received signal, $\hat{Y}$.

$$\hat{\hat{H}}_{LS} = argmin_{\{\hat{H}\}} \| \hat{Y} - Y \|^2 \qquad (10)$$

Thus, considering how the received signal has been defined in previous sections,

$$Y = \bar{H}X + N \qquad (11)$$

In order to estimate the channel, we can carry out the following operation,

$$\hat{\hat{H}}_{LS} = \frac{Y}{X} = \bar{H} + \frac{N}{X} \qquad (12)$$

Hence, LS Channel estimation is a simple method that provides good performance. However, since it depends on the noise when having a low SNR, the estimation error is increased, and its veracity is reduced.

B. MMSE Channel Estimation

The goal is to estimate the complex matrix $\overline{H}$. Assuming the training matrix is known, we can estimate the channel using minimum mean-square error, as described in,

$$\widehat{\overline{H}}_{MMSE} = \frac{SNR}{Nt} YX^{H}({R_{H}}^{-1} + \frac{SNR}{Nt} XX^{H})^{-1} \qquad (13)$$

being the MSE (Mean Squared Error),

$$J_{MMSE} = E\left\{\left\| \widehat{\overline{H}} - H \right\|_{F}^{2}\right\} \qquad (14)$$

where SNR is the signal to noise ratio, E{.} is the statistical expectation, $\|\,.\|_{F}$ refers to the Frobenius norm and R_H stands for the channel correlation matrix,

$$R_{H} = E\{H^{H}H\} \qquad (15)$$

In conclusion, the MMSE channel estimation has well performance but higher complexity. It requires the inversion of a $K \times K$ matrix, which implies a high complexity when K is large. Notice that it requires the channel statistical properties including the channel correlation matrix and that this method, unlike the previous one, considers the noise, what implies that for low SNR values it will present higher precision than the LS estimation technique.

5 Proposed Scheme to Estimate the Channel

This section will present a technical description of the channel estimation scheme used in this thesis. The most significant aspects to consider as well as a detailed analysis of how to approach the estimation and what issues to address in more depth.

The structure will be, first, present a technical description of the objective of this project, second, describe how to implement the channel estimation in a MIMO system and finally, explain the different technical aspects to consider when implementing the system as well as show an analysis of the performance for the different configurations that we find when implementing our MIMO system.

5.1 Technical Description of the Problem to be Addressed

In a MIMO system, since it is a wireless system, it is common to deal with a frequency selective channel. In previous work, a complete MIMO system has already been implemented assuming that the wideband channel is perfectly known by the receiver. Nevertheless, as discussed above, assuming the channel is known by the receiver is an ideal assumption since, in a real scenario, that could not be possible.

In this project, we aim to study how the wideband MIMO system would work without previous knowledge of the channel coefficients. This implies that a channel estimation technique will be required to be able to decode the received data with the minimum number of errors possible.

Thus, the first question to be answered is how to proceed to estimate the channel. Like we have seen in the section above, different techniques can be used to perform the estimation, however, we will estimate the coefficients by following the LS method since it is the simplest one.

Being the simplest method also implies lower quality results on its performance, then the point to be resolved is, would the performance quality given by this technique to estimate the channel be enough to perform reliable decoding?

Furthermore, once the estimation technique has been selected, we address several more technical questions that must be resolved for a good implementation of the channel estimation. These issues to be addressed are:

- How should we allocate the pilot symbols?
- How do we obtain the channel coefficients for the symbols transmitted out of the preamble?
- How many different channels should be generated to obtain reliable results?
- How does varying the length of the preamble affect our MIMO System?
- How does varying the number of taps affect our MIMO System?

These questions will be solved throughout the 5.2 section.

5.2 LS Channel Estimation Method

5.2.1 Proposed Scheme for LS Implementation

We have seen different ways of implementing the channel estimation since we cannot assume that the receiver has any knowledge about it. As we have said, we are going to use the LS method to perform the channel estimation.

First, before presenting the different issues to be addressed we are going to study how to implement the LS channel estimation for our scenario.

For this, several pilot symbols will be sent in a preamble of a length that must be selected to obtain a quality high enough to state that the channel estimation is reliable, in other words, the estimation of the coefficients and the real coefficients of the channel must present a low MSE.

Since a Rake receiver is going to be used, we have already discussed in section 2.4 that a knowledge of the coefficients is required. Implying that the LS channel estimation will be done at the receiver. As mentioned above, we will send some pilot symbols, allocated in a preamble, known to the receiver. Hence, if the symbols are received within the length of the preamble, the estimation will be performed.

Besides, we have already mentioned in previous sections the beneficial properties of ZC spreading sequences this type of sequence will be used to spread the pilot symbols. Hence, they will be orthogonal to each other, and no interference will appear.

Furthermore, they will be added a cyclic prefix, that is a copy of the last part of the symbol. Which is used to preserve orthogonality and to make the transmitted signal periodic, what plays a decisive role in avoiding inter-symbol and inter-carrier interference.

Considering the theory discussed in 4.2 and the transmission and reception schemes depicted in section 3.3.2 and 3.3.3 we know that the operation to be carried out is,

$$\widehat{\overline{H}}_{LS} = \frac{U}{b} = \overline{H} + \frac{N}{b} \qquad (16)$$

Where ***U*** is a matrix that contains all the correlated variables received, in other words, ***U*** contains the received symbol by each receive antenna (*Nr*), for each channel tap (*L*), and for each ZC circularly shifted code. Resulting in a 3-Dimensional matrix with all the output variables of the bank of correlators illustrated in Fig.13. Then, since it contains the received symbols, we must keep in mind that they will have noise mixed with the desired symbol to be decoded. On the other hand, ***b*** is the transmitted symbol.

Thus, to estimate the coefficients we must be careful when selecting the variables and do not forget that ***U*** is a matrix, and that ***b*** is a vector of *Nt* bits, where each bit composing the symbol is transmitted by a different transmitting antenna. This means being aware at all times of which antenna is transmitting, which one is receiving, as well as the ZC code that the transmitting antenna used to spread the sequence.

Implementing this in MATLAB is as simple as making a loop depending on those variables, resulting on:

```
for nr = 1:Nr
for nt = 1:Nt
for t = 1:L
H_estim(nr,nt,t)=U(nr,t,codes_used(nt)).*(b(nt)./((abs(b(nt))).^2));
end
end
end
```

Where ***U(nr,t,codes_used(nt))*** will give us the symbol received by antenna *nr*, at the tap *t* and correlated with the ZC code used to transmit it. In addition, ***b(nt)*** gives us the bit of the symbol transmitted by the transmitting antenna *nt*.

Then, once the channel coefficients have been estimated for each pilot symbol transmitted within the preamble length the next step is to wonder, where do we allocate the pilot symbols of the preamble? How do we obtain the coefficients of the channel when transmitting those symbols not known to the receiver? Both questions will be addressed in the following section.

5.3 Technical Aspects to be Addressed

5.3.1 Pilot Symbols Allocation

The LS channel estimation technique is a training-based method, meaning that it works by sending several symbols already known to the receiver, these are called pilot symbols. Hence, before starting to implement the estimation we should ask ourselves, which kind of pilot allocations can be found? Which one would suit better for our scenario?

When thinking about sending pilot symbols we find that there exist four generic time-frequency training symbol allocations.

A. This type of time-frequency allocation is useful in highly frequency-selective channels with moderate to slow fading (see Fig.15 a).

B. In contrast, this other allocation is commonly used when we have a moderate frequency selective channel, but the Doppler effect is relatively high, resulting in fast fading (see Fig.15 b).

C. This allocation strategy can be employed when the channel has moderate frequency selectivity and Doppler (see Fig.15 c).

D. The allocation type depicted in Fig.15 d, is employed when a scenario such as the one described in case C is presented.

