# MATLAB implementation of an emulator of the downlink physical layer of the LTE system

**A Degree Thesis**

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**by**

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**In partial fulfilment**

**of the requirements for the degree in**

**Telecommunications Systems Engineering**

## Advisor: Ferran Casadevall Palacio

## Barcelona, May 2016

## Abstract

LTE (Long Term Evolution) and LTE-A (Long Term Evolution Advance) are two mobile communication standards nowadays are intensively being deployed around the World. Their benefits are meaningful both for users and network exploiters; users take profit of a better bit data rate and network exploiters reduce costs related to network infrastructures.

In this project two main tasks have been performed. Firstly, an analysis of the LTE physical layer in downlink domain, secondly, a GUI (Graphical User Interface) has been developed as an academic tool with the purpose to study the LTE system. Both tasks have been carried out by the use of MATLAB software, which provides some features that allows performing these tasks.

The scope of this project is mainly academic. In one hand, a better comprehension for mobile communications networks has been acquired by the author. On other hand, a tool for other people is provided. They don't have to be aware how the code works: only they need to select the desired parameters and then the system simulation is performed.

## Resum

LTE i LTE-A són dos estàndards de comunicacions mòbils que s'estan desplegant de forma intensiva en tot el Mon. Els seus beneficis son rellevants tant per als usuaris com per als explotadors de les xarxes; els usuaris treuen profit d'una taxa de transmissió de dades més altes I els explotadors de xarxes redueixen costos relacionats amb les infraestructures de xarxes.

En aquest projecte s'han dut a terme dos tasques principals. Primerament, un anàlisis de la capa física de LTE en enllaç descendent. També s'ha creat una GUI com a eina acadèmica amb el propòsit d'estudiar com funciona el Sistema LTE. Ambdós tasques s'han fet mitjançant l'ús del software MATLAB, el qual proporciona moltes facilitats que permeten realitzar aquestes tasques.

El propòsit del projecte és bàsicament acadèmic. Per una banda, l'autor ha adquirit una millor comprensió de les xarxes de comunicacions mòbils. Per una alter banda es proporciona una eina perquè la facin servir altres persones sense que hagin de conèixer com funciona el codi, sinó que simplement han de seleccionar els paràmetres del Sistema LTE i amb això ja es duu a terme la simulació del sistema.

## Resumen

LTE y LTE-A son dos estándares de comunicaciones móviles que se están desplegando intensivamente en todo el Mundo. Sus beneficios son significativos tanto para los usuarios como para los operadores de redes; los usuarios sacan provecho de una mayor tasa de transferencia de datos y los operadores de red reducen costes relacionados con las infraestructuras de redes.

En este proyecto se han llevado a cabo dos tareas principales. Primeramente, se realizó un análisis de enlace descendente de la capa física del Sistema LTE. Posteriormente se ha creado una GUI como herramienta académica con el propósito de facilitar el estudio del sistema LTE. Ambas tareas se han llevado a cabo con el uso del software MATLAB, que proporciona muchas facilidades para realizarlas.

El propósito de este proyecto es académico. Por un lado al autor ha adquirido una mejor comprensión de las redes de comunicaciones móviles. Por otro lado, se ha desarrollado una herramienta para que puedan usarla otras personas, sin que sea preciso que conozcan cómo funciona el código: simplemente necesitan seleccionar los parámetros deseados del sistema y luego realizar la simulación del sistema.

## Dedication

This project has been possible thanks to advisor and supervisor Ferran Casadevall Palacio, who has given to me a set of guidelines and advisors. Also has giving to me an academic support, revising some concepts about LTE physical layer concepts.

Also I would like to mention my family and friends, whom have supported me not to fail on the road.

# Revision history and approval record

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| Position | Project Author | Position | Project Supervisor |

# Table of contents

# List of Figures

# List of Tables:

# 1. Introduction

Since the appearance of smartphones and tablets in the end-user life, the new set of available services has increased. Nowadays it's not necessary to use your personal computer or laptop for watching a video via streaming or for making a videoconference with somebody. Even it's not necessary to use Wi-Fi networks while using these services. It's just necessary to contract a data plan with a MNO (Mobile Network Operator) and use a device compatible with the standard.

LTE is the most well-known almost-4G ($4^{th}$ Generation) standard and, for its characteristics, fits correctly to provide the services described before. In fact, 4G mobile networks are the first to accomplish, with a good enough performances, the same services that wired technologies provide. ADSL (Asymmetric Digital Subscriber Line) or FTTH (Fiber to the Home) are examples of these technologies used in wired networks.

This document consists in describing the LTE physical layer analysis in downlink domain, performed by using MATLAB. Afterwards, some details of this analysis are used on the created GUI (Graphical User Interface), which allows the students to simulate the LTE system without having to go further in the details of the code. The author has chosen this thematic because he is really interested on mobile communications standards and, as being LTE one of them as well as has been developing while studying Degree in Engineering Telecommunications, realized that the matter was something new.

The project has been proposed by GRCM (Grup de Recerca de Comunicacions Mòbils) research group of the TSC (Teoria del Senyal I Comunicacions) department, and has been supervised by the professor Ferran Casadevall. The first part of the project is a tool which has a self-learning purpose, while the second part has an academic purpose.

This document consists of six sections, being this first section, the introduction where the project purposes, requirements and specifications are defined. Work plan, WP (Word Packages) and Gantt diagram of the project are also included. In the second section, a state of the art is carried out placing the reader into context. In the third section, the LTE system tools applied to the project are presented, being used at fourth section, which shows some obtained project results. Later on, the fifth section is devoted to provide a short economical explanation about the project. Finally, in the sixth section, conclusions and future lines are highlighted.

## 1.1. Target

- Obtain a detailed knowledge about how works the LTE physical layer in downlink domain TM1 (Transmission Mode 1) in FDD (Frequency Division Duplexing) mode.
- Analyze, by means of a MATLAB simulation program, the knowledge acquired at the point before.
- Create an academic-purpose GUI using MATLAB.
- The use of English, a non-native language for the writer, to develop the project. Besides, it's a way to improve the author's English skills.

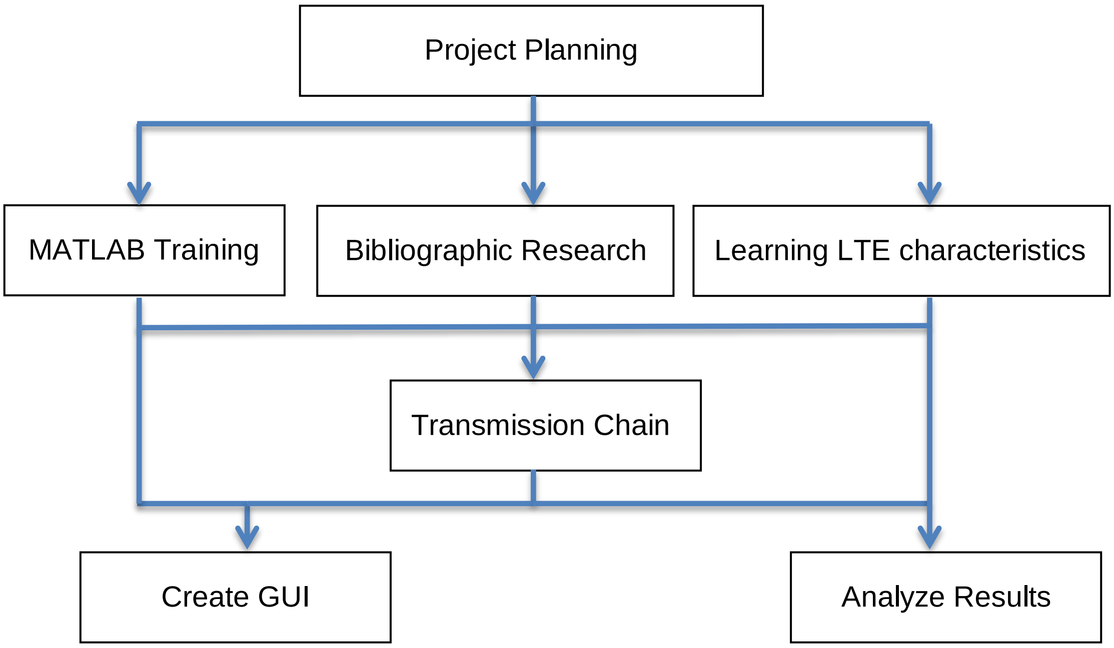
## 1.2. Incidences

In the critical report there was two WP (Word Packages), named 'Adding Advances Features' and 'Emulator Validation' respectively, that have been deleted due to the amount of time wasted in creating a GUI that works with the code. Besides, the time spent to write final report has been much greater than the expected, even when the advisor has warned me.

Period that comprised 18/12/2015 until 15/01/2016 there wasn't employed to do the project.

## 1.3. Work plan, Work packages and Final Grant Diagram

**Work Plan**



**Work Packages**

| | | |
|---|---|---|
| Project: MATLAB implementation of an emulator of the downlink physical layer of the LTE system | WP ref: 1 | |
| Major constituent: State of the art: review and planning | Sheet 1 of 5 | |
| Short description:<br><br>Do an initial bibliographical research about the topic in the literature and define the project scope, goals, how to manage time, work packages and interaction procedures. And, the most important, write this document. | Start date: 14/9/2015<br><br>End date: 08/10/2015<br><br>Start event:<br><br>End event: | |
| Internal task T1: Bibliographic research<br><br>Internal task T2: Project planning | Deliverables:<br><br>Project proposal and work plan | Dates:<br><br>8/10/2015 |

| | | |
|---|---|---|
| Project: MATLAB implementation of an emulator of the downlink physical layer of the LTE system | WP ref: 2 | |
| Major constituent: Simulation environment: start up | Sheet 2 of 5 | |
| Short description:<br><br>Acquire practical skills with software which carry out the project. | Start date: 05/10/2015<br><br>End date: 18/10/2015<br><br>Start event:<br><br>End event: | |
| Internal task T1: MATLAB training<br><br>Internal task T2: Simulink training | Deliverables: | Dates: |

| | |
|---|---|
| Project: MATLAB implementation of an emulator of the | WP ref: 3 |

| | | |
|---|---|---|
| downlink physical layer of the LTE system | | |
| Major constituent: Transmission chain: basic design | Sheet 3 of 5 | |
| Short description: Design the downlink LTE transceiver using MATLAB, taking into account the theoretically scheme. Shape the communication channel. Then, analyze the results obtained for different transmission chains. | Start date: 19/10/2015<br>Real end date: 15/03/2016<br>Start event:<br>End event: | |
| Internal task T1: Transmitter design<br>Internal task T2: Receiver design<br>Internal task T3: Communication channel design<br>Internal task T4: Analysis of the transmission chain | Deliverables:<br>Transmitter scheme<br>Receiver scheme<br>Communication channel scheme | Dates:<br>29/01/2015<br>29/01/2015<br>29/01/2015 |

| | | |
|---|---|---|
| Project: MATLAB implementation of an emulator of the downlink physical layer of the LTE system | WP ref: 4 | |
| Major constituent: GUI design and initial design validation | Sheet 4 of 5 | |
| Short description: Design a Graphic User Interface that allows users have soft experience while using emulator. Once the design is finished, emulator elements integration is needed. Finally a validation GUI is important in order to check that the system works properly. | Start date: 25/01/2016<br>End date: 05/05/2016<br>Start event:<br>End event: | |
| Internal task T1: GUI | Deliverables: | Dates: |

| | | |
|---|---|---|
| | GUI | 05/05/2016 |

| | | |
|---|---|---|
| Project: MATLAB implementation of an emulator of the downlink physical layer of the LTE system | WP ref: 5 | |
| Major constituent: Final report | Sheet 5 of 5 | |
| Short description: Develop the final report including all the work done previously with more significant outcomes, as well as doing a final report revision to have a coherent memory. | Start date: 01/04/2016<br>End date: 13/05/2016 | |
| | Start event:<br>End event: | |
| Internal task T1: Writing final report<br>Internal task T2: Revising final report | Deliverables:<br>Final Report | Dates:<br>13/05/2016 |

**Milestones**

| WP# | Task# | Short title | Milestone / deliverable | Date (week) |
|---|---|---|---|---|
| 1 | 2 | Project planning | Project proposal and work plan | 4 |
| 3 | 1 | Transmitter design | Transmitter scheme | 20 |
| 3 | 2 | Receiver design | Receiver scheme | 20 |
| 3 | 3 | Communication channel design | Communication channel scheme | 20 |
| 4 | 2 | GUI validation | GUI | 34 |
| 5 | 2 | Revising final report | Final report | 35 |

Table 1: Milestones

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## Gantt Diagram

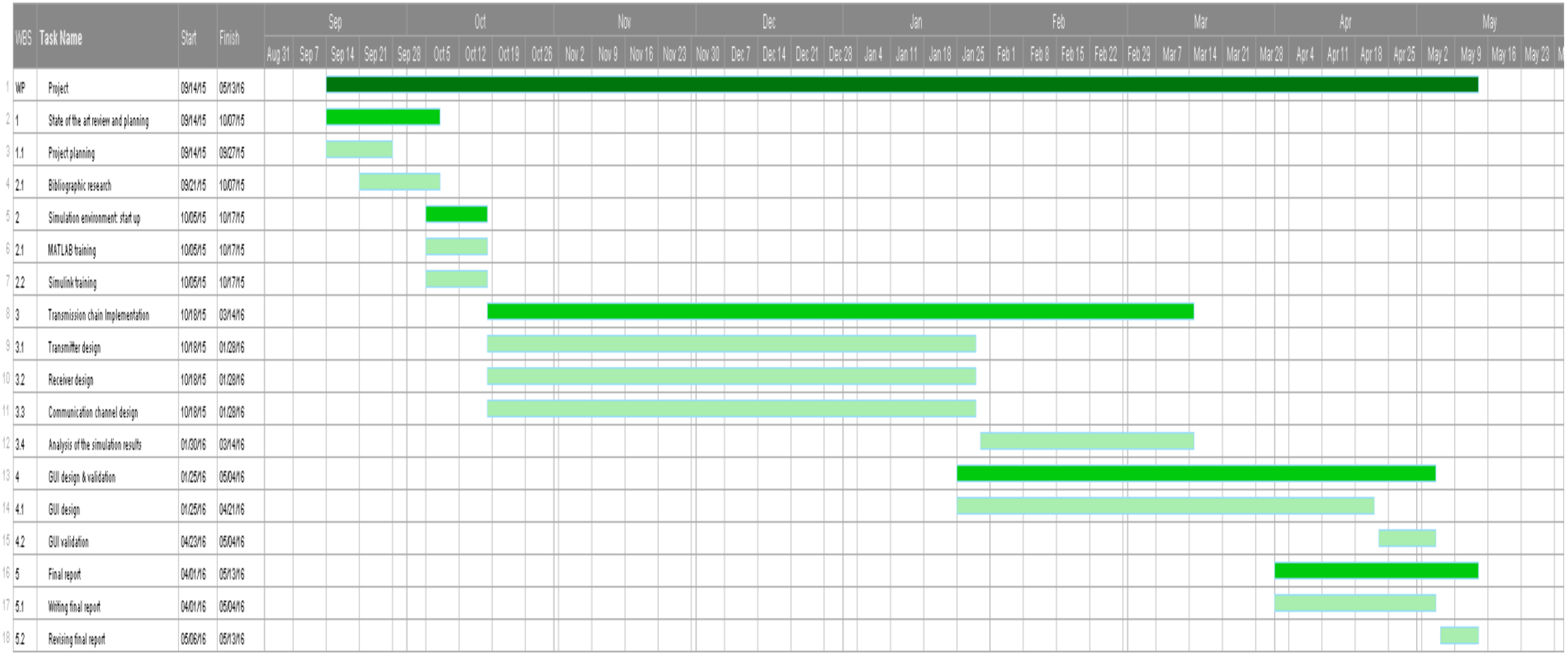


Figure 1: Gantt Diagram

# 2. State of the art of the technology used or applied in this thesis:

## 2.1. Frame of reference

### 2.1.1. An overview of digital mobile communications standards

In this section a reference of project context is provided. As the project is about LTE system, a general vision of it and about the used technologies is provided. In addition, other wireless communications that precede LTE are also commented.

