laSalle ENG
Ramon Llull University

Escola Tècnica Superior d'Enginyeria
Electrònica i Informàtica La Salle

Treball Final de Màster

Màster Universitari en Enginyeria de Telecomunicació

Study of low power multicarrier modulations for NVIS applications

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ACTA DE L'EXAMEN
DEL TREBALL FI DE MÀSTER

Reunit el Tribunal qualificador en el dia de la data, l'alumne

D. Tomás González Fontán

va exposar el seu Treball de Fi de Màster, el qual va tractar sobre el tema següent:

Study of low power multicarrier modulations
for NVIS applications

Acabada l'exposició i contestades per part de l'alumne les objeccions formulades pels Srs. membres del tribunal, aquest valorà l'esmentat Treball amb la qualificació de

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Abstract

Telecommunications systems have been growing up to such an extent of having almost all the world connected. In the last years, a lot of articles have been written to create a low-power and low-cost communication system for places with no telecommunicatons infrastructure. The data collection and data transmission in this kind of area is very challenging due to its hard orography that makes the radio-links have no line of sight propagations. The GRITS research group of La Salle University has been researching ionospheric radio-links for almost 20 years. The improvement of the Near Vertical Incidence Skywave (NVIS) channel which let signals rebounding in the ionosphere, has allowed the possibility of creating that media with a low cost system benefiting from the ionospheric communication with a 250 Km distance link. The aim of this project is the study of the Orthogonal Frequency-Division Multiplexing (OFDM) technique and the comparison between narrow-band modulations studied in previous studies of HF bands following the STANAG and MIL-STD standards. This type of modulation could be a very important improvement for the NVIS system due to its robustness. On the other hand, this technique requires much transmission power than the other studied modulations, for that reason, the OFDM design needs to be very accurate so that it can be comparable with low-power transmissions.

Keywords

HF, NVIS, wide-band, narrow-band, Low-power transmission, QAM, PSK, FSK, OFDM, STANAG, MIL-STD.

Resum

Els sistemes de telecomunicacions han anat creixent fins a tal punt que gairebé tothom està connectat. En els últims anys, s'han escrit molts articles per a crear un sistema de comunicació de baixa potència i baix cost per a llocs sense infraestructura de telecomunicacions. La recol·lecció i transmissió de dades en aquest tipus d' àrea és molt difícil a causa de la seva difícil orografia que fa que els radioenllaços no tinguin propagació amb visió directa. El grup de recerca GRITS de la Universitat La Salle ha estat investigant els radioenllaços ionosfèrics durant gairebé 20 anys. La millora del canal Near Vertical Incidence Skywave (NVIS) que permet que els senyals rebotin en la ionosfera, ha permès la possibilitat de crear aquest mitjà amb un sistema de baix cost que es beneficia de la comunicació ionosfèrica amb un enllaç de 250 Km de distància. L'objectiu d'aquest projecte és l'estudi de la tècnica de Multiplexació per Divisió de Freqüències Ortogonals (OFDM) i la comparació entre les modulacions de banda estreta estudiades en estudis anteriors de les bandes de HF seguint les normes STANAG i MIL-STD. Aquest tipus de modulació podria ser una millora molt important per al sistema NVIS a causa de la seva robustesa. D'altra banda, aquesta tècnica requereix molta potència de transmissió que les altres modulacions estudiades, per la qual cosa el disseny de la OFDM ha de ser molt precís perquè pugui ser comparable amb les transmissions de baixa potència.

Paraules clau

HF, NVIS, banda ample, banda estreta, transmissió de baixa potencia, QAM, PSK, FSK, OFDM, STANAG, MIL-STD.