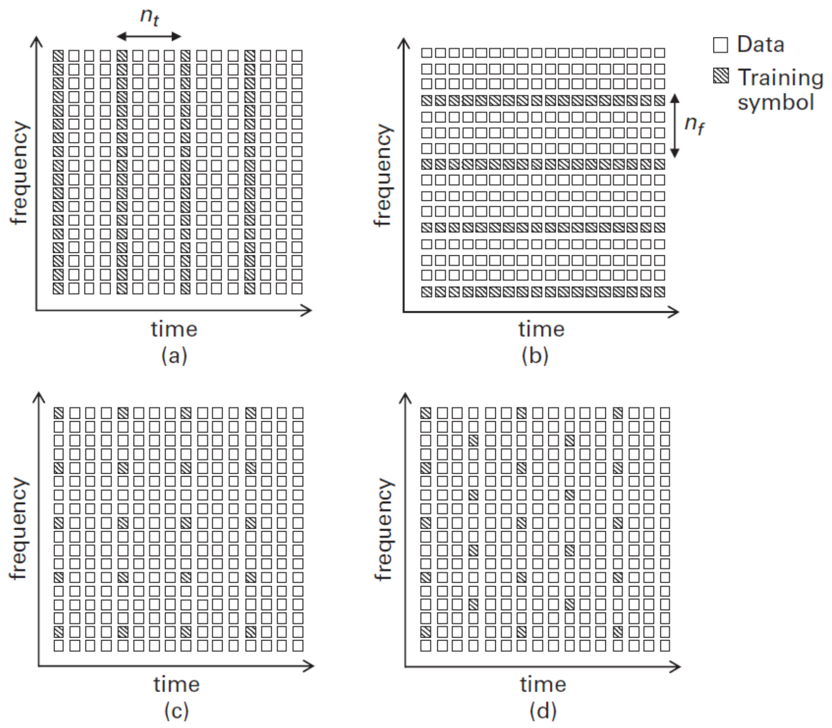

Figure 15. Four generic time-frequency training symbol allocations.

Let *ηt* denote the time spacing between pilots and *ηf* denote the frequency spacing between pilot symbols.

Even though these four types of allocations are used nowadays as far as a MIMO system is concerned the pilot symbols allocation may be a combination of these shown in the figure above.

Pilot allocations used in actual wireless MIMO systems are depicted in the illustration of Fig.16. Concretely, the type of allocation utilised by packet-based systems such as 802.11n is shown in Fig.16 a, whereas the one used by non-packet-based systems such as LTE, LTE-Advanced, and WiMAX is shown in Fig.16 b.

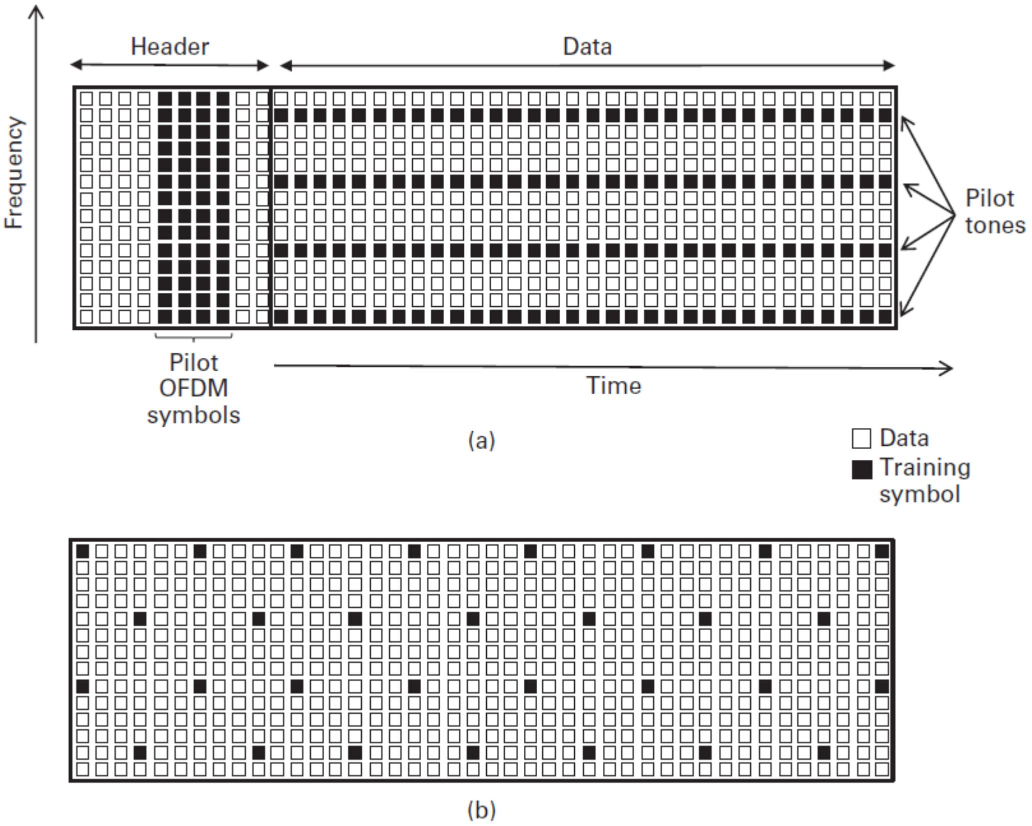

Figure 16. Pilot allocations used in actual wireless MIMO systems

Once presented the most used pilot symbols allocations, we must select which one to implement in our LS channel estimator. For simplicity, in this thesis we will send a preamble of pilot symbols at the beginning of the transmission. Then, the next step is to decide the length of the preamble as well as the process to be followed when there are no training symbols left.

5.3.2 Estimation of Channel Coefficients when Transmitting Data Symbols

The channel we are dealing with is a wideband/frequency selective channel that follows a Gaussian distribution, implying zero mean and variance.

In a real scenario our channel would vary in time, meaning that for each symbol transmitted the channel would have different coefficients. However, in this study we are going to assume a slowly changing channel, that is, the channel is approximately time invariant, and the coefficients will not vary much over time, being roughly the same for every transmitted symbol.

Considering this assumption, the complexity of the problem is highly reduced because if the channel was considered time variant, we should have to interpolate the results obtained for the channel estimation over the preamble. But, with a non-time variant channel where the pilot symbols are allocated in an initial preamble, the channel coefficients for the remaining symbols to be transmitted can be obtained by averaging all the coefficients already estimated in such a way that the obtained channel estimated coefficients are more precise and provide more reliable and robust results.

5.3.3 Number of Channels

In order to compare the results obtained we will generate the same channel for each SNR point, however, generating only one channel would give us poor results, i.e., they would be unreliable. To obtain accurate results, we are going to generate several channels and obtain values indicating how the performance in each of them has been. So, the graphs to be analysed will be obtained by averaging the results for each generated channel and each SNR value.

As a first approach, for the study of the performance in the following sections we had started with the generation of 100 different channels. However, if we look at Fig. 17, we can see that for the highest SNR values the behaviour of the estimated channel differs from the behaviour followed throughout the analysis. This happens because, as the quality of the received signal is better, we need to average over more channels to obtain a number of bit errors that shows the same behaviour as for lower SNR values, i.e., now the probability of finding an error is lower although it will never be zero as noise is always introduced when transmitting. Therefore we cannot rely on the results obtained when generating few channels.

To find the right number of channels to generate, we start by generating a number of channels so large that we can look at it as if we were generating infinite channels and so, by comparing, we can see if the result varies a lot by reducing the number of channels to average over. If it varies a lot, it means that we will have to generate more channels. In our case, we found that by averaging over 500 different time-invariant channels, the result seems to be like what we would get if we could average over an infinite number of channels.

Hence, in next sections we will average over 500 channels, a number high enough to obtain a graph showing the same behaviour for all SNR values.