In early 90s, 2G (2nd -Generation) wireless mobile networks were commercially launched. Two standards, GSM (Global Systems for Mobile Communications) and IS-54 (Interim Standard-54), were the most representative. GSM vas developed by the ETSI (European Telecommunications Standards Institute) and operated not only in Europe but also in the major part of the countries of the world. IS-54 vas standardized by EIA (Electronic Industries Alliance) and TIA (Telecommunications Industry Association) together, and operated in North America. Both 2G networks were based in circuit-switching TDMA (Transmission Division Multiple Access) access technology, and were built mainly to provide voice services. Later on, the GPRS (General Packet Radio Service) standard appeared. This new standard operates over GSM networks and allows transmitting IP (Internet Protocol) packets to provide data services as SMS, MMS or WAP.

All the end of the past Century, new standards for 3G (3rd-Generation) systems were proposed. These new standards suppose a fundamental improvement with respect to the previous ones, because they incorporate from very early stage not only circuit switching technologies (like 2G) but also packet-switching technologies to offer different set of Internet applications such as web browser or e-mail. Among all 3G standards the most important was UMTS (Universal Mobile Telecommunications Service), standardized by 3GPP (3rd Generation Partnership Project). Whilst at the beginning UMTS only operated in Europe and Japan, later this standard was applied to most of the World regions, mainly thanks to standardization efforts carried out. 3G standards were CDMA (Code Divided Multiple Access) based. Improvements over 3G networks such HSPA (High Speed Packet Access) or HSPA+ (High Speed Packet Access Plus) were launched for reaching higher data bit rates. These evolved standards are referred as 3'5G and 3'75G respectively.

In 2008 the first LTE release was developed by the 3GPP. LTE, which is sometimes considered as 3'9G standard, an echelon between 3G and 4G mobile networks. In comparison with the CDMA based standards, LTE is totally based in Internet Protocol (IP) for carrying out any kind of service, and provides more bandwidth, better speed transmission and more spectral efficiency than UMTS and its evolutions (HSPA, HSPA+).

Also in 2008, specifically in March, the ITU-R (International Telecommunications Union-Radio) specified a set of requirements for 4G standards named IMT-Advanced (International Mobile Telecommunications Advanced) specification. Within 4G two standards must be highlighted: WiMax (Worldwide Interoperability for Microwave Access) or IEEE 802.16, standardized by IEEE (Institute of Electrical and Electronics Engineers); and LTE-A, a LTE evolution, standardized by 3GPP. 4G systems have the following characteristics:

- Internet protocol (IP) based as packet switching.
- Does not support traditional circuit switching telephony service.
- OFDMA (Orthogonal Frequency Division Multiple Access) as medium access technique.
- Downlink peak data transmission rates of 1 [Gbps] in low mobility and 100 Mbps in high mobility environment.

Nowadays, although is not standardized yet, telecommunications enterprises are developing the first 5G ($5^{th}$-Generation) prototypes, and some tests have been made. The results announce outstanding improvements in terms of data transmission speed and latency.

In Table 2 a comparison of the achievable (theoretical) data peak rate for both uplink and downlink and different standards is shown.

| Short Term | Standard | Data Rate Downlink | Data Rate Uplink |
|---|---|---|---|
| 2G | GSM | 9.6 [Kbps] | 9.6 [Kbps] |
| 2'5G | GPRS | 53.6 [Kbps] | 26.8 [Kbps] |
| 3G | UMTS | 384 [Kbps] | 128 [Kbps] |
| 3'5G | HSPA | 7.2 [Mbps] | 3.6 [Mbps] |
| 3'7G | HSPA+ (R8) | 42.2 [Mbps] | 11.5 [Mbps] |

| | | | |
|---|---|---|---|
| 3'9G | LTE | 100 [Mbps] | 50 [Mbps] |
| 4G | LTE-A | 1 [Gbps] | 500 [Mbps] |

**Table 2: Maximum data peak rate (theoretical) comparison for different mobile communications standards**

### 2.1.2. LTE

As described in previous subsection, LTE standard is almost 4G mobile network developed by the 3GGP. Its apparition is due to different reasons that are listed below:

- To offer a network that could satisfy the exponential increase of data traffic.
- The apparition of new services over Internet, such as videoconference or video streaming, which requires an enhancement in terms of data transmission speed.
- By the point of view of MNO, a necessity of a new standard that drastically decreases the network costs (both CAPEX and OPEX).

LTE standardization was reached at 2008 and its requirements are listed below:

- Improved system capacity and coverage with respect UMTS release $4^{th}$.
- High peak data rates.
- Low latency.
- Reduced operating costs.
- Multi-antenna support.
- Flexible bandwidth operations.
- Seamless integration with existing systems (UMTS, Wi-Fi, etc.).

This project is based in LTE release 8 (3GPP version 8.8.0). The next LTE releases (in fact release 10) are already considered 4G standards, and a new acronym, LTE-A (LTE-Advanced), is used for referring them. However, the system core of these new releases is deeply related with the main LTE features. For this reason a good comprehension in LTE it's useful to understand LTE-A.

# 3. Theoretical background:

In this section the methodology applied in this project is exposed. Basically there are two different kinds of knowledge necessary to carry out this document: firstly, how it works the LTE physical layer in the downlink side; secondly, it's necessary to have basic notions in MATLAB language programming and how it works the software with the same name.

Therefore, before to exhibit the project results, it's mandatory to have a look at the LTE physical layer in downlink side and how MATLAB works.

## 3.1. Some theoretical concepts about mobile communications channels [1]

To understand the LTE behavior, and to familiarize the reader with the document terminology, it's necessary to briefly explain some concepts about mobile communications channels that the LTE physical layer faces-on.

Multipath propagation

Multipath propagation happens because, in mobile environments, the path between transmitter and receiver is non-unique. This fact means that, while the transmitted signal is being propagated, multiple indirect paths appear as consequence of reflection and diffraction. Two kinds of multipath propagation appear:

- Close echoes: Also called fast fading, occur at the receiver proximities due to the multiple signal reflections within short time scale. There are two models used to characterize this fading: Rayleigh and Riccian. Throughout this document only Rayleigh model is going to be used.
- Far echoes: Associated with reflections far to the receiver, these echoes occur within a large time scale. These reflections produce channel scattering, which importance is related to transmitter symbol time $T_s$. Delay Spread parameter is a way to measure this scattering and it can be calculated in a statistical way. A common, well-accepted distribution model for the different path delays related to the different echoes is to assume that they take an exponential probability distribution function [2]. Taking into account this distribution, the delay spread is calculated as its standard deviation. The Equation 1 is used to calculate an upper boundary for the delay spread, where $\tau_M$ refers the moment that last reflection arrives to the receiver, while $\tau_0$ refers to the first signal to arrive.

$$D_S \leq \tau_M - \tau_0 \ [s]\ ; \quad M \geq 0 \qquad (1)$$

Coherence bandwidth

Parameter that ensures that channel impulse response doesn't introduce distortion over the signal transmitted. Taking into account that channel impulse response is a stochastic process, it's possible to determinate this parameter, from a statistical point of view by means of the channel response autocorrelation function for two different frequencies. So, two different frequencies separated less than coherence bandwidth see almost the same channel response. On the other hand, if the frequencies are separated more than coherence bandwidth, the channel response for each of these frequencies is independent with respect the others. A well-accepted relation between delay spread and coherence bandwidth is given by the equation 2, assuming that there is an exponential distribution probability function for the delay spread.

$$B_{coh} = \frac{1}{2\pi D_S} \ [Hz] \qquad (2)$$

ISI (Inter-Symbolic Interference)

In scattering environments, ISI is produced when the delay spread is greater than symbols duration ($D_s > T_s$), causing that during one symbol time, the received signal coming from main path is contaminated with delayed versions of the same transmitted signal that come over other paths. As a result, the multipath propagation produces distortion.

When ISI occurs is necessary to make use of equalizers to improve the original transmitted signal recovery.

Doppler Effect

Sometimes the UE (User Equipment) is moving while receiving data and this fact implies that the signal is received at different carrier frequency than it was transmitted. As a result, the formula for the received carrier frequency can be expressed as shown in equation 3, where $f_{tx}$ and $f_{rx}$ are the frequencies which signal is transmitted and received respectively, while $f_d$ is called Doppler frequency.

$$f_{rx} = f_{tx} \pm f_d \qquad (3)$$

Depending on where receiver is moving to, $f_{rx}$ will be larger or smaller than $f_{tx}$. Doppler frequency can be calculated by using equation 4, where $\lambda$ is the wavelength of the carrier frequency of the transmitted signal, $v$ stands for the velocity which is moving the receiver and c is the light speed. Doppler frequency can be expressed in terms of transmitted carrier frequency and speed light as shown in equation 4, if taking into account that both parameters are related to wavelength.

$$f_d = \frac{v}{\lambda} = \frac{v f_{tx}}{c}\ [Hz] \qquad (4)$$

Coherency time

From Doppler Effect derives coherency time concept. Can be defined as the time allowed elapsing before the envelope signal significantly changes. A theoretically value can be expressed as equation 5.

$$\tau_c = \frac{1}{5'58 f_d}\ [s] \qquad (5)$$

In high-mobility environments Doppler frequency will be higher and, therefore, the Coherence Time value will be small, implying that the UE will see different channel conditions in short time intervals, combining situations where the received signal is good with moments when the signal fades.

## 3.2. Learning about LTE standard: Downlink Physical Layer

### 3.2.1. LTE channels in physical layers

As can be shown in Figure 2, in LTE standard there are three channel categories, namely: Logical channels, Transport Channels and Physical Channels. Logical channels are on the top while physical channels are on the bottom. Multiple logical channels are multiplexed into one or more transport channel, which in turn are multiplexed into one or more physical channels. Not all the physical channels provide from one transport channel, but they can be created to cope as functionality related to the physical layer.

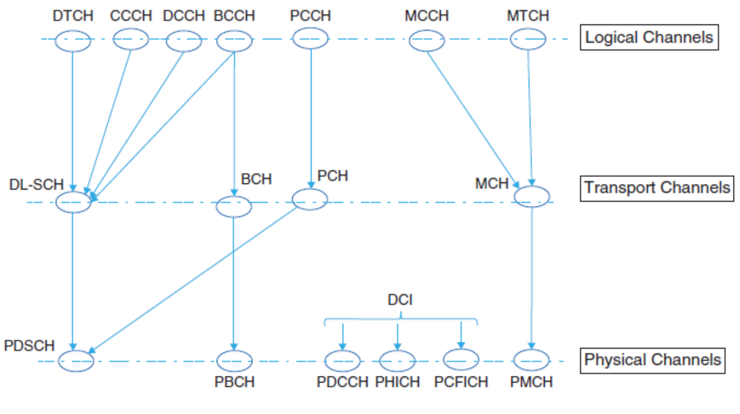


Figure 2: Relation among logical, transport and physical channels in LTE downlink side [3]

In downlink there are two physical channel types: traffic channels and control channels. Before going further with an explanation of these channels, it's important to remark that, unlike GSM or UMTS systems, the traffic physical channels in LTE are shared instead of dedicated; in other words, only when the network needs to send common control data or when user has to receive data, these physical channels are enabled to the user. Thus, resources are non-wasted while the channel is not being used.

Within physical traffic channels outstands PDSCH (Physical Downlink Shared Channel), responsible to transport user data and information delivered by DLSCH (Downlink Shared Channel). Although is not going to be used within this document, there is another physical channel for traffic data called PMCH (Physical Multicast Channel), used to transmit broadcast and multicast data.

There are four control physical channels: PBCH (Physical Broadcast Channel), PDCCH (Physical Downlink Control Channel), PCFICH (Physical Control Format Indicator Channel) and PHICH (Physical Hybrid ARQ Indicator Channel), which are used for signaling purposes.

### 3.2.2. Medium access techniques

In LTE there are different medium access techniques depending if the communication is in downlink or uplink side. In the uplink medium access technique used is SC-FDMA (Single Carrier – Frequency Division Multiple Access), but as the uplink is out of the scope within this project, in this document only the OFDMA medium access technique, which is used in downlink side, is studied

OFDMA (Orthogonal Frequency Division Multiple Access) technique is based on the OFDM (Orthogonal Frequency Division Multiplex) transmission technique, which consists on multiplexing a set of symbols over a set of subcarriers. There is no problem at the receiver side because by implementing some signal processing techniques (Cyclic Prefix insertion), each subcarrier signal is orthogonal respectively with each other, so with the right receiver these signals can be separated.

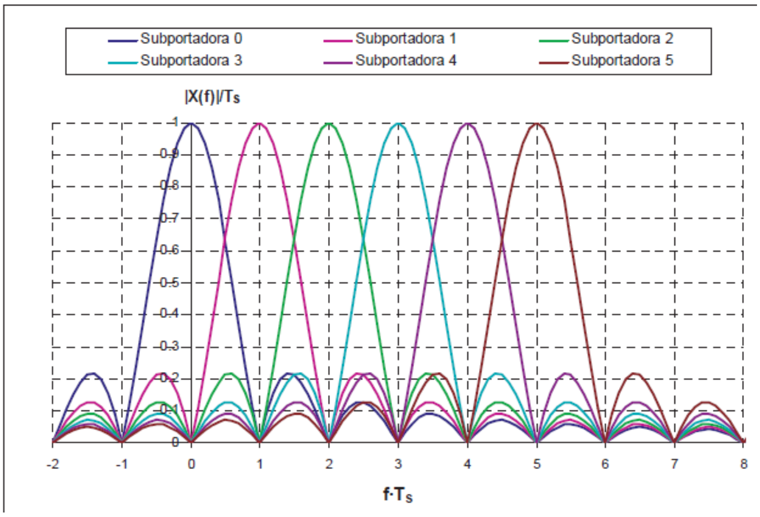


Figure 3: OFDM spectrum example [4]

The use of OFDMA as a multiple access technique has a lot of advantages; some of them related to a single user in the system are listed below:

- Robustness to multipath propagation: This occurs due to cyclic prefix insertion, which tries to deal with the inter-symbolic interference caused by the multipath propagation. Despite this robustness, it could be necessary to equalize in frequency domain at the receiver in order to erase the multipath propagation, if link adaptation technique is not used.
- Frequency diversity: Refers to the possibility to assign to a single user multiple non-adjacent subcarriers, separated enough to perceive statistical independent channel behavior of the different subcarriers.
- Digital-domain easy implementation: Thanks to the possibility to use chips that performs FFT (Fast Fourier Transform) /IFFT (Inverse Fast Fourier Transform), it's easy to implement optimized real systems in both economic and performance terms.