Resumen

Los sistemas de telecomunicaciones han ido creciendo hasta tal punto que casi todo el mundo está conectado. En los últimos años, se han escrito muchos artículos para crear un sistema de comunicación de baja potencia y bajo costo para lugares sin infraestructura de telecomunicaciones. La recolección y transmisión de datos en este tipo de área es muy difícil debido a su difícil orografía que hace que los radioenlaces no tengan propagación con visión directa. El grupo de investigación GRITS de la Universidad La Salle ha estado investigando los radioenlaces ionosféricos durante casi 20 años. La mejora del canal Near Vertical Incidence Skywave (NVIS) que permite que las señales reboten en la ionosfera, ha permitido la posibilidad de crear ese medio con un sistema de bajo costo que se beneficia de la comunicación ionosférica con un enlace de 250 Km de distancia. El objetivo de este proyecto es el estudio de la técnica de Multiplexación por División de Frecuencias Ortogonales (OFDM) y la comparación entre las modulaciones de banda estrecha estudiadas en estudios anteriores de las bandas de HF siguiendo las normas STANAG y MIL-STD. Este tipo de modulación podría ser una mejora muy importante para el sistema NVIS debido a su robustez. Por otra parte, esta técnica requiere mucha potencia de transmisión que las demás modulaciones estudiadas, por lo que el diseño de la OFDM debe ser muy preciso para que pueda ser comparable con las transmisiones de baja potencia.

Palabras clave

HF, NVIS, banda ancha, banda estrecha, transmisión de baja potencia, QAM, PSK, FSK, OFDM, STANAG, MIL-STD.

Dedicated to GRITS investigation group especially to Joaquim Porté and Josep Masó who let me start in the investigation world and they became friends in a short period.

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Acronyms

ADC: Analog-to-Digital Converter.

AWGN: Additive White Gaussian Noise.

BER: Bit Error Rate.

BW: Bandwith.

CCI: Co-channel Interference.

CDF: Cumulative Distribution Function.

CFO: Carrier frequency offset.

CIR: Carrier-to-interference Ratio.

DAC: Digital-to-Analog Converter.

EbN0: Energy per bit to Noise power spectral density ratio.

FEC: Forward Error Correction.

FPGA: Field-Programmable Gate Array.

FSK: Frequency Shift Keying.

HF: High Frequency.

IBI: Inter Block Interference.

IBO: Input Back Off.

ICI: Inter-channel nterference.

ISI: Inter-carrier interference.

LNA: Low-Noise Amplifier.

MMSE: Minimum Mean Square Error.

NVIS: Near Vertical Incidence Skywave.

OFDM: Orthogonal Frequency Division Multiplexing.

OFDMA: Orthogonal Frequency Division Multiple Access.

PSK: Phase Shift Keying.

QAM: Quadrature Amplitude Modulation.

SC-FDE: Single Carrier frequency-domain equalization.

SC-FDMA: Single Carrier Frequency Division Multiple Access.

SDR: Software Defined Radio.

SNR: Signal-to-Noise Ratio.

ZF: Zero-forcing.

Acknowledgements

I want to say thanks to David Badia and Joan Lluís Pijoan because they trusted me without any knowledge of me, just small feedbacks from Joaquim Porté and Josep Masó. Also Jordi Malé who became my work-partner and we are going to go to Antarctica next year. Thank you all! I have felt part of the group since day one.

Joan Gomez, who was the first person I started to speak during the Master and we shared a lot of walks on our way home, coffees, different kind of talks and he became a friend in a short period.

Marc Vilella, who travelled abroad and the friendship became stronger even with the COVID virus. I want to keep the phone calls and the good moments.

Also, I want to thank my entire family for supporting me in any situations, when I was in a bad mood or in the time of taking difficult decisions. I know that sometimes I am not as easy, but I love you so much.

Finally, I want to thank the person who had continuous headaches sharing moments since 2001, and hopefully, this won't rest on paper, and we will keep sharing these bad and good moments. Thank you Marc Diez.

Chapter 1

Introduction

1.1 Project Introduction

The GRITS research group of La Salle University had much seniority in telecommunications research, especially in the field of ionospheric communications. Many articles related to the challenge of providing an affordable channel communication for areas with no infrastructure have been written for the last 20 years.

Nowadays the GRITS has already a stable platform that works in HF around 5 MHz and let users to be communicated just for emergencies situations as an alternative to satellite communications.

NVIS channel which the GRITS started to investigate it four years ago, is a technique where the transmissions of signals are performed through the ionosphere. The transmitted signal rebounds giving a coverage range around 250 Km.

This channel was already tested in Antarctica which is a problematic area for wireless communications field because of its lousy landscape in the sense of transmitter and receptor deployment. For that reason, NVIS is a right choice for these areas in terms of costs.

Apart from its availability due to the ionosphere, a weak point of NVIS is the low transmission speed and the multipath effect formed by the different ionosphere layers. Because of that, the focus of this project is to study the feasibility of multicarrier modulations for NVIS in order to be more robust against the multipath.