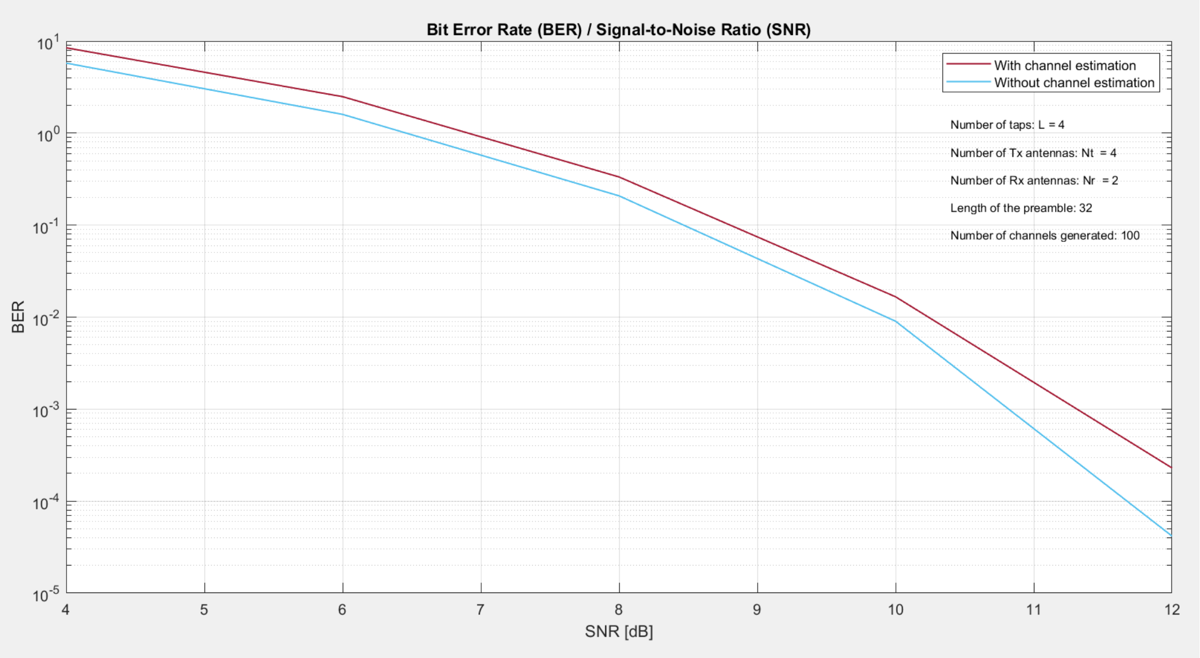

Figure 17. Not reliable BER/SNR graph for a 4x2 MIMO System

5.3.4 Length of the Preamble

Once the technique to estimate the channel has been selected, the assumption of having a time invariant channel and the decision of allocating the pilot symbols in an initial preamble have been done, the next step is to figure out the minimum length of the preamble to obtain a reliable performance.

This is an important aspect, because the longer the length of the preamble the greater the accuracy of the estimation, however we are using more power to transmit pilots and therefore wasting power that could be used to transmit data. Hence, having more precise channel estimation implies sacrificing power destined to transmit data. Then the question is, how long must the preamble length be to obtain accurate results but not waste too much power?

Usually, powers of two are the lengths set for the preamble. In the next point, the estimated channel coefficients will be compared with the real channel coefficients, and it will be studied the impact of changing the length of the preamble.

Although no results have been observed yet, as previously discussed, we should expect some results showing that the larger the length of the preamble, the better the accuracy of the estimation.

5.3.4.1 Discussion & Results of Different Preamble Lengths

First, a preamble length of 2^4 has been selected, which will be increased in powers of two thereafter, resulting in 16, 32, 64 and 128 the different lengths to be analysed. More concretely, we are going to study how affects changing the length of the preamble in a 2x1 MIMO. For this, to compare the performance for different SNR values, the same invariant channel has been generated for each SNR point.

In the case of illustration 18, a MIMO 2x1 channel with 4 taps and length of the preamble 16 pilot symbols, we can see that for SNRs between 4 and 10.5 dB, approximately, the BER is almost one. Meaning that the quality of the channel is so poor that it is not possible to transmit under these conditions because there are going to be errors for sure. But, when the SNR increases the BER starts to decrease reaching BERs of almost 10^{-2} when the SNR equals to 14 dB, what indicates that with this SNR value a transmission could be possible. However, a high SNR is required to be able to transmit in a reliable way.

In addition, when focusing on the channel estimation performance we observe that both performances are quite accurate, in other words, there is not a significant change in its performance when the channel is estimated, as the coefficients are unknown, so we can state that the channel estimation seems to work properly for our scenario since both curves follow the same behaviour.

It can also be highlighted the fact that when estimating the channel, we are producing an error and therefore the BERs we get when estimating the coefficients (independently of the SNR value) are always higher than the ones we get when we assume that the receiver has previous knowledge of the channel.

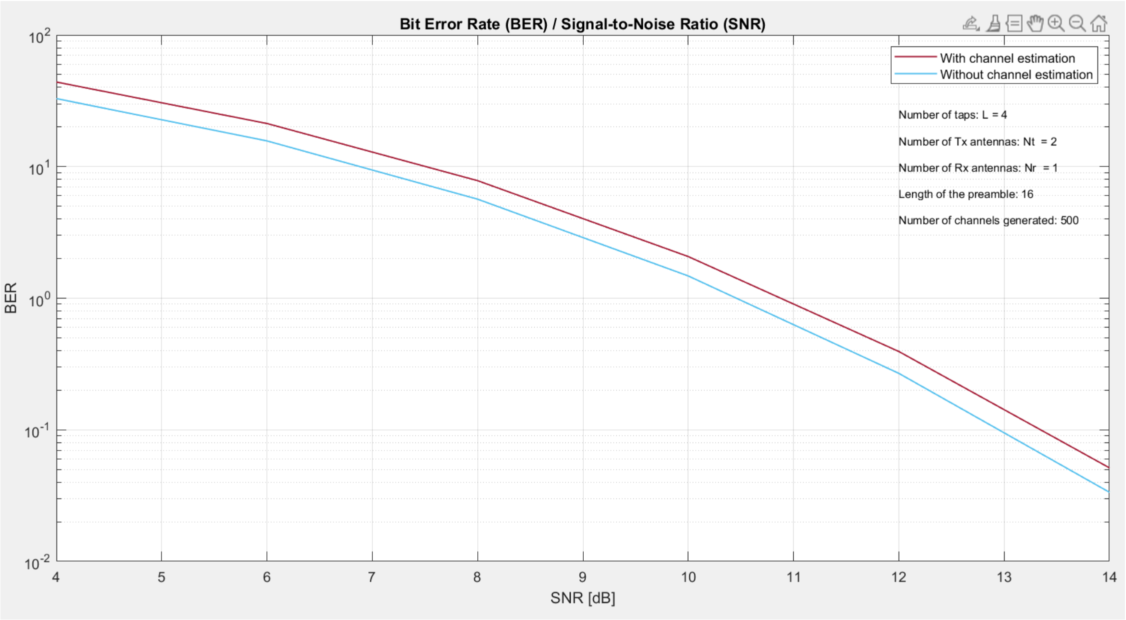

Figure 18. BER/SNR for a MIMO 2x1 channel with 4 taps and length of the preamble 2^4 pilot symbols

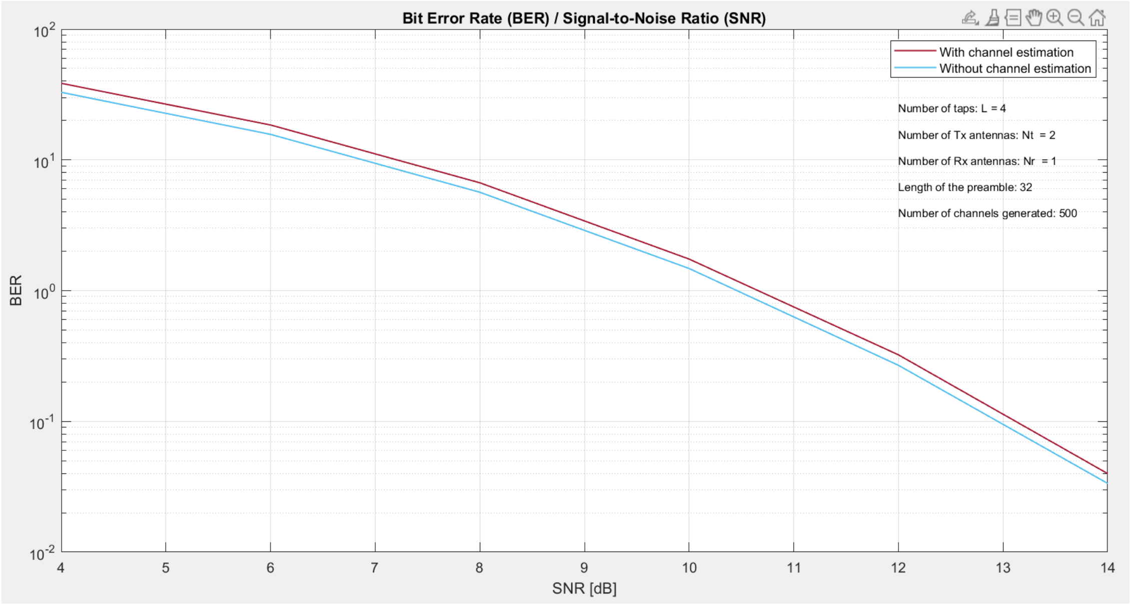

Figure 19. BER/SNR for a MIMO 2x1 channel with 4 taps and length of the preamble 2^5 pilot symbols