In the case of multi-user scenarios, some benefits, related to the multi-user diversity and flexibility within assigned bandwidth have also to be mentioned.

### 3.2.3. Frame structure

There are two types of frame structures; one for TDD (Time Division Duplexing) and another for FDD. Since the first is out of the scope, we only are going to explain frame structure for FDD in downlink side.

An LTE frame takes up 10 [ms] and is composed by 10 subframes, which is the minimum transmitted unit and takes up 1 [ms]. Within a subframe 2 TS (Time Slot) are transmitted, taking each one up 0'5 [ms], and each TS is composed by 6 or 7 OFDM symbols, depending if extended CP (Cyclic Prefix) or normal CP is used. In Figure 4 a graphical interpretation is exposed.

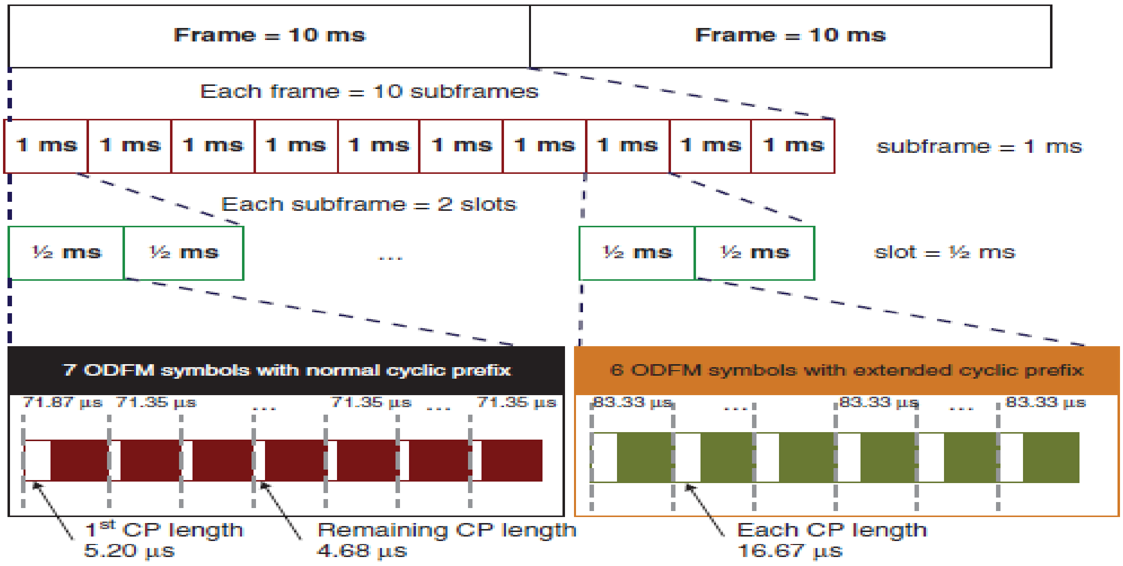


Figure 4: Time-domain frame structure [3]

Also in Table 3 the relation between OFDM symbols numbers within TS in function of CP value is shown.

| # OFDM Symbols | CP 1st OFDM Symbol [µs] | CP other symbols [µs] |
|---|---|---|
| 7 | 5.2 | 4.7 |
| 6 | 16.67 | 16.67 |

Table 3: Relation between number of OFDM symbols within TS in function of CP

For each transmitted subframe there is a time-frequency representation, which is called resource grid. Each resource grid is divided into different resource blocks, and in turn each resource block is divided into different resource elements. Resource grid can be represented in two axes. The horizontal axis represents time and the minimum unit is an OFDM symbol, while the vertical axis represents frequency and the minimum unit is subcarrier bandwidth, represented by $\Delta_f$. So, each resource element is represented by a cell, and takes up one OFDM symbol and one subcarrier. In Figure 5 there is a representation for resource grid.

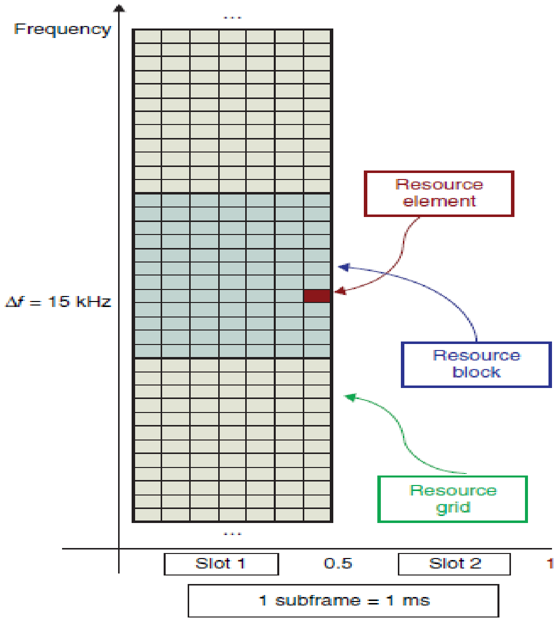


Figure 5: Time-frequency resource grid [3]

The resource grid is filled with different physical signals, which are listed below:

- CSR (Cell Signal Reference): Used to estimate the channel impulse response, to obtain link quality measures, to implement the cell research procedures and for the initial synchronization mechanisms. There are two types of these signals, namely: RSP (Reference Signals Primary) and RSS (Reference Signals Secondary).
- DCI (Downlink Control Information): Carries the content of the PDCCH (Physical Downlink Control Channel), PCFICH (Physical Control Format Indicator Channel) and PHICH (Physical Hybrid-ARQ Indicator Channel) channels.
- BCH (Broadcast Channel): Carries basic parameters of the network, used by the mobile terminal during attaching procedure at the network.
- Synchronization: Used to guarantee a frame-level and subframe-level synchronization. P-SCH (Primary Synchronization Channel) is related to subframe-level synchronization, while S-SCH (Secondary SCH) is related to frame-level synchronization.
- User-Data: Information useful for the user.

As not all the subframes are filled in the same way, Table 4 shows a description of which signals compose each frame.

| | User-Data | CSR | DCI | BCH | SYNC |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| Subframe 0 | X | X | X | X | X |
| Subframe 5 | X | X | X | | X |
| Other Subframes | X | X | X | | |

Table 4: Signals involved in each subframe

### 3.2.4. LTE transmission modes

LTE release 8.0 provides up to seven transmission modes. Although within this project only the first mode is employed, it is convenient to provide a short description of all of them. Table 5 summarizes the main features of the different transmission modes.

| TM | Description | Comment |
|---|---|---|
| TM1 | Single transmit antenna | There are two variants of this mode: SISO (Single Input Single Output) when there is only one antenna at the receiver; SIMO (Single Input Multiple Output) when there is more than one antenna at the receiver. |
| TM2 | Transmit diversity | The same information is sent via different antennas. Each antenna's stream uses different coding and different frequency resources. With this mode an improvement of the SNR (Signal-to-noise ratio) is achieved if comparing with TM1 |
| TM3 | Open loop spatial multiplexing | Uses open-loop spatial multiplexing and is intended for transmissions in high-mobility scenarios. |
| TM4 | Closed loop spatial multiplexing | Uses spatial multiplexing with precoding and closed-loop channel feedback. Intended for low-mobility scenarios. |
| TM5 | Multi-user MIMO | Very similar than TM4, except by the fact that one layer is dedicated for one UE. |

| | | |
|---|---|---|
| TM6 | Closed loop spatial multiplexing using a single transmission layer | TM4 variant. However, only one layer is used. UE estimates the channel and sends the index of the most suitable precoding matrix back to the BS (Base Station). |
| TM7 | Beamforming | Uses UE specific reference signals. Because the UE requires only UE specific reference signals to demodulate PDSCH, the data transmission for the UE appears to have been received from only one transmit antenna. In other words, the transmission appears to be transmitted from a single 'virtual' antenna. |

**Table 5: LTE transmission modes in downlink**

### 3.2.5. MIMO

MIMO (Multiple Input Multiple Output) technique allows considering different transmission methods, thanks to the use of multiple antennas in both receiver and transmitter. The main purpose of using MIMO is to increase the system's capacity. Although MIMO technique is not going to be used within this project, its importance in LTE deserves a brief explanation of different transmission/reception techniques that can be implemented by using MIMO technology:

- Reception diversity: Consists in to use of multiple antennas at the receiver side to gather the transmitted signal and combine them in order to cope with the fading problems. The receiver can mainly use two kinds of combining techniques to process the receiver signals: MRC (Maximum Ratio Combining) and SC (Selection Combining). While in SC only the highest SNR signal is selected to estimate the transmitted data, in MRC the received signals are weightily added in phase in order to improve the overall signal to noise ratio.
- Transmission diversity: Consists in transmitting the same information by different antennas in transmission. Each signal transmitted has different path propagation.
- Space multiplexing: Based in the use of multiples antennas both transmission and reception, where each antenna transmits different data flows. By using appropriate signal processing techniques in both transmitter and receiver, the radio channel behaves as multiple and simultaneous independent propagation paths, and, therefore, both the channel capacity and the user throughput increase.

### 3.2.6. Link adaption

When channel conditions are not good enough to guarantee the minimum signal to noise and interference ratio $(SINR)_{min}$ , LTE allows changing the transmission parameters in order to has a better response to the channel conditions. These parameters that can change are the modulation and code techniques, also called MCS (Modulation Coding Schemes), channel bandwidth and the number of antennas used both in transmission and reception.

LTE has mechanisms to detect when has to make use of link adaptation. To enable when is necessary to change transmission parameters, UE (User Equipment) transmits to eNodeB (Evolved Node B) three kinds of channel state reports:

- CQI (Channel Quality Indicator): Measures the channel quality in order to determinate which MCS has to be used.
- PMI (Precoder Matrix Indicator):
- RI (Rank indicator):

In base of these parameters, it's possible to change the Transmission Mode in order to use efficiently the system in function of channel conditions, resulting in a higher net bit data rate.

### 3.2.7. How to calculate data peak rate in LTE for SISO mode

One of the mandatory challenges of the LTE is higher data peak rates in comparison of previous standards. In order to know how to increase this parameter let's explain first how to calculate it. Suppose that LTE channel bandwidth is BW, being this parameter one of six values to choose within first row Table 6.

| Channel Bandwidth [MHz] | 1'4 | 3 | 5 | 10 | 15 | 20 |
|---|---|---|---|---|---|---|
| Available subcarriers | 73 | 181 | 301 | 601 | 901 | 1201 |
| FFT size | 128 | 256 | 512 | 1024 | 1536 | 2048 |
| Channel sample rate [MHz] | 1.92 | 3.84 | 7.68 | 15.36 | 23.04 | 30.72 |
| PRB (Physical Radio Blocks) | 6 | 15 | 25 | 50 | 75 | 100 |
| Data peak rate [Mbps] | 6 | 15 | 25 | 50 | 75 | 100 |

Table 6: Relation between channel bandwidth and data peak rate

PRB is the minimum information element that the eNB (Evolved Node B) can assign to a UE. A PRB comprises twelve subcarriers (180 [KHz]) transmitting during a Time slot (0'5 [ms]). Transmitted peak date rate transmitted can be expressed as equation 6, where $N_{SC}$ is the number of subcarriers available, $\Delta_f$ is the bandwidth space between subcarriers and is equal to [15 KHz], $m$ the number the number of bits transmitted per symbol and depends on modulation, and $R_b$ is the gross bit rate coded data.

$$R_b = (N_{SC} - 1)\Delta_f m \qquad (6)$$

If user gross bit rate (coded data) wants to be calculated, it has to be considered that around 85% of the transmitted data is data from user, while the remaining 15% corresponds to signaling data. Therefore, the gross bit rate is given by the **equation 7, where $\alpha_{USER,DATA}$ is the percentage of user data** transmitted over the total and $R_{b,USER}$ the gross bit rate of the transmitted user data. This percentage depends on the channel bandwidth and, especially, on the number of symbols dedicated to transmit control data (data from PDCCH channel) [5].

$$R_{b,USER} = (N_{SC} - 1)\Delta_f m \alpha_{USER,DATA} \qquad (7)$$

And if user net bit rate wants to be calculated, simply it's necessary to multiply by the channel coding rate, r.

$$R_{b,USER,net} = (N_{SC} - 1)\Delta_f r m \alpha_{USER,DATA} \qquad (8)$$

The maximum peak bit data rate for one single user in LTE SISO mode is $R_{b,USER,net} = 30'6\ [Mbps]$ when channel bandwidth selected is equal to 20 [MHz], modulation chosen is 64QAM (64 Quadrature Amplitude Modulation, which is the modulation scheme with highest spectral efficiency) and number of OFDMA symbols (per subframe) dedicated to transmit control data is equal to 1 .

MATLAB is a programming language widely used in academic and industry areas. It has been developed by MathWorks and allows a numerical computing environment.

MATLAB is characterized by the following properties:

- Complete tools to analyze data, develop different applications by the use of algorithms. Also data visualization is available.
- Create user interfaces.
- Interface with other languages such as C, Java or FORTRAN, among others.
- Different toolboxes available: specific sort of functions and script oriented to a specific area. These allow the end-user to take profit of the MATLAB capabilities.

In this report an academic license of MATLAB R2015b (8.6) version has been used as shown in Figure 6. This license has been provided as UPC student.

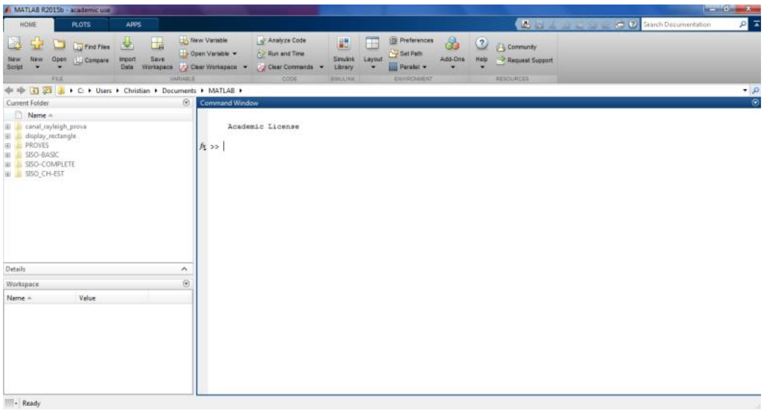

**Figure 6: MATLAB software screenshot**

Initially the code to simulate the LTE downlink air interface was not expected to be provided, so the author had to create himself using existing MATLAB libraries and toolboxes. These have been listed just below:

- Signal Processing Toolbox
- DSP system toolbox
- Communication system toolboxes

Despite of this, while reading the book *'Understanding LTE with MATLAB'*, it was noticed that part of the envisaged code could be also provided [3] from a third part. The provided code has constituted the initial framework of the project, however, the author has still spent so much time understanding the code, modifying it to develop simple cases for academic purposes, deleting parts of the code and adding, when necessary, some other news.