Finally, the results are going to be tested and compared with narrow-band modulations, especially with QAM modulations which has the best results until now.

1.2 Motivation

When I started the Master, Joaquim Porté and Josep Masó did their first lecture of Radio Systems, including concepts as signal processing and radio links design for the Antarctica Project.

At that time, I already had a job; however, I asked for more information about the project because it was so exciting to me.

After some explanations, they told me that there was a vacant post. That new was too interesting for passing up the opportunity so, I gave my job up, and I did all the possible to reach the post.

One of the most motivation points was that they had almost the same age as me, so it was an extra motivation seeing that they had a lot of experience in that field.

Finally, I'm working on the project that I want to. I work with people who I can call friends, and I learn every day in a non-monotonous environment and the most interesting point is that I'm going to go to Antarctica.

1.3 Objectives

The main goals presented in this project are as follow:

1. Study of the feasibility of the multicarrier modulations for ionospheric communications using NVIS communications system.

2. Comparison the performance of the different multicarrier modulations with the narrowband.

1.4 Document structure

This document is divided into different sections as follows:

- **Chapter 2. State of art:** shows a general view of the different approaches that the Antarctica project suffered.

- **Chapter 3. Theorical Framework:** explains previous concepts in order to follow the whole project in an easier way including the study of the multicarrier modulations.

- **Chapter 4. Current platform and implementation:** explains the entire system including the software modifications.

- **Chapter 5. Simulation and results:** shows the different tests and the comparison of the results as well as how the tests were designed.

Chapter 2

State of art

This Master's Dissertation is just a small contribution to the Antarctica project which has been under study for almost twenty years. The GRITS investigation group of La Salle University started this long research in 2003 with different goals which some of them share similarities of the current studies. The focus of the entire project lies in giving an alternative solution to satellite communications for places with a complex environment with inexistent infrastructure where the attempt to deploy transmitters and receptors is not always viable.

The studies started with the study of the ionospheric channel between the Antarctic base and the Observatori de l' Ebre in Spain being 12.000 Km communication distance to get values as multipath, Doppler spread, Doppler shift,SNR, channel availability[32].

Once the channel study was successful, an unidirectional transmission was deployed. After that, the GRITS focused on oblique ionospheric communications, where the transmissions need 5 rebounds in the ionosphere in order to reach a long-haul transmission, where the results gave a significant contribution.

Recently, the current research addresses the use of NVIS, which is still under investigation, and the optimization is every day better. The main differences with oblique transmissions are: NVIS has just a single rebound, different channel effects and the small but enough coverage which is 250 Km. The use of IoT is booming, and the challenge of the low power systems requires hard design decisions because of the need for small batteries to have portable devices, for that reason NVIS working in high frequencies opens a wide range of possibilities for remote sensors. Apart from that, the platform design has to be affordable with the aim of let people to have a minimum way of communications even just for a small text message to ask for help. Its versatility is obtained with the advent of Software Defined Radio satisfying multiple design options.

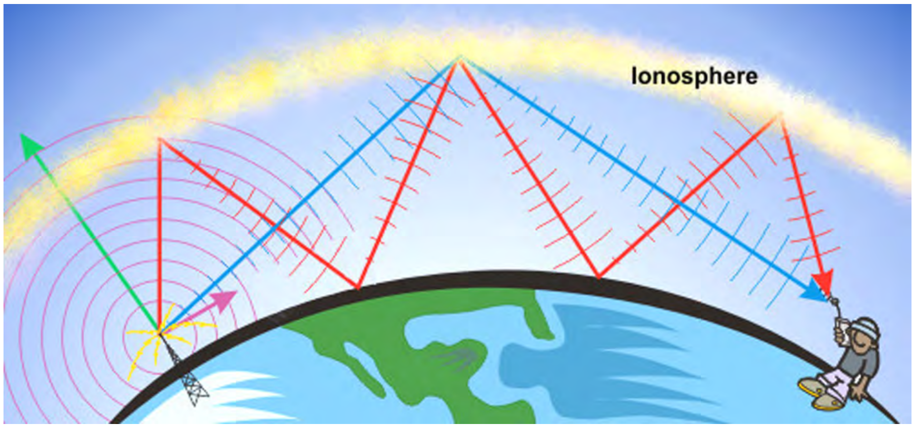

Figure 2.1: Ionospheric communications[27]

Chapter 3

Theoretical Framework

3.1 The ionosphere

Depending on the existing solar radiation in the ionosphere, a signal can be rebounded relying on the value of the signal frequency.