If we increase the length of the preamble up to 2^5 (Fig.19), we do not observe any improvement regarding the quality of the system. Nevertheless, the accuracy of the estimated channel highly improves, but since the quality of the system is still poor under these conditions, we should have SNR values such as 13-14 dB for being able to have a reliable transmission.

On the other hand, Fig.20 depicts the behaviour of a MIMO 2x1 channel with 4 taps and length of the preamble 2^6. Like in the previous cases analysed, the BERs reached are of the same order. However, there is a very significant improvement over the estimation of the channel since both lines are sufficiently narrow to be barely distinguishable.

We have stated before that higher estimation quality implies lower values of power to transmit data. Therefore, at this point, looking at Fig.20, we can deduce that we will not need higher values of the preamble length since the accuracy of the estimated system is already very high.

Finally, the last graph (Fig. 21) indicates that with a preamble length of 128 the channel estimation is almost perfect, obtaining practically the same results as if the channel was known to the receiver. Although the estimation is of very good quality a transmission under these conditions is not the best option since the probability of error does not decrease until we reach SNRs such as 13.5-14 dB. Moreover, as explained for the case of length 64, we do not need such a good quality of channel estimation to make it worth spending more power on transmitting more pilot symbols and thus wasting the possibility of using it with data symbols.

After having analysed the different cases, it can be concluded that independently of the length selected for the preamble, the 2x1 MIMO system with 4 channel taps requires high SNR values, that is, high transmit power, to be able to perform reliable communications. But, why do not we see any improvement in transmission quality when we increase the length of the preamble?

Changing the length of the preamble does not affect to the quality of the system but only to the accuracy of the estimation. This is because to increase the quality we should add more diversity, in other words, we should increase the number of transmit and/or receive antennas or increase the number of channel taps to approach higher diversity order. To verify this, we are going to analyse the same cases but when having a 4x2 MIMO system.

Would the estimation improve for systems with higher diversity order? Would we obtain a higher quality transmission than for a 2x1 system? All these aspects will be solved when analysing the 4x2 MIMO System in the section below.

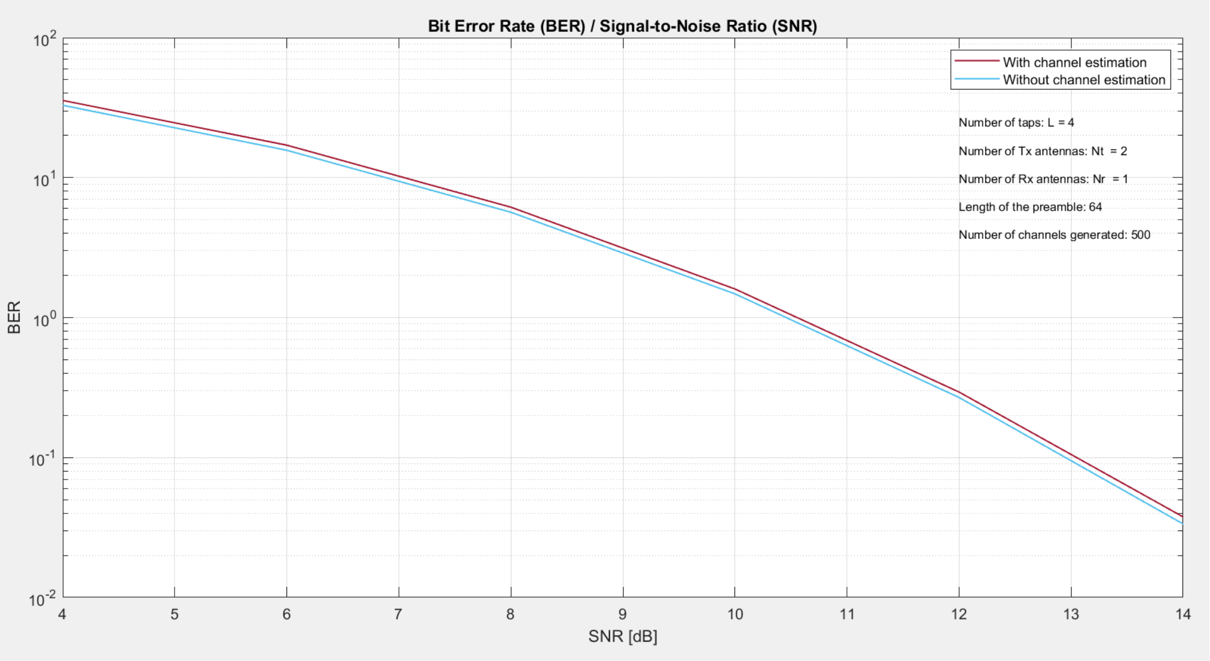

Figure 20. BER/SNR for a MIMO 2x1 channel with 4 taps and length of the preamble 2^6 pilot symbols

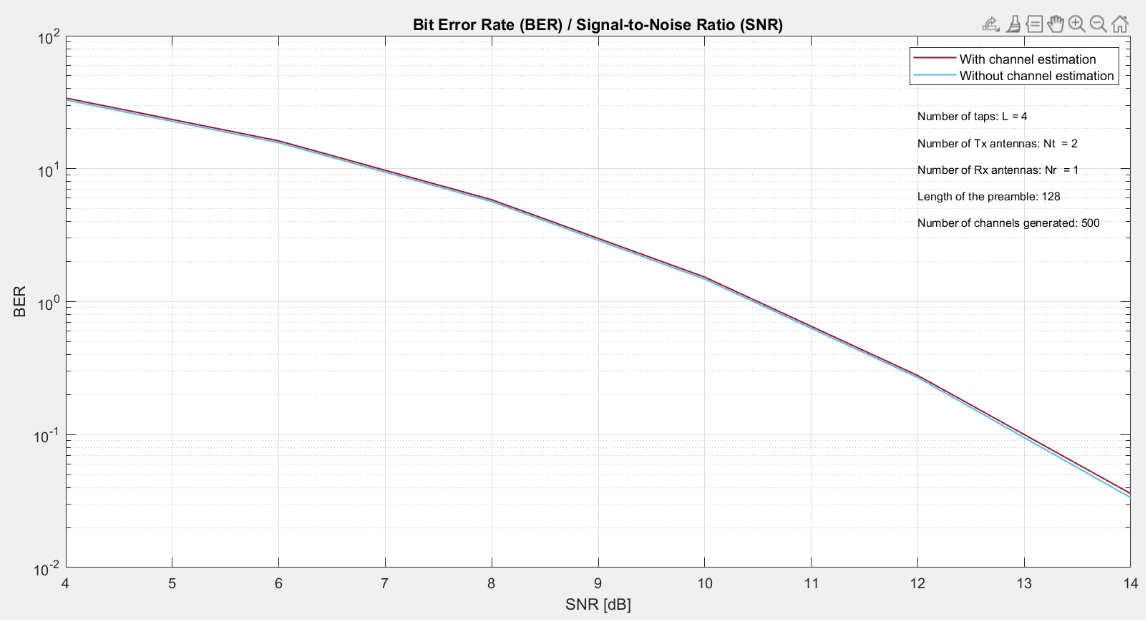

Figure 21. BER/SNR for a MIMO 2x1 channel with 4 taps and length of the preamble 2^7 pilot symbols

5.3.4.2 Discussion & Results of Different Preamble Lengths in a System with Higher Diversity Order

To analyse the impact of changing the length of the preamble in a higher quality system, the diversity order must be increased. We can add diversity to the system in many ways, however, in this thesis we have decided to increase the diversity by increasing the number of transmit and receive antennas. Hence, for this section we will be analysing a 4x2 MIMO System.