In addition a Graphical User Interface (GUI), MATLAB based, has also been created. The GUI allows the user to select (in a smart way) different LTE parameters and then to set up a valid transmission/reception chain to perform the envisaged simulation.

Although the author had been working with MATLAB before, MATLAB's reference manual [6], GUI manual [7] and the company's website [8] has been helpful source

# 4. Results

This section is divided in two parts. In the first part simulation results of LTE Transmission Mode 1 in are shown. In the second part a GUI for SISO mode is created as an academic tool.

## 4.1. Simulating the LTE Downlink Transmission Mode 1

The scope of the section is to demonstrate the evolution of the BER (Bit Error Rate) when improvements in the chain transmission are made. Firstly, a basic transmission chain is considered, which allows the link establishment with poor BER performance. Then, some gradual improvements are assumed until we get a SISO mode with a great enough performance. Finally, a brief simulation of SIMO mode is presented.

Before going further, it's important to enumerate the limitations referred to Transmission Mode 1:

- FDD mode is assumed.
- Normal cyclic prefix is considered.
- Full bandwidth is used.

All the systems studied within this section can be structured as a classical communication system. This is composed of a transmitter, a channel and a receiver, as it is shown in Figure 7.


Figure 7: Transmission chain

In this section an objective is purposed; obtain the minimum BER with highest bit data rate possible. On consequence, most of the time if the system has a good performance the selected modulation will be 64QAM and channel bandwidth equal to 20 [MHz].

### 4.1.1. SISO mode

Throughout this section an analysis of SISO transmission mode is performed. We first simulate a basic system, which is not using techniques to estimate the channel. As we go forward, different channel estimation techniques are progressively applied and, as a result, better BER will be obtained.

File **commlteeSISO_params.m** is a custom script where you can choose from different LTE parameters. In Figure 8 a script screenshot is shown. Parameters that are equal to X are susceptible to be changed throughout this section, while others remain constant.

```
commlteSISO_params.m
% Customizable parameters selection
%% PDSCH
numTx          = 1;    % Number of transmit antennas
numRx          = X;    % Number of receive antennas
chanBW       = X;    % Index to chanel bandwidth used [1,....6] for [1.4,3,5,10,15,20] MHz
contReg       = 1;    % No. of OFDM symbols dedictaed to control information [1,...,3]
modType      = X;   % Modulation type [1, 2, 3] for ['QPSK,'16QAM','64QAM']
%% DLSCH
cRate              = 1/3; % Rate matching target coding rate.
maxIter          = 6;      % Maximum number of turbo decoding terations
fullDecode     = 0;     % [1,0] Whether "full" or "early stopping" turbo decoding is performed
%% Channel model
chanMdl          =  'X'; % Choose 1 from 4 channel kinds ['flat-low-mobility', 'flat-high-mobility',...
                         %'frequency-selective-low-mobility', frequency-selective-high-mobility']
corrLvl              = 'Low'; %Correlation between antennas in reception
%% Simulation parametrs
Eqmode        = X;      % Type of equalizer used [1,2] for ['Zero Forcing', 'Minimum...
                        % Mean Square Error']
chEstOn          = X;     % [1,0] Whether channel estimation is done or ideal channel model used
maxNumErrs = 1e7; % Maximum number of errors found before simulation stops
maxNumBits = X;  % Maximum number of bits processed before simulation stops
visualsOn      = X;      % [1,0] Whether to visualize channel response and constellations
snrdB              = X;   % Value of SNR[dB] used in this experiment
```

**Figure 8: Parameters file for Transmission Mode 1**

Also an explanation for almost all parameters is given in Figure 8. In the case of the parameter *chanMdl,* which stands for channel model, is possible to choose from four channel types with parameters that are described in Table 7. Path delays are related to the channel sample rate, *chSRate*, i.e. a delay with 10 value means that this delay is 10 times the inverse of the channel sample rate. As it was seen in section 3.2.7, channel sample rate is related with the channel bandwidth.

In order to shape the communication channel, four types have been defined, although is possible to define new channels by modifying the **MIMOFadingChan.m** function.

| Channel type | Path delays | Path gains [dB] | $f_{d,max}$ |
|---|---|---|---|
| flat-low-mobility | 0 | 0 | 0 |
| flat-high-mobility | 0 | 0 | 70 |
| frequency-selective-low- | [0,10,20,30,100] | [0,-3,-6,-8-172] | 0 |

| | | | |
|---|---|---|---|
| mobility | | | |
| frequency-selective-high-mobility | [0,10,20,30,100] | [0 -3 -6 -8 -172] | 70 |

Table 7: Channel types used in transmission chain

#### 4.1.1.1. SISO basic

This analysis is performed assuming basic features, which don't include channel estimation and frequency domain equalization. In Figure 9 the transmission chain for this mode is illustrated.

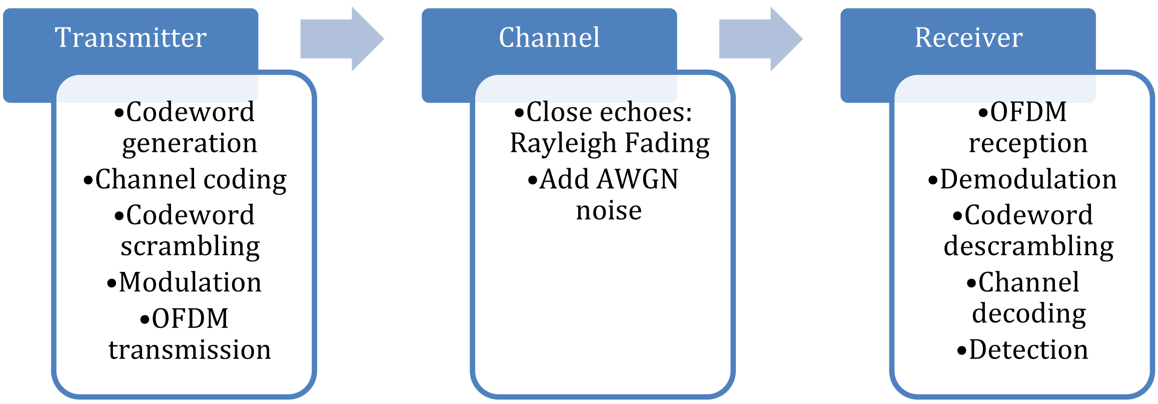


Figure 9: Basic SISO transmission chain

In Table 8, the parameters chosen to simulate this mode are indicated.

| Parameter | Value | LTE value |
|---|---|---|
| *modType* | *2* | 16QAM |
| *chanBW* | *6* | 20 [MHz] |
| *contReg* | *1* | 1 symbol per subframe to transmit the content of PDCCH channel (control data) |
| *snrdB* | *50* | 50 [dB] |
| *chanMdl* | *'flat-low-mobility'* | Flat channel impulse response and there is no Doppler Effect |

| | | |
|---|---|---|
| maxNumBits | 1e7 | Maximum number of bits processed before simulation stops |

Table 8: Parameters for SISO basic

Despite that a higher number of processed bits could be chosen, the selected value 1e7 is great enough to ensure that the simulation properly works, without the simulation time being excessive.

Once the parameters are chosen, it's time to run the simulation. In Figure 10 a constellation of received data and a spectrum of both transmitted and received signal are shown. The simulation also gives the BER value as a result. Throughout the simulation time, it has been observed that the received signal spectral density (blue-colored) remains constant because coherence time is very long, as we have chosen a low-mobility channel. In addition, the received signal spectral density value is always below the transmitted signal (yellow-colored). This could be explained by the fact that received signal is affected by non-selective fading due to the close echoes that produce that received signal is affected by phase and amplitude changes. These amplitude and phase changes can also be shown in constellation diagram. The received constellation is a scaled and shifted version of the transmitted constellation.

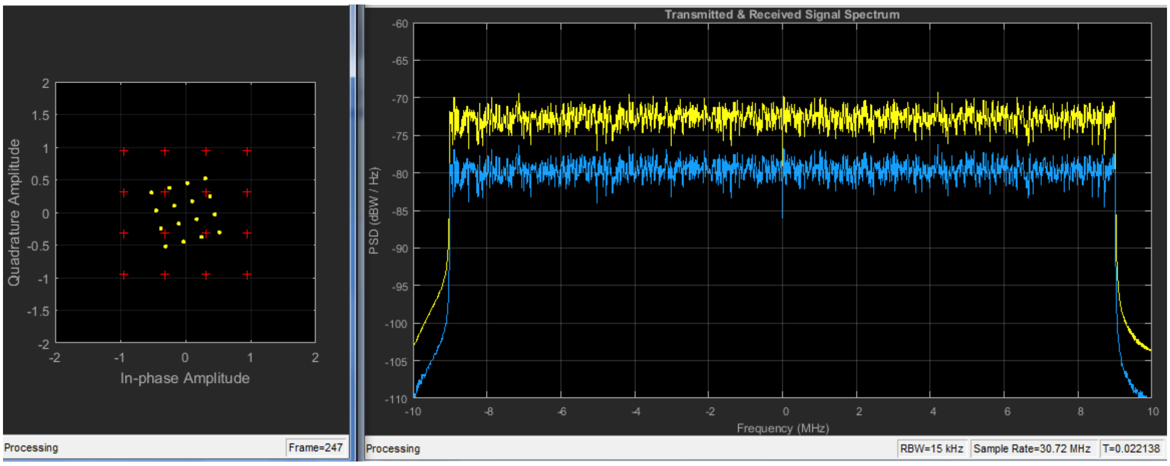


Figure 10: SPD & Constellation Diagram for 16QAM for SISO basic

The simulation also gives a BER equal to 0.5. Such high value is due because there isn't any mechanism to estimate the channel at the receiver, so the imperfections observed before are not corrected, even when the SNR has set to very high value.

#### 4.1.1.2. SISO phase corrector

The scope of this subsection is to compensate (as much as possible) the close echoes modelled by Rayleigh channel. The transmission chain is almost the same that used in SISO basic except by an addition of a phase corrector, as shown in Figure 11

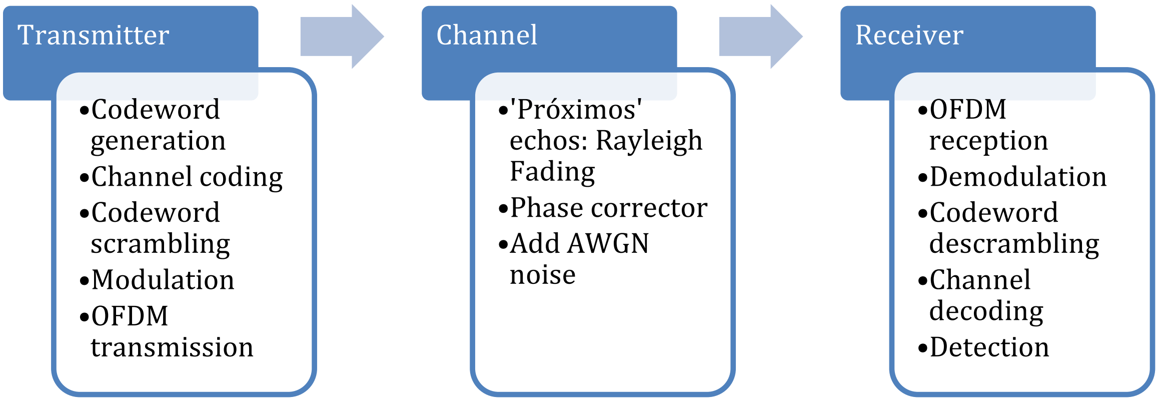


Figure 11: Transmission chain for SISO phase corrector

The received signal for the model used before is given by the expression 9, **where r(t) is the received signal at the OFDM receiver**, s(t) is the OFDM transmitted signal, h(t) is the channel response and n(t) is AWGN noise.

$$r(t) = s(t) * h(t) + n(t) \qquad (9)$$

Suppose now that the channel has a flat frequency response and the receiver is totally static, from a point of view of mobility. Then, the channel response can be expressed as shown in equation 10, **where N is the number of reflections close to the receiver**.

$$h(t) = \sum_{n=0}^{N-1} |h_n| \exp(j\varphi n) = R.\exp(j\phi).\delta(t) \qquad (10)$$

Then, if assuming that we can estimate the phase parameter (ϕ) of equation 10, a slightly improvement will be reached. The implementation of phase corrector into the function **commlteSISO_step.m** is performed using the code lines shown below. We can see in the code that this block is implemented just before the AWGN (Additive White Gaussian Noise) addition:

```
% Balance out phase rotation due of Rayleigh Channel (this implementation is valid for channel with flat frequency response)
ang = phase(chPathG);
complex = exp(-(1i).*ang);
rxComp = rxFade.*complex;
```

As a result, the received signal at the receiver entry is the last equality in equation 11.

$$r(t) = R.\exp(j\phi).s(t)\exp(-j\phi).+n(t) = R.s(t) + n(t) \quad (11)$$

Since the phase corrector has been defined, it is time to see the performance of this new transmission chain.

Firstly, a simulation using QPSK (Quadrature Phase-Shift Keying) modulation (*modType* = 2) is presented, with the rest of the parameters the same than used in Table 8.

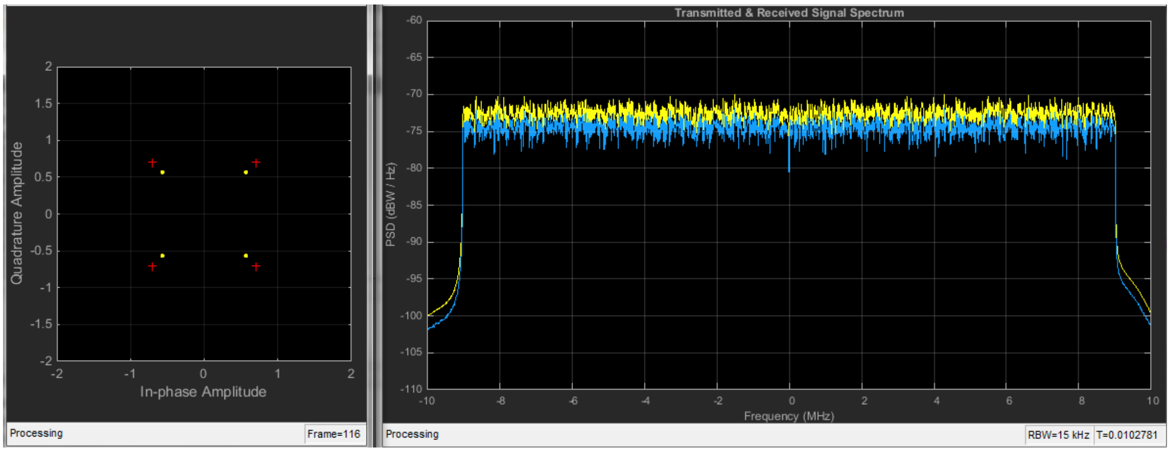


**Figure 12: SPD & Constellation Diagram for QPSK, flat-low-mobility channel in SISO phase corrector**

Looking at the Figure 12, it is clear that received constellation is almost the same than reference constellation, and received SPD (Spectral Power Density) is almost with the same wave-shape and power than transmitted SPD. Simulation results also provide BER value equal to 0, a consistent result when taking into account the comments explained before. In summary, for a flat-low-mobility channel and with QPSK modulation the system works.