The ionosphere has four different layers that appear or disappear depending on the day phases changing the solar radiation and as a consequence, the carrier frequency of the system must be changed to take advantage of the characteristics of the ionosphere.

The ionosphere layers are D, E and F which is divided in two sub-layers depending of the season and the solar cycle.
The D is not used for this project due to the absorption of signal for frequencies below 10 MHz and also has the inconvenient of appearing just during the day[17].
The E layer is one which let the signals rebound, even not being the principle one.
At last, the F which is composed by the F1 during the day and the F2 which appears the whole day. This layer is the principle one for our purpose.

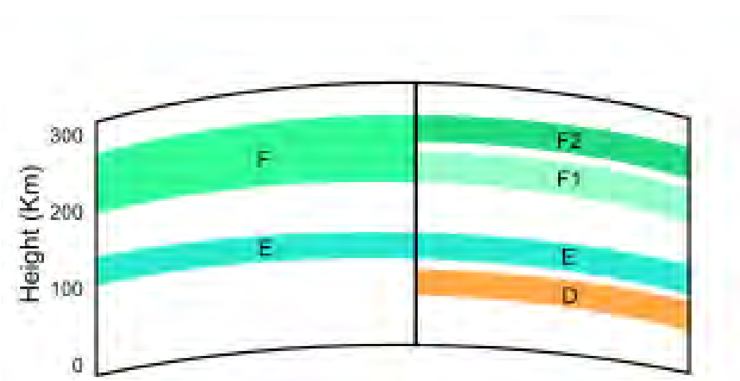

Figure 3.1: Ionosphere layers[33]

The principal reflected rays of the ionosphere called Ordinary and Extraordinary give meaning to the NVIS channel. Both rays are formed in the same layers but changing the polarization.

With the help of ionograms, the ionosphere layers are always in mind to select the correct frequency which is stated as 90% of the critical frequency. The critical frequency is the highest frequency, at which a signal will be rebounded in some layer of the ionosphere and for the extraordinary wave is a little bit higher than the ordinary one.[35]

It is known that for HF from 3 to 30 MHz oblique ionosphere communications (incidence angle $< 70^{o}$) works good. For NVIS communications ($70^{o} <$ incidence angle $< 90^{o}$), these frequencies are limited to 10 MHz.

These communications have the virtues of having a big coverage around 250 Km without the need for a direct view between transmitter and receptor or any repeater. In contrast to oblique communications, the NVIS technology uses just one rebound.

Since NVIS does not need the support of any operator, the price is reduced significantly. The principal negative point of ionosphere communications is of course its availability due to the ionosphere.

One of the tricky points of the NVIS applications is the power consumption, which must be low on points of battery to be portable sensors.

Also, this kind of use could be extrapolated to non-infrastructure areas letting people the possibility to communicate in case of emergency. Of course, speed communication is not so high but is fully adequate for sending messages and photos.

3.2 NVIS channel efects

Multipath

Multipath effect resides with the multiple paths that a signal can take to reach the receiver. For two paths, it could be two scenarios depending on how the signal arrives at the receiver. If the signal comes in phase with the other path, they are both summed constructively. Contrarily, this may be the case where the resulting signal will be null due to the destructive sum.

In ionospheric communications, the shorter path can arrive to the receiver antenna and rebound again with the floor arriving to ionosphere producing another path.

This effect produces ISI where the symbol is interfered with the adjacent one due to the delay of the second path. Sometimes the equalization can solve this issue.

The Delay Spread is just a measure of the multipath with gives the difference between the most delayed path and the first one. In the figure 3.2 different paths are shown and we can see that they have different powers depending on how the signals rebounded. In this case the Ds is 3 microseconds (longest path).