In the above section the performance of a 2x1 MIMO System was presented, and the analysis of it has led us to take advantage of the diversity to try to rise the quality of the system and thus have reliable transmissions for lower SNR values, being able to obtain lower BERs.

In this section we will illustrate how the system works when the length of the preamble equals to 32, 64 and 128. The first case analysed in the last section, length equal to 16 pilot symbols, has not been included for this analysis since the aim is to observe how increasing the diversity order and the length of the preamble affects to the behaviour of the system. That is, including the case of length 16 pilot symbols will not facilitate the understanding of it because, as concluded in the section above, the quality of the system will be approximately equal to the cases depicted below (length 32, 64 and 128).

In Fig.22 it is shown how having added diversity to our system makes it significantly more reliable. Comparing it to the one analysed in Fig.19, now we obtain BER values under 1 for SNR higher than 8/8.5 dB, approximately, instead of 10.5 dB that were required for the 2x1 MIMO.

Regarding the performance of the channel estimation, we can see that the difference between both curves is almost the same as the one analysed in the previous section. Although it is similar, the difference obtained between estimated and non-estimated channel differs in 1 unit for the 2x1 MIMO (preamble length=32), however, it differs in 2 units for a 4x2 MIMO (preamble length=32), meaning that the accuracy of the estimation has been better for the 2x1 system. Indeed, it is important to remark that the lower the number of transmit/receive antennas the lower the number of channel coefficients to estimate, then, there exists less likelihood of having a large error in the estimation.

This result follows as expected since there is no direct relationship between the performance of the estimation method and the number of transmit/receive antennas.

On the other hand, if we focus on Fig.23 and Fig.24, a great improvement in the estimation of the channel coefficients is observed. Specifically, in Fig.23 both curves are relatively close, whereas, in the case of Fig.24 the curve obtained by estimating the channel practically does not differ from the curve obtained assuming that the channel is known, resulting in an almost perfect estimation. Aspect that has already been concluded for the case of a 2x1 MIMO system.

Therefore, regarding the length of the preamble necessary to obtain reliable transmissions, the results coincide with those obtained previously, as expected. A length equal to 32 or 64 is a sufficiently long length to provide a good estimation quality, taking into account the fact that it is wasted energy from the point of view of the power that could be used to transmit data.

Nevertheless, from the point of view of having a good quality system to do not need high SNR values to obtain reliable results, it can be observed that with a 4x2 MIMO System we can achieve BERs of the order of 10^{-3}, whereas with a 2x1 MIMO System the lowest BER we had obtained was almost 10^{-2}. This implies that by adding diversity we have reduced the probability of error by an order of magnitude. As an example, in a 4x2 MIMO System with length of the preamble 128, for a SNR = 12 dB, a BER equal to 10^{-2} is obtained, however, in a 2x1 MIMO System with length of the preamble 128, for a SNR = 12 dB, a BER a little bit lower than 10^{-1} is achieved.

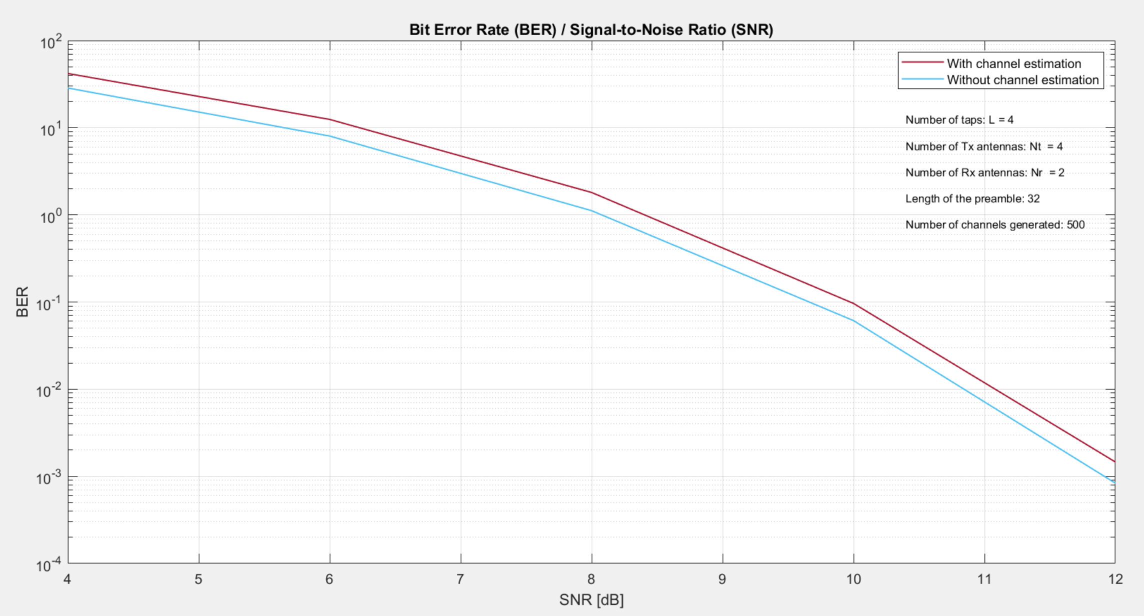

Figure 22. BER/SNR for a MIMO 4x2 channel with 4 taps and length of the preamble 2^5 pilot symbols

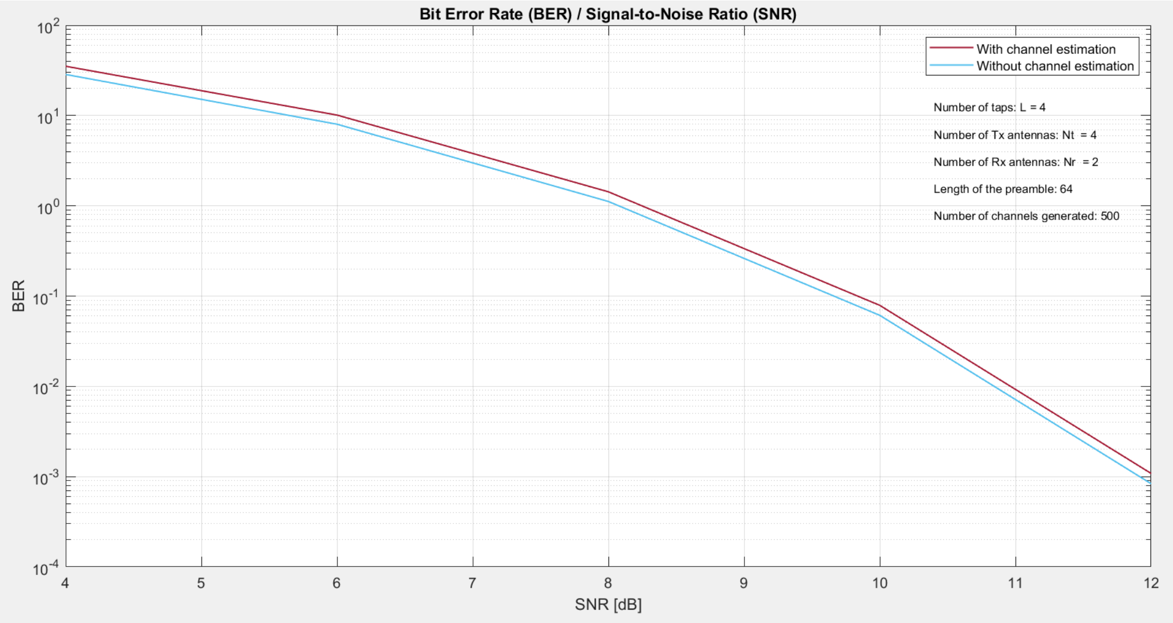

Figure 23. BER/SNR for a MIMO 4x2 channel with 4 taps and length of the preamble 2^6 pilot symbols