The same conclusions, than extracted with QPSK modulation, can be formulated when setting a 16QAM (16 Quadrature Amplitude Modulation) modulation. However, when 64QAM modulation is set the simulation results provides a BER value equal to 0.0909, which is a non-acceptable value. An explanation of this BER results for 64QAM can be obtained looking at Figure 13. Despite the received constellation remains non-rotated, the received symbols amplitude is a scaled version of the transmitted one, and considering that the distance between neighbor symbols in 64QAM is approximately a quarter than the available in 16QAM, there are more symbols concentration in the interior squares, so it's more difficult to properly detect the right symbol. Note that for the border symbols, the probability to wrongly detect a symbol is smaller than for the middle symbols.

So, the proposed phase correction scheme will work properly if selecting QPSK or 16QAM modulation.

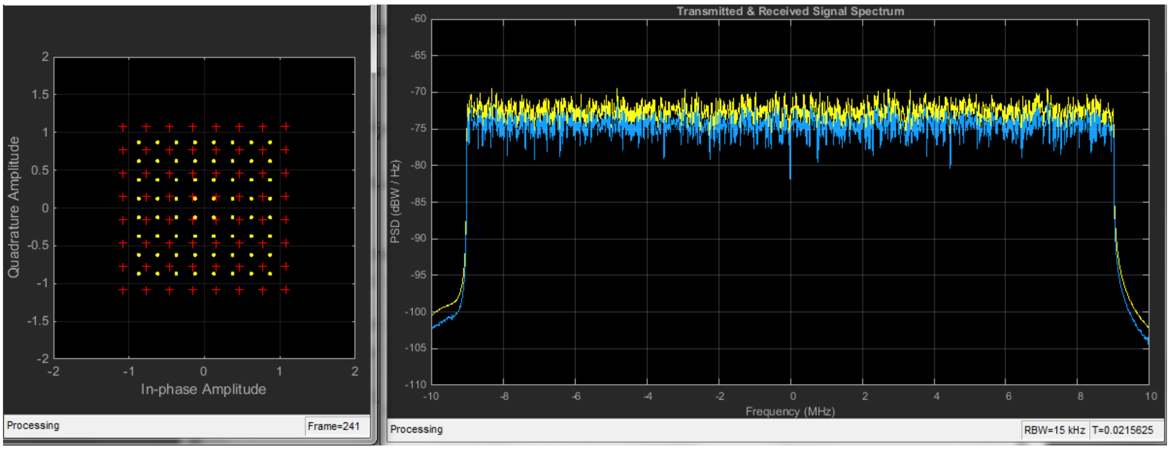


**Figure 13: SPD & Constellation Diagram for 64QAM, flat-low-mobility channel in SISO phase corrector**

Suppose now that 64QAM modulation option is not considered. What would happen with the modulation behavior when changing channel type?

To check this, the selected channel type is set to 'flat-high-mobility' and the modulation scheme is set to QPSK, while other parameters remain the same than the indicated in Table 8.

A screenshot of the results is shown in Figure 14. The amplitude of the received constellation is swapping, but the phase doesn't change in any moment. The simulation results provide a BER value equal to 0. It could seem a little strange because sometimes the received symbol is not close to the reference symbol, but there is an explanation for such BER behavior. As the received symbols are always oscillating inside the right-detection quadrant, the detector always detects the right symbol transmitted, even when the distance between received and reference symbol is significantly.

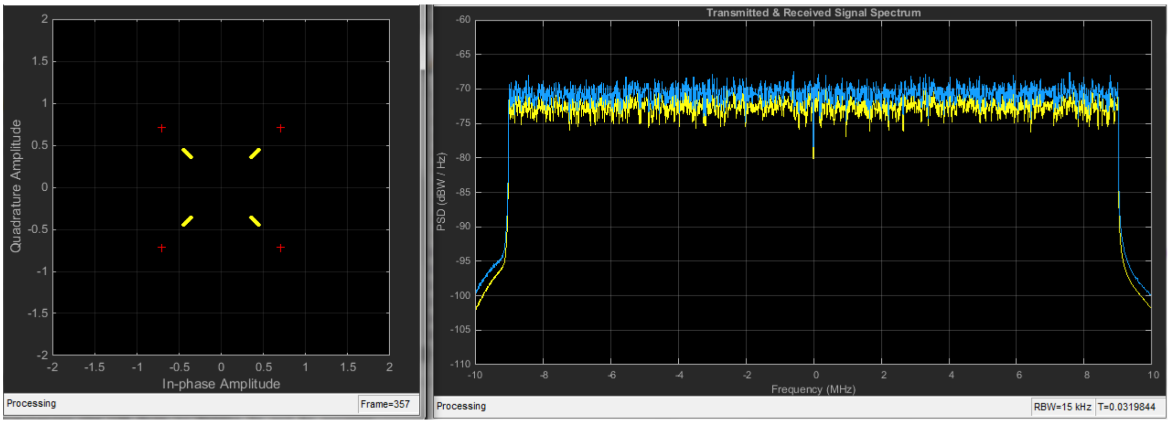


**Figure 14: SPD & Constellation Diagram for QPSK, flat-high mobility in SISO phase corrector**

When modulation is set to 16QAM a screenshot of the constellation diagram and spectrum is shown in Figure 15. As it happened with QPSK, constellation diagram is oscillating from 0 to the reference constellation by simulation elapses. But now the BER result is equal to 0.1210, a non-acceptable value for a mobile communication system. This high BER value is caused because not all the symbols have the same amplitude. When the received constellation is close from reference constellation the BER will take low values, but when it is far (close to the [0,0] point) the detector won't detect correctly the transmitted symbol and the instantaneous BER value will be very high.

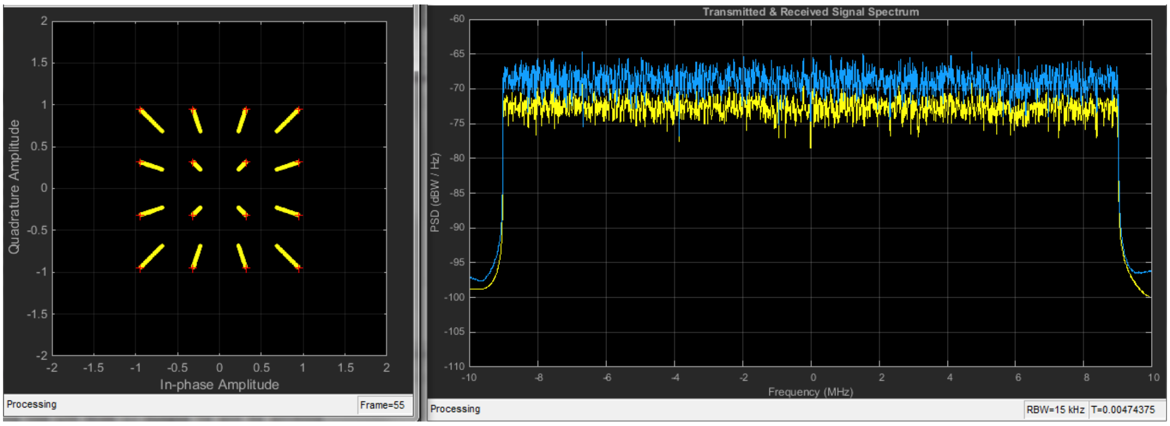


**Figure 15: SPD & Constellation Diagram for 16QAM, flat-high mobility in SISO phase corrector**

Until now, it has been checked that the proposed scheme only works for QPSK modulation when using a flat channel response. It's easy to realize that when setting the channel behavior to a frequency-selective response, the proposed LTE transmission chain won't properly work, because there isn't any mechanism to estimate and equalize the channel at the receiver.

#### 4.1.1.3. SISO with channel estimator

This transmission chain, which is shown in Figure 16, is more sophisticated than the used before, and takes better profit of LTE physical layer capacities.

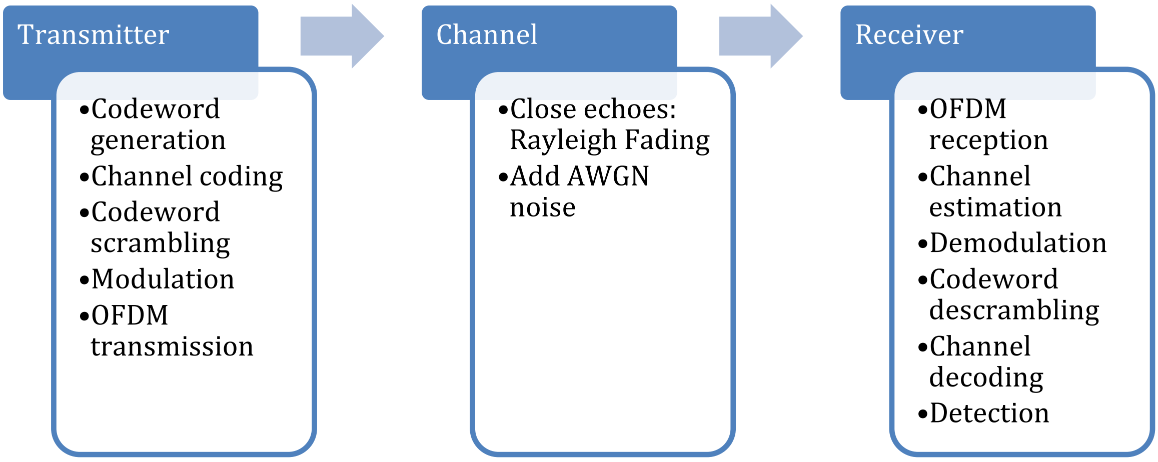


Figure 16: SISO channel estimation + basic transmission chain

LTE supplies a method to estimate the channel response. To carry out this channel identification, a set of reference signals, also called pilots or CSR (Cell Signal Reference), are placed throughout resource grid. An example of one possible resource grid is shown in Figure 17, where CSR signals are plotted in cream color.

The function **chanEstimate_1Tx.m** is the responsible of performing the channel estimation. An enumerated explanation of how the channel estimation works followa:

1. Extract CSR cells values from received signal and store them in a matrix called, *csrRx*.
2. Divide one by one each of the *csrRx* matrix field per each corresponding CSR reference value, which are stored in the so called is *csr_Ref* matrix in the code. The result is stored in a matrix called *hp*.

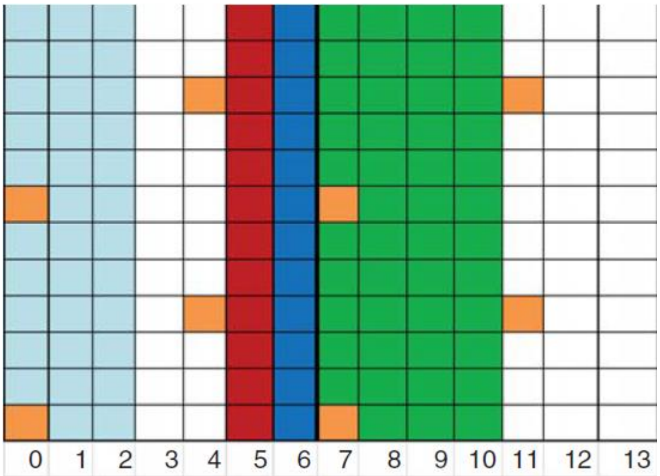


**Figure 17: An example of LTE's subframe resource grid**

3. Once the channel response for the pilot cells is given, an expansion (interpolation) of the channel response throughout the rest of the elements of the resource grid has to be performed. Different interpolation methods can be selected. After the interpolation a matrix, called *hD*, is returned with the resultant channel response.

Once the channel estimation is done, only it is necessary to divide received data *dataRx* by the channel response obtained *hD* to obtain the recover signal *yRec*.

Throughout this section, several channel configurations will be analyzed to see how the system works in each case. The parameters to carry out the simulations are set as described is Table 9.

| Parameter | Value | Comments |
|---|---|---|
| *modType* | *3* | 64QAM. If the system works for this modulation will also works for the other two. |
| *chanBW* | *6* | As there are no significant differences as changing this parameter, set the value to 20 [Mhz] in order to have the maximum bit data rate. |
| *contReg* | *1* | 1 symbol per subframe to transmit the content of PDCCH channel (control data) |
| *snrdB* | *50* | 50 [dB] |
| *est_mode* | *1* | Interpolate method to obtain channel response for all symbols. |

| | | |
|---|---|---|
| maxNumBits | 1e7 | Approximately, number of bits processed |

Table 9: SISO Channel Estimation parameters

Firstly, the channel class is set to flat-low-mobility, and simulation returns a BER equal to 0. In Figure 18 the SPD for transmitted signal and received signal before and after channel estimation are plotted. In addition, the constellation diagrams of the received signal, before and after channel estimation, are also plotted. When comparing with Figure 13, it's clear to that now the received constellation and SPD (plot in orange color) after channel estimation and compensation procedures are more similar to the transmitted one.

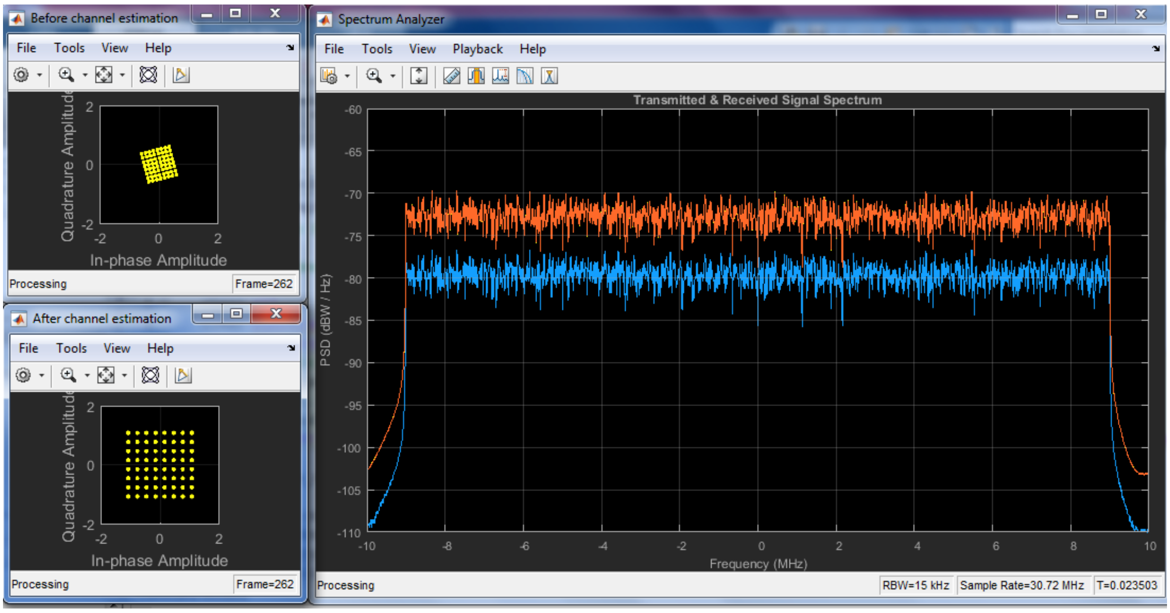


Figure 18: SPD & Constellation Diagram for 64QAM, flat-low-mobility in SISO with channel estimator

Let us proceed now checking the system when channel configuration is flat-high-mobility. A screenshot of the simulation results is shown in Figure 19. After channel estimation, the received constellation practically remains constant and quite similar to the reference constellation during all the simulation, except in some specific moments, when the constellation looks wider than reference one. The BER tool provides a BER value equal to 4.56e-04.

Hitherto, this scheme has a great performance for flat channels regardless the channel even suffers high-mobility conditions. But, what would happen when the channel conditions change? What would happen if, besides the reflections close to the receiver there would also be reflections from the receiver location?

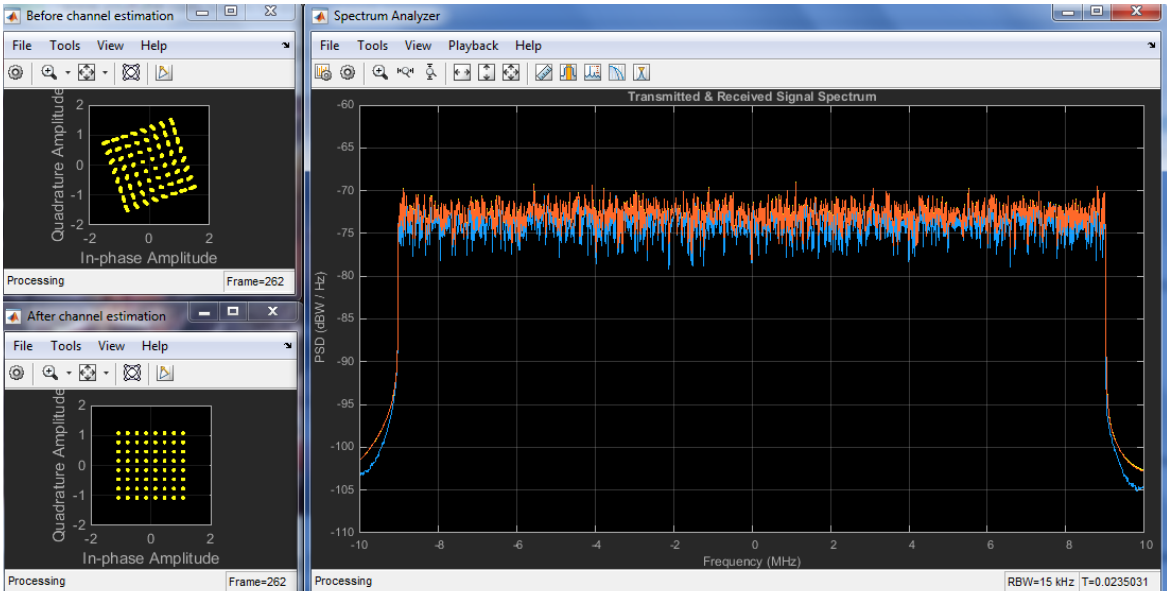


**Figure 19: SPD & Constellation Diagram for 64QAM, flat-high-mobility in SISO with channel estimator**

In order to answer the previous questions, a simulation considering a frequency-selective channel is carried out. According to Table 6, Table 7 and equation 1, this channel has a maximum delay spread of 3.25 [μs].

The simulation results for a low mobility are shown in Figure 20. The received signal before channel estimation (blue-colored) is affected by frequency selective fading associated to the different path delays. In spite of this, the received signal after channel estimation (orange-colored) overlaps the transmitted signal (yellow-colored). Furthermore, the received constellation after the channel estimation clearly looks like a 64QAM constellation. These observations, which indicate that BER may take small values, are consistent with the obtained BER results. Once the simulation is finished, the BER value is displayed and is equal to 9.97e-08.

The reason why the BER value takes this small value is the following: although the channel is selective in frequency domain, the cyclic prefix insertion deals with the multipath propagation. According to Table 3, cyclic prefix is equal to 4.7 [μs], a greater value than the delay spread. On consequence, the cyclic prefix deals with the multipath propagation. Furthermore, thanks to the channel estimation is possible to recover the original data.

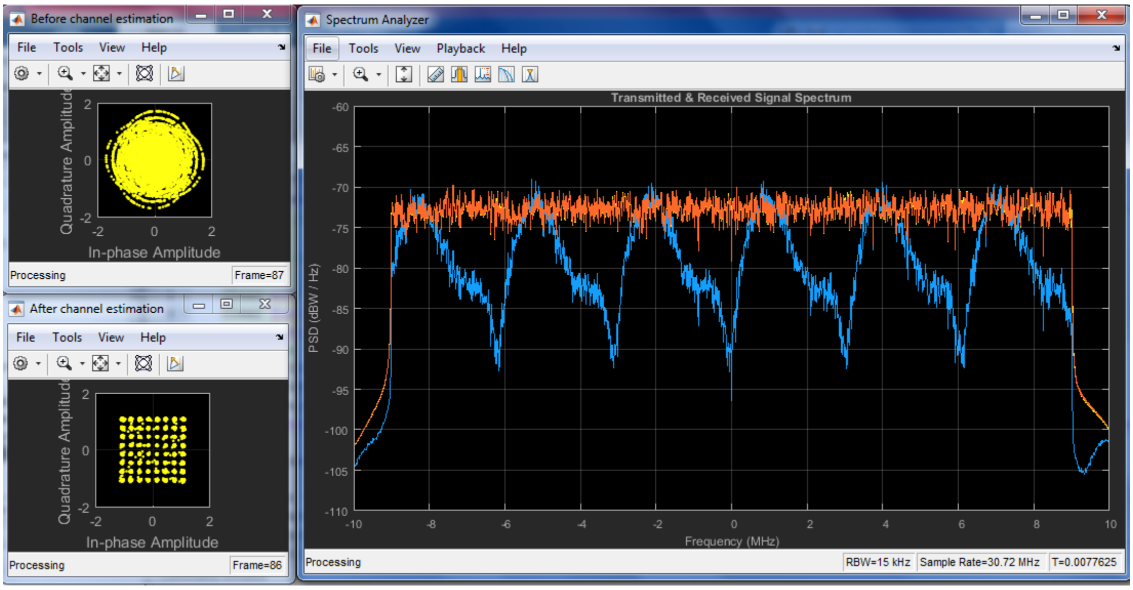


**Figure 20: SPD & Constellation Diagram for 64QAM, frequency-selective-low-mobility in SISO with channel estimator**

Would the system works, even for high mobility environment? To check this, a frequency-selective-high mobility channel is now assumed. Looking at Figure 21, an approximate idea of the system behavior can be obtained. Whilst the signal before channel estimation (blue-colored) is clearly affected by multipath propagation, the signal after channel estimation combats the multipath propagation and a low BER value is obtained, and BER value for this configuration is equal to 1.21e-05.

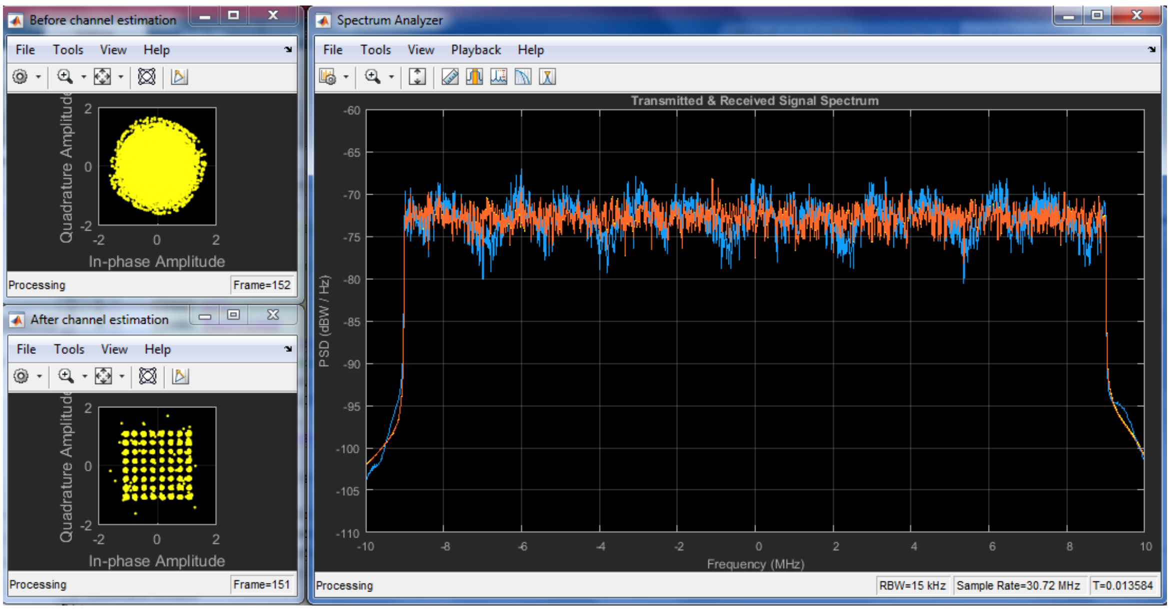


**Figure 21: SPD & Constellation Diagram for 64QAM, frequency-selective-high-mobility in SISO with channel estimator**

In summary, this system, hitherto, is performing correctly. By using Table 6, Table 7 and equation 1 and applying them in equation 2, the coherence bandwidth for this channel can be obtained. Thanks to the use of cyclic prefix, which for this case is greater than delay spread ($T_{cp} > D_s$) regarding Table 3, is possible to combat ISI due to the frequency selective channel, even when the coherence bandwidth is smaller than the transmitted signal bandwidth as is shown is equation 12.

$$B_{coh} = \frac{1}{2\pi D_S} = \frac{1}{2\pi(3'25)} [MHz] = 48'9\ [KHz] \ll\ BW = 20\ [MHz] \qquad (12)$$

Suppose now a new channel type, the one called frequency-selective-distortion-low-mobility, with parameters are described in Table 10. This channel type is added to the function **MIMOFadingChan.m**, and then the system is simulated by using Table 9 parameters.

| *chanMdl* | path delays | path gains [dB] |
|---|---|---|
| flat-low-mobility | [0,30,90,150,300] | [0,-3,-6,-8,-172] |

**Table 10: Frequency-selective-distortion-low-mobility channel parameters**

The obtained results are shown in Figure 22. Looking at the received constellation it's clear to see that even after channel estimation the constellation doesn't look like a 64QAM. The main reason is because the cyclic prefix is not long enough compared with the path delays and, as a result, some remaining traces of the inter-carrier interference (ICI) and inter-symbol interference (ISI) still exist. Notice that SPD for received signal before channel equalization (blue-colored) still has some fading due to the long channel response and, even when the received signal after channel estimation (orange-colored) is more similar to transmitted signal (yellow-colored), the wave-shape doesn't reach the transmitted signal. These observations should conclude that BER has to take a non-acceptable value and once the simulation ends, the BER value is equal to 0.0921.

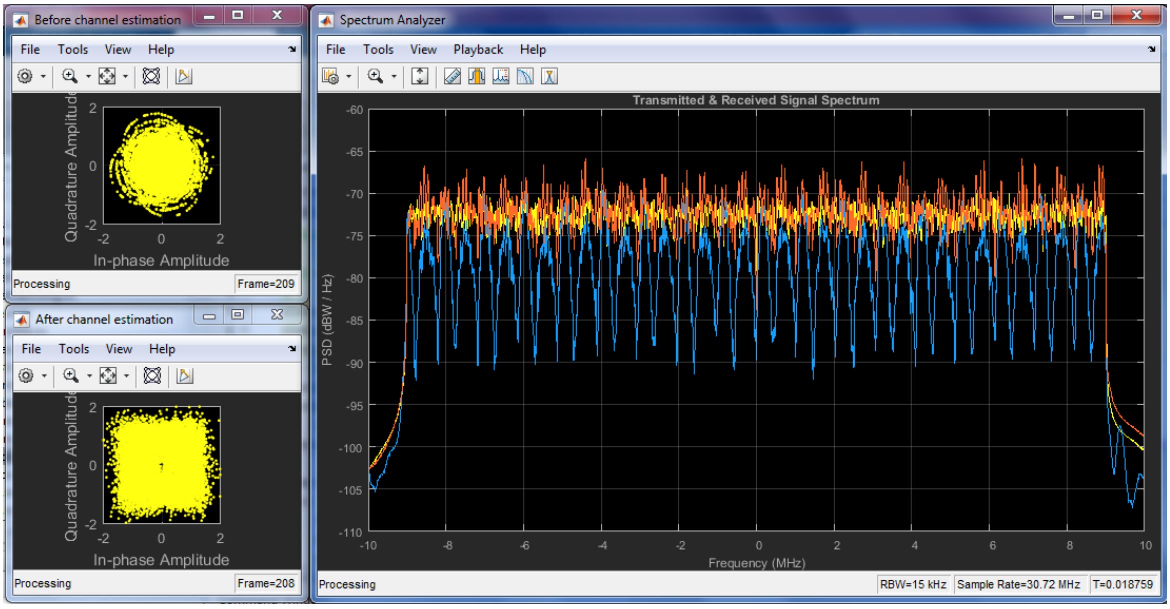


**Figure 22: SPD & Constellation Diagram for 64QAM, frequency-selective-distortion-low-mobility in SISO with channel estimator**

Throughout these previous simulations, we have assumed a noiseless channel by setting the *snrdB* value equal 50 [dB]. But this is an ideal assumption. What would happen when setting this parameter to lower values? Will the system still have a good performance? In order to check this, a simulation where different values of signal to noise ratio (SNR) were considered, was run, and the obtained results are plotted in Figure 23.