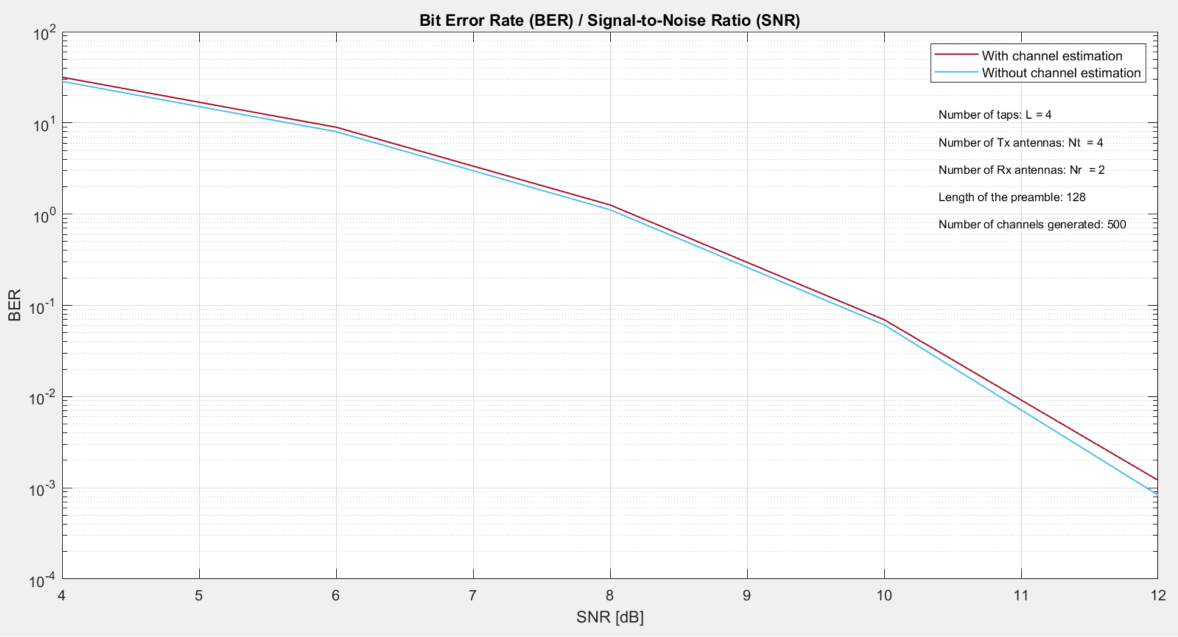

Figure 24. BER/SNR for a MIMO 4x2 channel with 4 taps and length of the preamble 2^7 pilot symbols

Finally, another important aspect to be aware is that since the results obtained when employing the channel known to the receiver and the ones obtained when employing the estimated channel are similar enough, we can state that having selected an initial preamble to send all the pilot symbols has been a choice that works properly for our scenario. Hence, there is no need to change the pilot symbols allocation.

Besides, the accuracy of the estimation is sufficiently good for high SNR values, what would not be like that if we had SNRs such as 0 dB. This aspect is because of the LS method does not consider the noise when performing the estimation, what means that when transmitting with high values of noise the precision of the estimation will be negatively affected as it has no way of reducing/considering noise effect when estimating.

5.3.5 Number of Taps

In section 4.1 we discussed the impact of increasing the number of channel taps when a coherent detection technique such as LS estimation is carried out.

We have reached the conclusion that for this type of techniques, the higher the number of taps the better the performance. However, is this how our implemented system works?

Moreover, in previous points a higher order of diversity has been approached by adding more transmit and receive antennas. Nevertheless, another way of rising the diversity order is increasing the number of taps, what has not been analysed yet.

The aim of the following section is to analyse the impact of changing the number of taps and thus, confirm that what we obtain follows the theory previously explained. To achieve this, the system to be analysed will be a 4x2 MIMO System with 64 pilot symbols in the preamble although the same conclusions would be approached analysing a 2x1 MIMO System.

5.3.5.1 Discussion & Results of Different Number of Taps

Since we already know the number of channels that we must generate to obtain reliable results, how varying the length of the preamble affects, as well as the diversity effect in our MIMO system, for this analysis we will be varying the number of channel taps in a 4x2 MIMO System with a fixed preamble length of 64 pilot symbols, to observe if, following the theory seen, the higher the number of taps the better the performance.

First, we will start by analysing the performance of a 4x2 MIMO System with L=1. Observing Fig.25 we can appreciate how the quality of the system has significantly decreased when comparing it with the quality of the 4x2 MIMO System with L=4 and preamble length 64 seen in the previous section (Fig.23). Specifically, the minimum BER obtained is not much lower than 10^{-1} for a SNR=12 dB. Hence, it can be seen as like the performance obtained for a 2x1 MIMO wit L=4 and length of the preamble 64.

Indeed, the purpose of increasing the number of taps as well as the number of transmit/receive antennas is to add diversity, then, it is understandable that the results for a 4x2 MIMO with L=1 are similar to the ones obtained for a 2x1 MIMO with L=4, since although for the case in Fig.25 we have increased the diversity order by adding antennas, at the same time, it has been decreased by using less number of taps.

However, in the case of 2x1 MIMO with L=4, BER equal to approximately 10^{-1} is approached for SNR=14 dB, what implies that increasing the number of transmit/receive antennas provides better quality communications than increasing the number of taps.

On the other hand, when adding 1 order of diversity by increasing the number of taps by one, that is we have L=2 taps, and transmitting with 12dB of SNR a BER of a little bit less than 10^{-2} can be obtained (Fig.26). This result seems to follow the theory discussed in 4.1 because the quality has improved when we have transmitted with a greater number of taps. Nevertheless, in order to state this a deeper analysis must be performed.

Continuing with the study, depicted in Fig.27 it can be seen how the BER has decreased until 10^{-3} for a SNR equal to 12 dB. Moreover, if we compare the illustration in Fig.27 (L=3) and the illustration in Fig.23 (L=4), we can see a slight improvement in the resulting BER for 12 dB of SNR when transmitting with 4 taps instead of 3, however it is easy to see the improvement of the quality of the link for L=1 and L=2.

To conclude, regarding the analysis performed of the impact that varying the number of taps has on the quality of the system performance, we can state that as seen in the theory above, the greater the number of taps the better the performance of the system.

Another significant conclusion to highlight is that there exists a number of taps for which increasing it more is not worth it since, although the quality of the system is better, the improvement is not highly significant.

It is important to remark that these two conclusions are not contradictory as the quality increases with the number of taps but does not increase in the same way when changing from L=1 to L=2 than from L=3 to L=4 since the quality is already quite high.

Finally, it has been seen how the different ways of increasing the diversity affect the system. On one hand, it has been proved that adding more transmit/receive antennas provides better results regarding the diversity than increasing the number of taps but, why does this happen? It is because if we have 1 transmit antenna with 2 taps for a transmission path, when we increase the number of transmit antennas (Nt=2) we are, indeed, doubling the diversity as now each antenna transmits over 2 channel taps, making a transmission over a total of 4 channel taps.

On the other hand, although the best results have been obtained for a 4x2 MIMO with L=4 we should be aware of our physical limitations, like the memory required, or our economic limitations since maybe adding more antennas is not possible.

In addition, in a real scenario the number of taps cannot be selected because it depends on the Power Delay Profile, in other words, it depends on the multipath propagation scenario we are facing on that precise instant. Meaning that the number of channel taps depends on the quantity of reflections produced by the different objects that can be found in the environment and then, it is a parameter that cannot be fixed or known in advance.