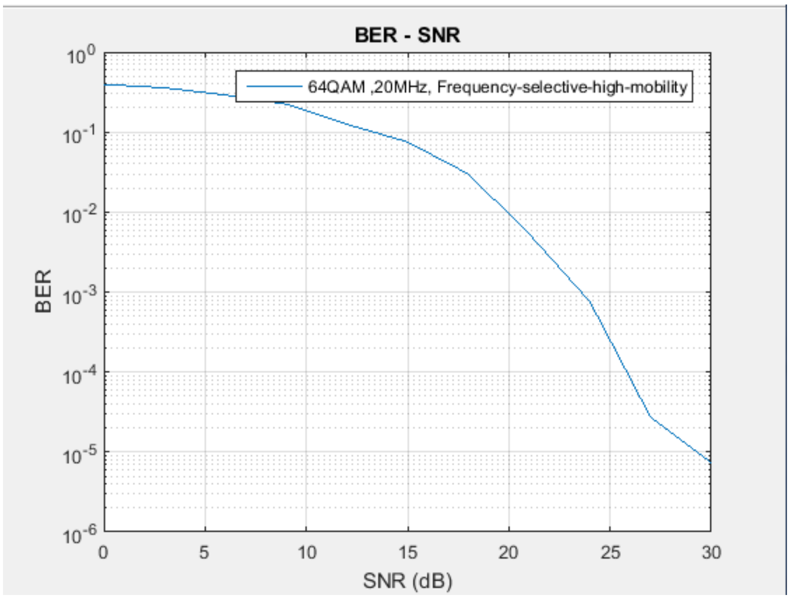


**Figure 23: BER vs SNR; 64QAM in frequency-selective-high-mobility**

As we can observe in the figure, the system has a good performance when SNR takes high values, i.e. $SNR \geq 20\ [dB]$. But for low SNR values the BER value drastically increases, and maybe it would be better to change the modulation to 16QAM or QPSK in order to reduce the BER value.

#### 4.1.1.4. SISO complete

This scheme is the definitive for SISO transmission mode and its transmission chain is shown in Figure 24. When comparing with the scheme presented in the previous section an equalizer has been added to deal with multipath propagation.

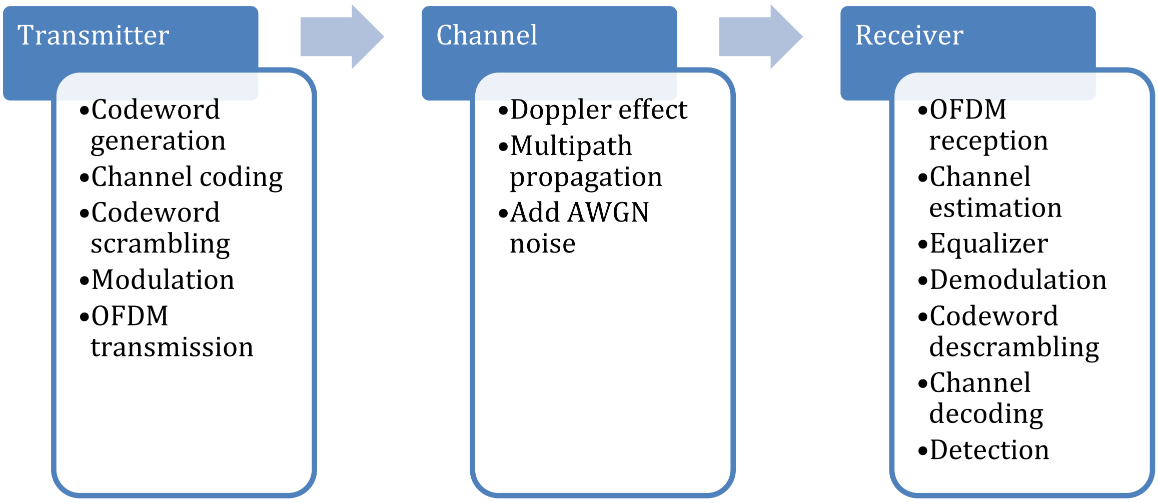


Figure 24: Transmission chain for SISO complete

We choose parameters from Table 9 and we also set the equalization mode to Zero Forcing. The simulation carried out shows that throughput has a peak value of 30.58 [Mbps] and a BER is equal to 7.98e-06.

The spectrum analyzer and constellation diagram before and after equalizer are displayed in Figure 25. Clearly we can see that, with the use of an equalizer, the received constellation looks clear and quite similar to the transmitted one. In terms of spectrum analysis, it’s easy to see the multipath effect in the received signal before equalizer, which is printed in blue-color. We can also observe how blue-colored signal is affected by multipath propagation and how it changes the waveform. However, the equalized signal (orange-colored) is almost the same that transmitted signal – displayed in yellow-colored- and practically non-appreciable.

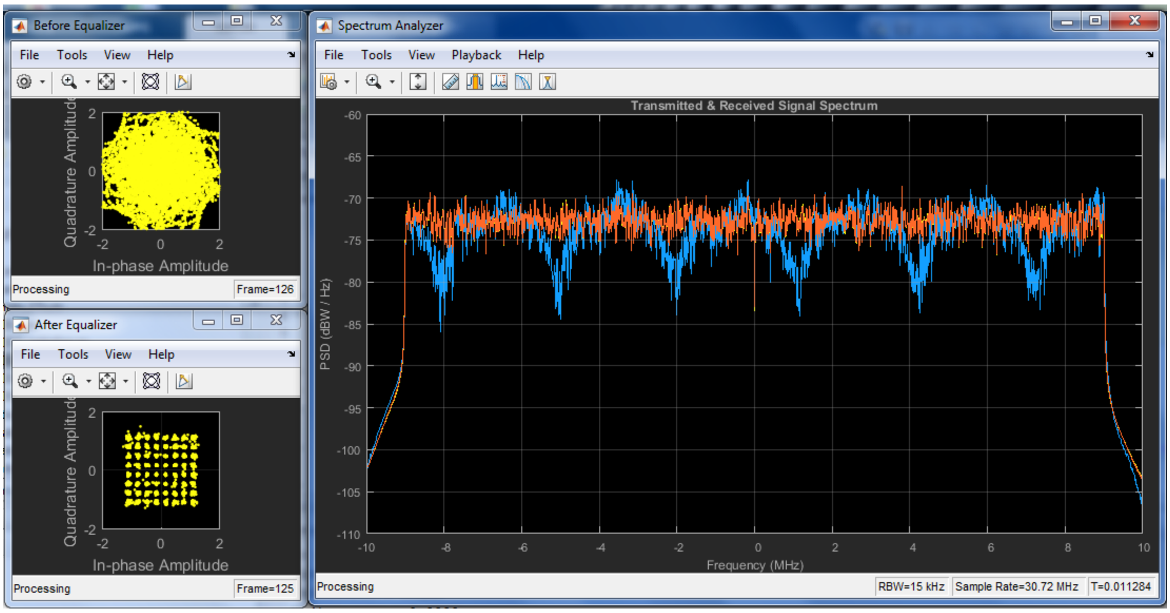


**Figure 25: SPD & Constellation Diagram for 64QAM, frequency-selective-high-mobility in SISO complete**

Under these conditions the system works well. But it is important to take in consideration that a SNR equal to 50 [dB] is assumed, which in real environments is not a usual value. Therefore, now let's simulate the system swapping the SNR value for different modulations in order to determinate the BER behavior as function of SNR and the chosen modulation. The parameters, expect SNR and modulation, are shown in Table 8. The BER results are displayed in Table 11 and a curve for each modulation is plotted in Figure 26.

| SNR | 0 [dB] | 3 [dB] | 6 [dB] | 9 [dB] | 12[dB] | 15[dB] | 18[dB] | 21[dB] | 24[dB] |
|---|---|---|---|---|---|---|---|---|---|
| QPSK | 0.2644 | 0.1802 | 0.0816 | 0.0238 | 8.2e-3 | 1.6e-3 | 1’7e-4 | 1’1e-5 | 8e-6 |
| 16QAM | 0.3315 | 0.2807 | 0.1962 | 0.1252 | 0.0479 | 1.1e-2 | 2’7e-3 | 0’8e-3 | 2’4e-5 |
| 64QAM | 0.3943 | 0.2578 | 0.2903 | 0.2241 | 0.1241 | 7.7e-2 | 3e-2 | 5’1e-3 | 8’1e-4 |

**Table 11: BER results in function of SNR and modulation**

According to the Figure 26, when SNR is very small (approximately equal to the unity) the system takes high BER value regardless which modulation is chosen. As SNR increases we can clearly observe that QPSK is, from far away, the modulation which obtains better BER values. When comparing BER results for 64QAM modulation with 16QAM we can also observe that 16QAM obtains significantly better BER values since SNR takes medium values ($SNR \geq 6\ [dB]$). Despite of these, when the channel conditions gets better, the channel becomes clearer and 64QAM is a good enough choice ($SNR \geq 20[dB]$) when a high data rates wants to be obtained.

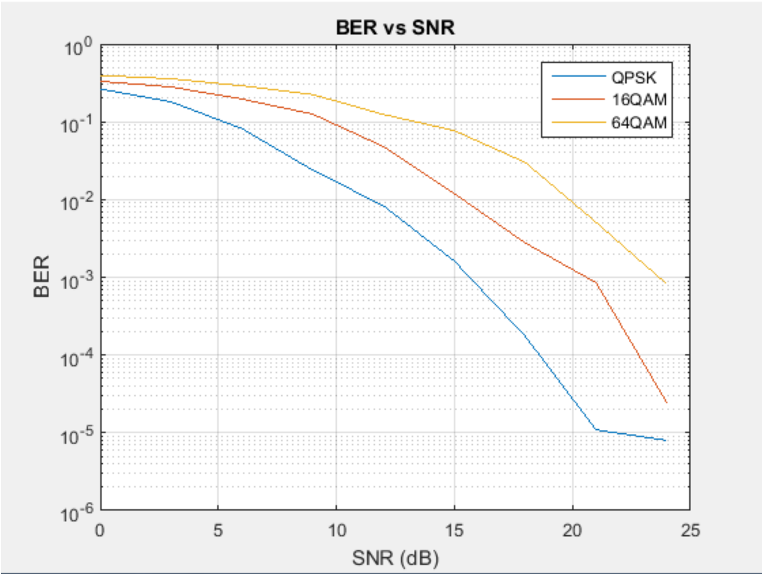


Figure 26: BER graphic in function of SNR and modulation for SISO complete mode

Moreover, notice that this transmission chain admits two equalization modes: ZF (Zero Forcing) and MMSE (Minimum Mean Square Error). The selection of one or other depends of UE's manufacturer preferences. Here simply let's compare the performances of the both - by swapping SNR value. The obtained simulation results are displayed in Table 12 and Figure 27. For very low SNR values (0-6 [dB]) both equalizers have almost the same performance, but when the SNR value increases the MMSE method provides better BER values.

| SNR | 0 [dB] | 3 [dB] | 6 [dB] | 9 [dB] | 12 [dB] | 15 [dB] | 18 [dB] | 21 [dB] | 24 [dB] |
|---|---|---|---|---|---|---|---|---|---|
| ZF | 0.3940 | 0.3577 | 0.2901 | 0.2236 | 0.1246 | 0.0759 | 2.9738e-2 | 5.184e-3 | 6.34e-4 |
| MMSE | 0.3940 | 0.3493 | 0.2901 | 0.1443 | 0.1037 | 0.0328 | 1.03e-2 | 1.671e-3 | 0 |

Table 12: BER results in function of SNR using ZF or MMSE equalizer

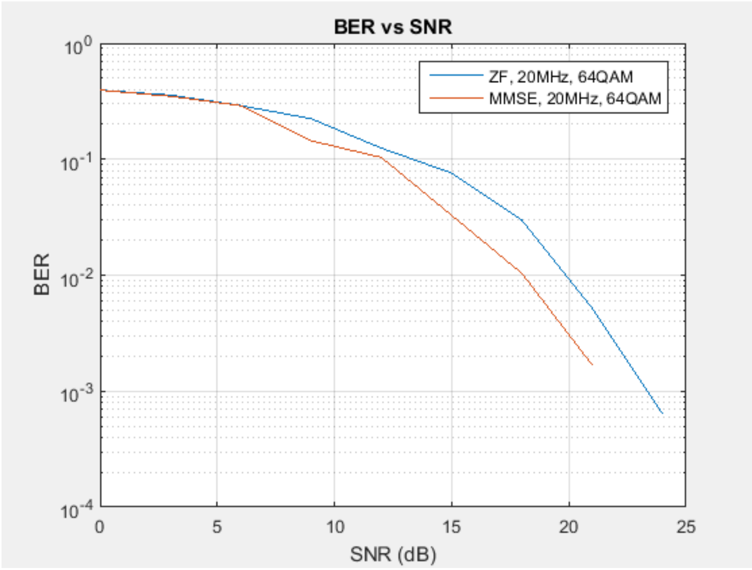


Figure 27: BER graphic in SNR function using ZF or MMSE equalizer

### 4.1.2. SIMO mode

Such as it has been previously discussed in section 3, SIMO is a variant of SISO operation mode wherein multiple antennas are used in reception, with the purpose of increasing the SNR at the receiver thanks to the spatial diversity. In LTE the number of antennas used in reception can be 1, 2 or 4. The theoretical SNR value at the receiver side is given by the following formula, assuming that each receiver branch has the same weighting:

$$\gamma_o = \sum_{n=1}^{N_{Rx}} \gamma_n \tag{13}$$

The code for simulating SIMO mode it's very similar than the used for SISO simulation. The transmitter and channel block are the same, but not the receiver, which has been implemented with multiple antennas and provides a specific equalizer adapted to this case.

Let us check the improvement in BER terms as function of the SNR value under the same conditions that the considered when complete SISO mode was. As SIMO mode is more complete than SISO mode, the settings script must be upgraded. The relevant parameters for the SIMO configuration are shown in Table 13.

| Parameter | Value | LTE value |
|---|---|---|
| chanBW | 6 | 20 [MHz] |

| | | |
|---|---|---|
| modType | 3 | 64-QAM |
| *contReg* | *1* | 1 symbol per subframe to transmit the content of PDCCH channel (control data) |
| chanMdl | 'frequency-selective-high-mobility' | Multipath propagation and significantly Doppler effect. |
| corrLvl | 'Low' | Low correlation level among antennas |
| Eqmode | 1 | Zero Forcing |
| SNR | 16 | 16 [dB] |

**Table 13: Parameters for SIMO mode**

Table 14 summarizes the obtained BER results when run the script commlteSIMO_test_timing_ber.m, and considering different number of reception antennas. As it was expected, taking into account equation 14, the BER value have been reduced although there isn't an improvement in data user bit date, which is the same than in SISO mode.

| | | | |
|---|---|---|---|
| Number of antennas | 1 | 2 | 4 |
| BER | 0.015 | 0.02 | 0 |

**Table 14: BER in function of number of antennas**

## 4.2. Creating the GUI

In this section the main steps followed for developing a basic student-oriented GUI for SISO transmission mode is presented. A UI (User Interface) is a graphical display that enables the user to perform interactive tasks without the requirement that user understands how the code works.

MATLAB offers two ways to create a GUI: one is to use a GUIDE tool, which has an own graphic interface and is more appropriate for a quick, non-complicated apps; another one is create it programmatically, using the MATLAB language, which gives more flexibility to merge with the existing code.

The choice for the GUI implemented in this project was to use the MATLAB language for creating it. The reasons are the following:

1. More flexibility while coding.
2. Allows the use of nested callback functions. In programmatic UIs, when using these kinds of functions, there is a shared workspace with the main function. As a result, these have access to all the UI components and variables defined in the main function.

The scope is to create a GUI that allows choosing from a set of parameters and later on then simulates the whole system, displaying then constellation diagram and spectrum analyzer.

To carry out the GUI some tutorials and a manual of building GUI with MATLAB have been used [7].

GUI is basically composed by figures, components and callbacks. In the case of figures we can insert a set of components such as tables, panels or axes. Any component can have its own callback; an action when the user does something over the component, such as selecting an item from popup menu or clicking a push button.

Create a GUI programmatically is composed of the following phases:

1. Layout: Structure, organize and place all the components that compose the GUI in an m file.
2. Writing the callbacks: Callbacks are the routines that execute in response to user-generated events such as mouse click and key strokes.
3. Utility functions: Can be placed inside the callbacks or as an auxiliary function.

Once the user set the parameters and press the start pushbutton, the GUI has to store the customable parameters into a structure and then simulate the whole system with these parameters. To carry out this procedure it’s necessary to create a command that performs this task. A graphically interpretation of what the GUI does is shown in Figure 28.

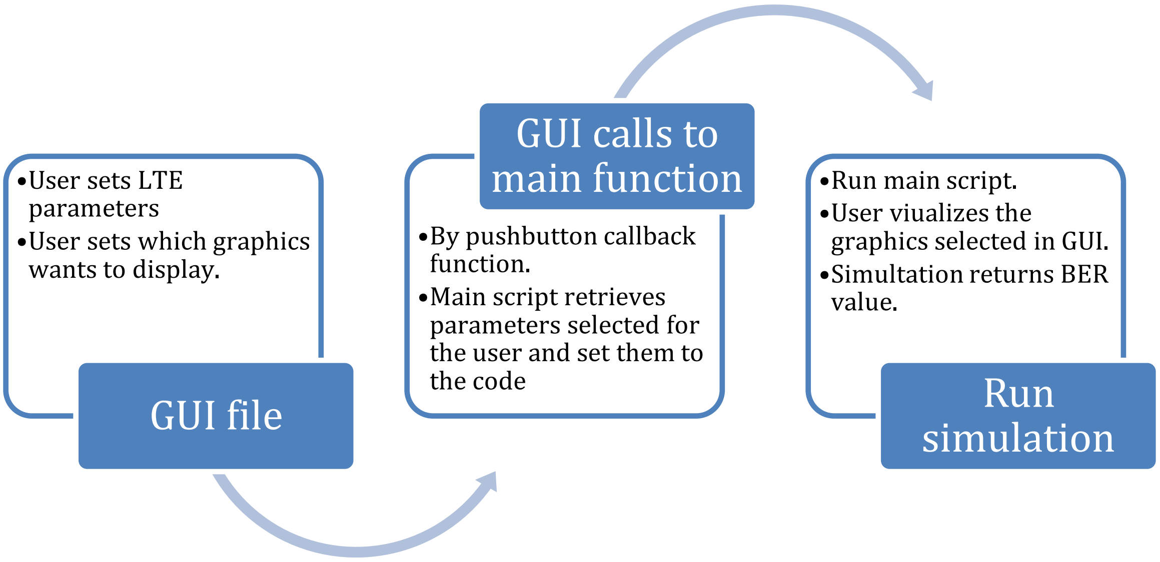


**Figure 28: GUI workflow**

Below there are a summary of steps that have been taken to implement the main GUI:

1. Create an m extension function file
2. Identify which LTE parameters and graphics users can choose from
3. Create a structure with these parameters and graphics, and initialize them
    - User can choose whether SPD and constellation diagram for relevant signals are displayed or not.
4. Construct the components
    - Different component types are created. For example, for selecting channel bandwidth a popup menu component is created, whilst a checkbox component is created for selecting the SPD visualization.
5. Create a callback for each component
    - Each component has associated its own callback. The callback functions saves the desired choice selected by the user and store it as a structure cell. This step is the main reason why the author has decided to create a programmatic GUI instead of GUIDE GUI.
6. Modify functions and scripts of original code
    - This is the most important step because it's here when we have to merge into a single script four different implementations of the LTE transmission chain.
7. Copy the main script to the pushbutton callback
8. Add to the existing structure a set of variables to enable/disable graphics visualization

In Figure 29 we can see a GUI screenshot. It is possible to select one of the four SISO-based transmission chain studied within section 4.1.1. Besides, for each transmission chain we can choose the following parameters:

- Modulation type
- Channel bandwidth
- Channel type
- Signal-to-Noise ratio, in dB
- Equalization mode (when selecting SISO_COMPLETE transmission chain)

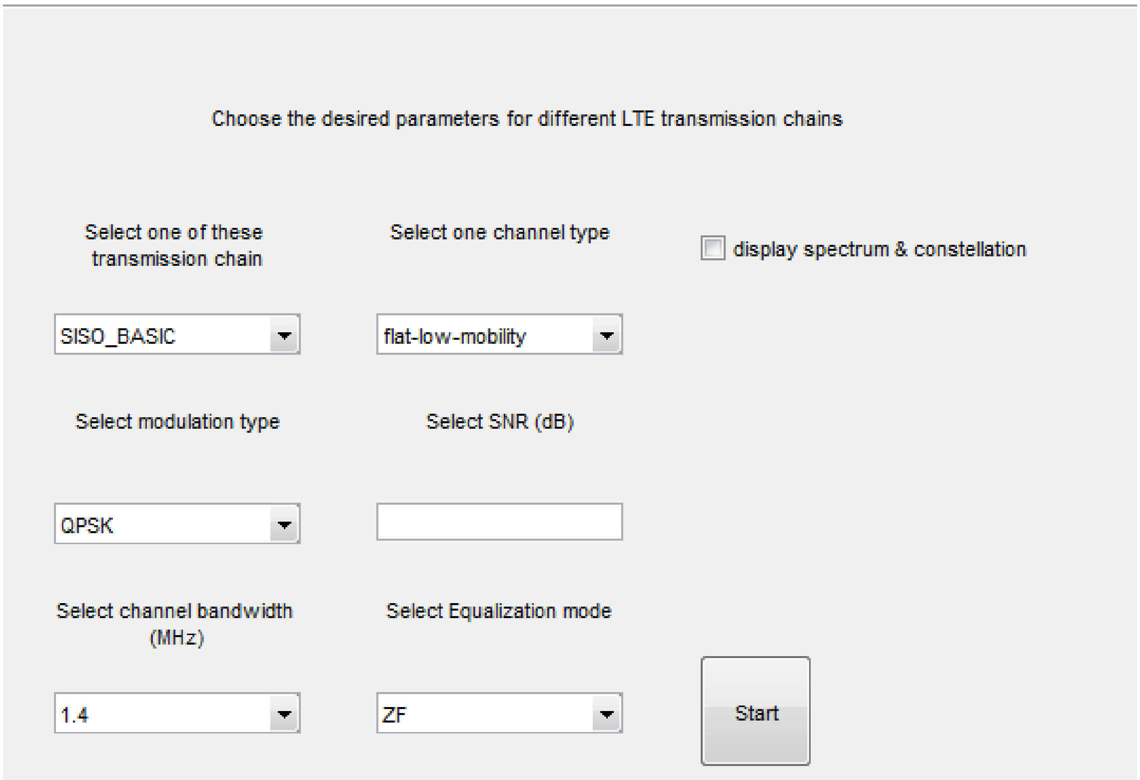


Figure 29: GUI to simulate LTE SISO mode

Moreover, it would be useful for the user to see the resource grid as a function of the number of transmitted subframe. For this reason, another GUI where resource grid is displayed has implemented. In this GUI the user selects the desired number of subframe, channel bandwidth and number of OFDMA symbols dedicated to control data. Then, by clicking on the start pushbutton, the resource grid is displayed.

In Figure 30 two figures are displayed: the left figure is the resource grid GUI, where the user selects the parameters which resource grid is related to. The right figure is the resource grid plot, which is displayed by pressing the start push button at the left figure.

The selected parameters in this case are: channel bandwidth equal to 3 [MHz], number of subframe equal to 0 and number of OFDMA symbols dedicated to control data equal to 2.

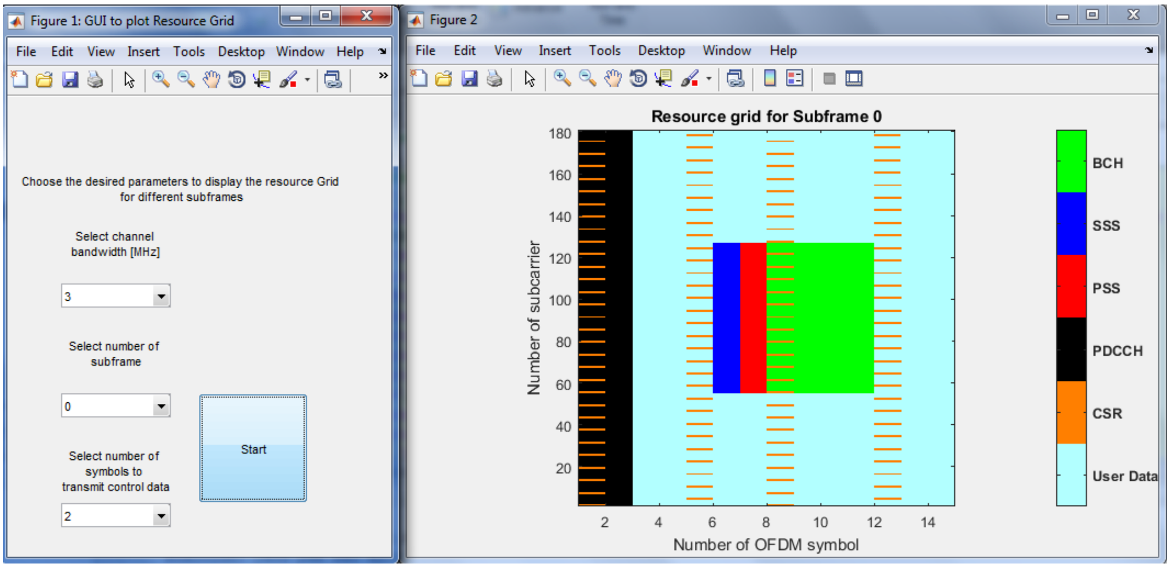


Figure 30: GUI to display resource grid

The code related to both GUI's is provided in an annex to this document.

# 5. Budget

In this project a MATLAB R2015b student license has been used as being the author UPC student, which doesn't has any directly economic cost.

On the other hand, taking into account that this project could be an enterprise project, we could consider two different cases:

- Case 1: Who is contracted is not familiarized with LTE standard but they know how mobile communications systems work. Also has basic MATLAB and Microsoft Word knowledge.
- Case 2: Who is contracted is familiarized with LTE standard. Also has basic MATLAB and Microsoft Word knowledge.

## 5.1. Labor Cost

The personnel cost table below (Table 15) is based on the following figures:

- ✓ A junior engineer perceiving 13.04 Euros per hour.
- ✓ The employee costs a 30% more to the employer than the perceived remuneration due to social security and other taxes, elevating the cost per hour to 17.4 Euros.

| | Case 1 | Case 2 |
|---|---|---|
| Amount of hours | 1050 | 600 |
| Salary [€/hour] | 17.4 | 17.4 |
| Labor cost | 18270 [€] | 10440 [€] |

Table 15: Labor cost

## 5.2. Amortizations

The development of this project only used a single laptop computer for development tasks.

| | Case 1 | Case 2 |
|---|---|---|
| Laptop for the developer<br>Purchase cost | 900 [€] | |

| | | |
|---|---|---|
| Amortization period, 4 years, Residual value | 25% | |
| Used for | 140 days | 80 days |
| Software cost | 86[€] | 50 [€] |

**Table 16: Depreciation**

# 6. Conclusions and future development:

Firstly, by analyzing the LTE physical layer in TM1 some concepts studied throughout the degree have been applied. Also the author finishes this project being more convinced (although it was) of the set of capabilities that MATLAB could provide in different and despair areas, above all in academic areas.

Focusing on the first part of the project, which concerns to LTE analysis, the main conclusion is the good behavior of the OFDMA signals for transmitting at high bit rate in wireless communications, even where there is multipath propagation. Certainly the use of cyclic prefix jointly pilot signals allows at providing very good performances, even at very high rates, without using time equalizer, as it should be necessary in other mobile communications standards.

There are a lot of singularities to study about the downlink physical layer. In particular, SISO mode is considered the system performance as function of channel coding (and modulation schemes as well) is one of the studies that can be easily performed using the framework developed in this project. Other additional studies related to the MIMO characteristics and performances (other transmission modes) are also envisaged, by assuming further developments of the tool.

Referring to the GUI implementation, the main conclusion extracted is: despite there are fewer information available than GUDE way, programmatic GUI is more appropriate if you want to merge an existing code to implement a user interface from it.

The proposed GUI is easy to use and some useful graphics could be also provided. Despite of this, is possible that more graphics could be added in future works about LTE. In this sense, one proposal could be to implement in the GUI a tool to show the resource grid in power terms as 3D graphic.

# 7. Bibliografía

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# Glossary

## 1

16QAM
16 Quadrature Amplitude Modulation, 35, 38, 39, 40, 48

## 2

2G
2nd -Generation, 18, 19

## 3

3G
3rd-Generation, 18, 19
3GPP
3rd Generation Partnership Project, 18, 19

## 4

4G
4th Generation, 12, 19, 20

## 5

5G
5th-Generation, 18, 19

## 6

64QAM
64 Quadrature Amplitude Modulation, 31, 33, 38, 39, 42, 43, 44, 46, 47

## A

ADSL
Asymmetric Digital Subscriber Line, 12
AWGN
Additive White Gaussian Noise, 37

## B

BCH
Broadcast Channel, 27
BER
Bit Error Rate, 33, 34, 36, 37, 38, 39, 40, 43, 44, 45, 46, 47, 48, 49, 50, 51
BS
Base Station, 29

## C

CAPEX
Capital Expenditure, 20
CDMA
Code Divided Multiple Access, 18
CP
Cyclic Prefix, 26
CQI
Channel Quality Indicator, 30
CSR
Cell Signal Reference, 27, 41

## D

DCI
Downlink Control Information, 27
DLSCH
Downlink Shared Channel, 24

## E

EIA
Electronic Industries Alliance, 18
eNodeB
Evolved Node B, 30
ETSI
European Telecommunications Standards Institute, 18

## F

FDD
Frequency Division Duplexing, 13, 25, 33

## G

GPRS
General Packet Radio Service, 18, 19
GRCM
Grup de Recerca de Comunicacions Mòbils, 12
GSM
Global Systems for Mobile Communications, 18, 19, 24
GUI
Graphic User Interface, 3

## H

HSPA
High Speed Packet Access, 18, 19

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## W



## Z