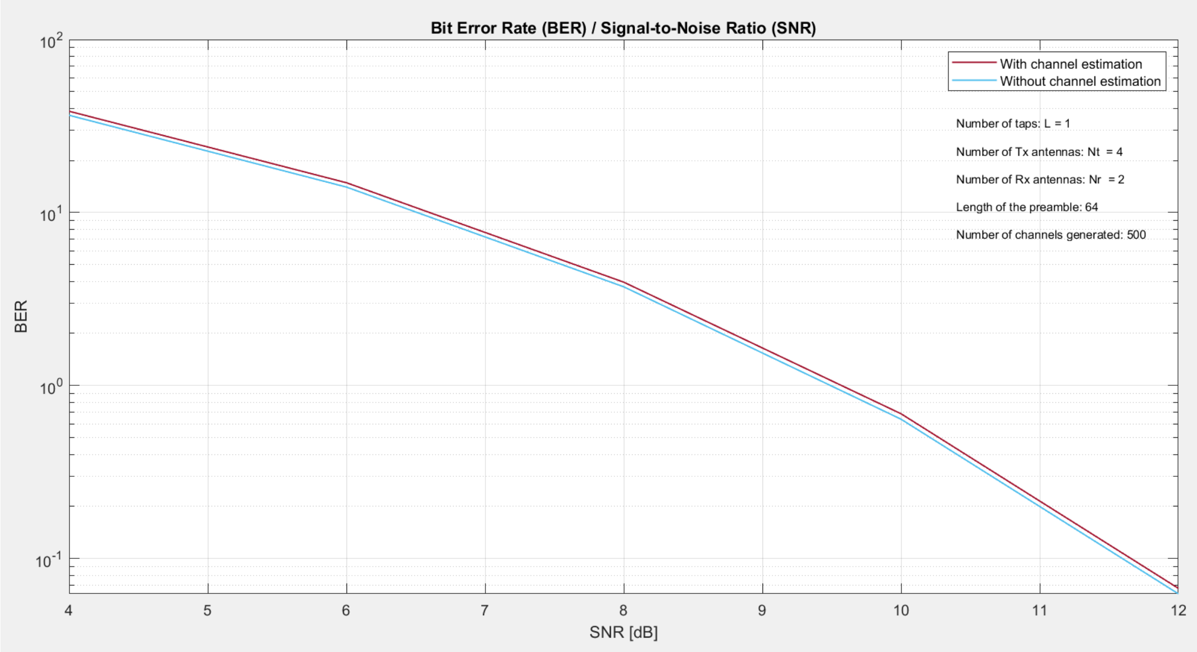

Figure 25. BER/SNR for a MIMO 4x2 channel with 1 tap and length of the preamble 2^6 pilot symbols

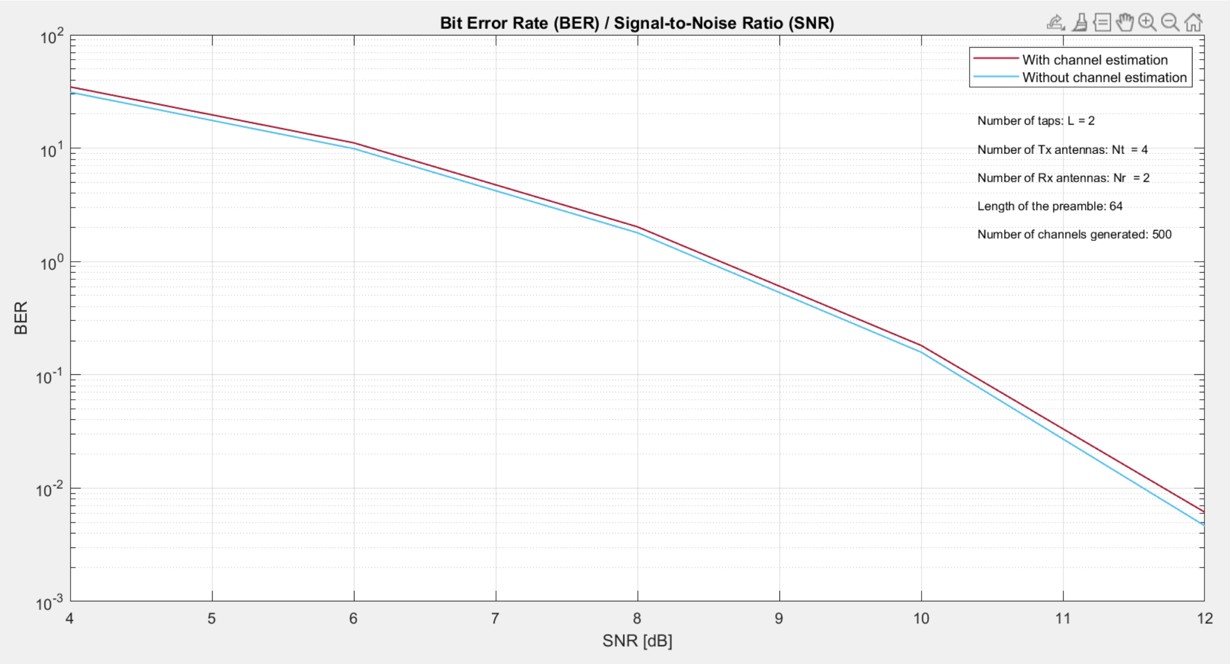

Figure 26. BER/SNR for a MIMO 4x2 channel with 2 taps and length of the preamble 2^6 pilot symbols

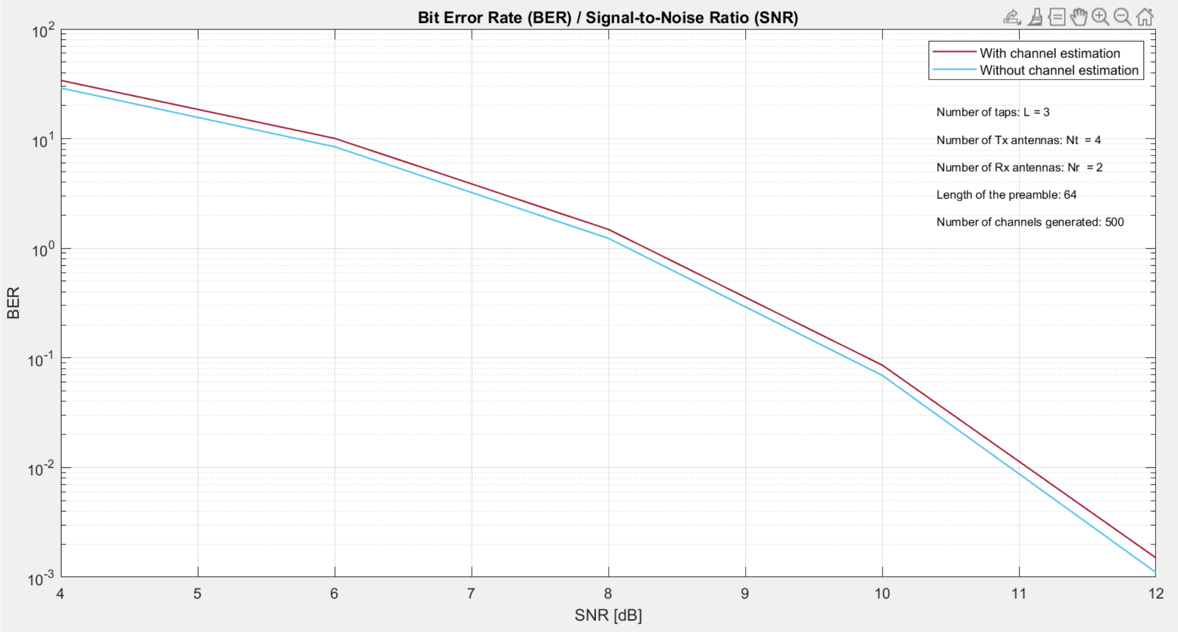

Figure 27. BER/SNR for a MIMO 4x2 channel with 3 taps and length of the preamble 2^6 pilot symbols

6 Evaluation of Results and Future Work

The results of the proposed scheme for the LS channel estimation were overall successful. We have shown how to overcome the problem of estimating the channel coefficients when facing a Rayleigh Frequency Selective channel.

The figures depicting the Bit Error Rates show that we achieved the desired diversity order to provide robust and reliable communications in a frequency selective channel. In addition, the simulations show that the LS technique provides significantly good accuracy in estimating the channel for the studied scenario. Nevertheless, it has also been showed that it is problematic to increase the length of the preamble with pilot symbols since it implies less power available to transmit data, thus, there exists such a length for which increasing it more is not worth it.

However, there are some aspects that have not been extensively researched in this thesis and could be of interest to analyse in future work. To increase the quality of the transmission we presented another scheme based on an increase in the number of channels taps, but it has been showed that this is not possible in a real scenario as the number of taps depend on the Power Delay Profile, hence, it would be interesting to analyse the performance of the estimation for other Power Delay Profiles (PDP).

In addition, it could be of interest introduce different coding techniques to obtain more reliable communications and analyse how the system responds for each one and whether it offers lower values of BER or conversely the improvement of the system performance is not highly significant.

On the other hand, for all the schemes presented in the thesis we have assumed a time invariant channel. Meaning that we estimated the coefficients for each pilot symbol sent, then these results were averaged to obtain a value closer to the actual channel coefficients and finally, when transmitting data, we did not need to change any coefficient since we could assume they remained approximately constant for the whole transmission. However, studying a scenario without this assumption might be attractive as an interpolation between estimated coefficients may be performed.

Indeed, there remains work on studying a proper technique to estimate the channel when we face a time variant frequency selective channel as well as on how to improve the quality of the system and decrease the BER. Moreover, other type of spreading techniques as well as other estimation methods can be examined.

Finally, all the results are a result of stochastic simulations. As the results were overall successful, it would be interesting to test the LS estimation technique scheme in an actual physical system

7 Conclusion

Two DSSS MIMO schemes in frequency selective channels are presented in this thesis to test the LS channel estimation technique as well as the impact of varying the length of the preamble and the number of taps. The main problem to overcome is that in a real scenario for conventional, coherent receivers, the effect of the channel on the transmitted signal must be estimated to recover the transmitted information. In this project it has been examined the performance of the Least Square Technique in a Frequency Selective Rayleigh channel.

Firstly, after studying different ways of allocating the pilot symbols, an initial preamble has been selected for its simplicity and because it fits well with our scenario as we have assumed a time invariant channel. It has been showed that the results obtained with this allocation are significantly successful, meaning that the accuracy of the estimation when using LS technique and an initial preamble is good enough. Moreover, after a deep analysis of the impact of varying the length of the initial preamble it has been showed that we need large lengths to obtain accurate results but there exists a length for which increasing it more is not really worth it since we are wasting resources, that is, we are wasting power available for data transmission.

Secondly, different ways of increasing the diversity order have been compared and tested. The first attempt was to increase the number of transmit and/or receive antennas in order to reduce the BER and to obtain more reliable and robust transmission results. Another option presented was to increase the number of channel taps, as another way of increasing the diversity order. However, as already explained, this is not a parameter that can be selected when facing a real transmission and for this case, we have also concluded that there exists a number of taps for which increasing it more does not offer significant improvements.

Finally, it has been proved that adding more transmit/receive antennas provides better results regarding the diversity than increasing the number of taps, however, there still remain other ways of increasing the diversity order as well as other channel estimation techniques that have not been analysed in this project and could present attractive results for our communication scenario.

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Appendix

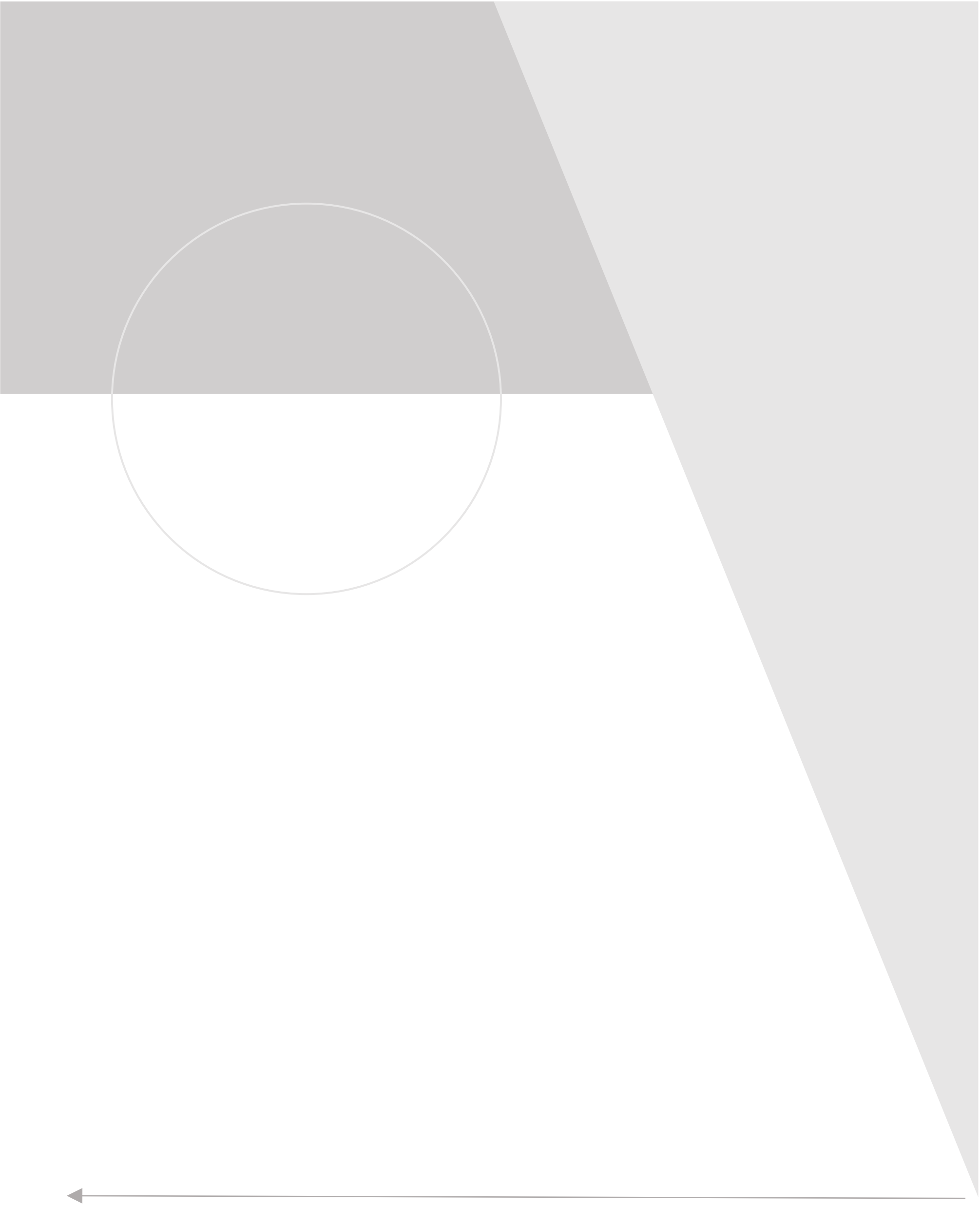
This annex includes the MATLAB code used to implement and test the performance of the MIMO System described in the thesis.

The complete code can be accessed through the following link:

Github_Matlab_Code_Bachelor_Thesis_Paula_Ballester

In this Github repository we can find the following files:

- *MIMO_NrxNt_channel_Estim_V2:* Main script, includes the whole MIMO System implementation.
- *Channel_EstimationLS:* Function that includes the code to estimate the channel coefficients using the LS Technique.
- *create_Ulib:* Function that includes the code to create a matrix with all the possible received messages.
- *create_Ulib_estim:* Function that includes the code to create a matrix that includes all the received messages.
- *select_codes:* Function that includes the code that indicates the Zadoff-Chu code employed by each transmit antenna.
- *decodif:* Function that includes the code to decode the received message.



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