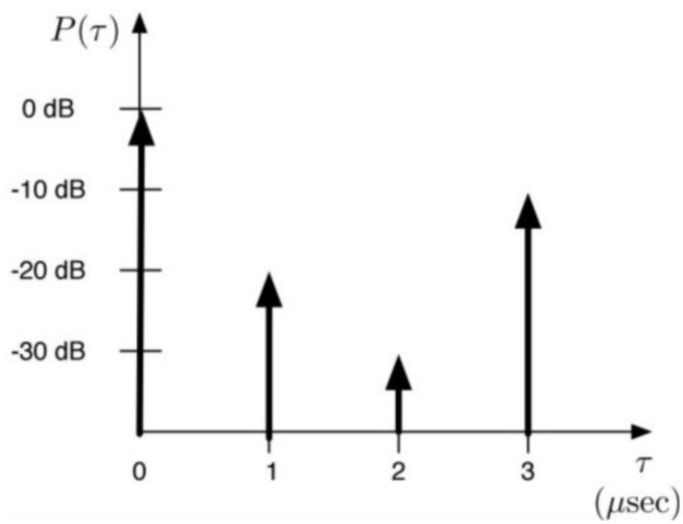

Figure 3.2: Three paths of the same signal[2]

Doppler shift

The Doppler shift affects signals producing fadings due to the movement of the transmitted signal and received one due to the ionosphere layers movement. It shows the channel frequency variety related to the maximum speed of the ionospheric layers.[17]

In ionospheric communications the frequency of the signal can be shifted between 1 or 9 Hz [18].

Doppler spread and Coherence time

The Doppler spread is an effect where the receiver receives the signal with a displacement in the frequency due to the transmission distance. In this scenario the frequency values of the Fourier transform in the time-domain of the auto-correlation function of the channel response is not zero [32][25]. This is produced by the movement of the ionosphere layers or the polarization changes.

The inverse of the Doppler spread (Bd) gives rise to the coherence time (tcoh) which states the time when the channel is considered constant.

In the next chapter there is a subsection where the PN-sequence is explained which apart of synchronization, serves to know the fadings profile.

Coherence bandwidth

Just as there is a coherence time, so there is a coherence bandwidth which is defined as a set of frequencies where the channel is considered constant. It is inversely proportional to the delay spread [9].

In figure 3.3 we can see that the range of frequencies in the marks are similar in terms of channel. In contrast, in the figure 3.4, the values will show a very narrow coherence bandwidth, that means that the bandwidth of the symbols must be very short in order to avoid a lot of fadings.

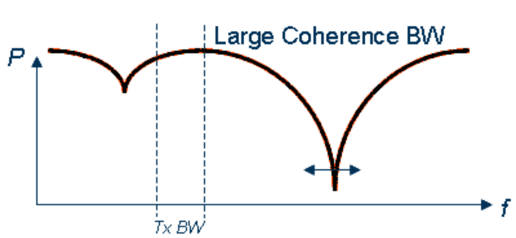

Figure 3.3: Wide coherence Bandwidth[14]

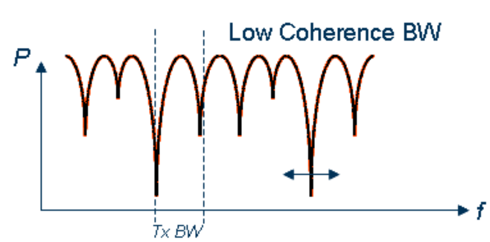

Figure 3.4: Narrow coherence Bandwidth[14]

3.3 Polarization Diversity and Diversity Combining

The polarization diversity profiting the ordinary and the extraordinary rays available opened a new study point which can be read in [15].

Basically, the use of multiple antennas provides a performance enhancement in terms of robustness and throughput despite of being a complex processing in order to separate the different paths.

MIMO is a method which follows the tendency of the use of a lot of antennas including smart antennas. It took so much strength with the use of 3G due to the space-time transmit diversity. Nowadays, the premium routers have at least eight antennas and use MIMO and other variatios of it.

The current platform uses the SIMO technique with two antennas in the receiver receiving the ordinary and the extraordinary waves to reduce errors and make the communication more robust. It is being tested with different modulation orders and powers keeping in mind that extraordinary wave has EbNo two times less than the ordinary wave, for that reason if we compare both waves separately the ordinary wave has most of the times better results. In this project [19], receiver diversity was studied having the results of the Selection Combining technique overcomes the ordinary transmissions due to its BER/EbNo selection. Besides, the EGC is also studied but depending of the scenario the results can be better or worst due to the sum of two channels.

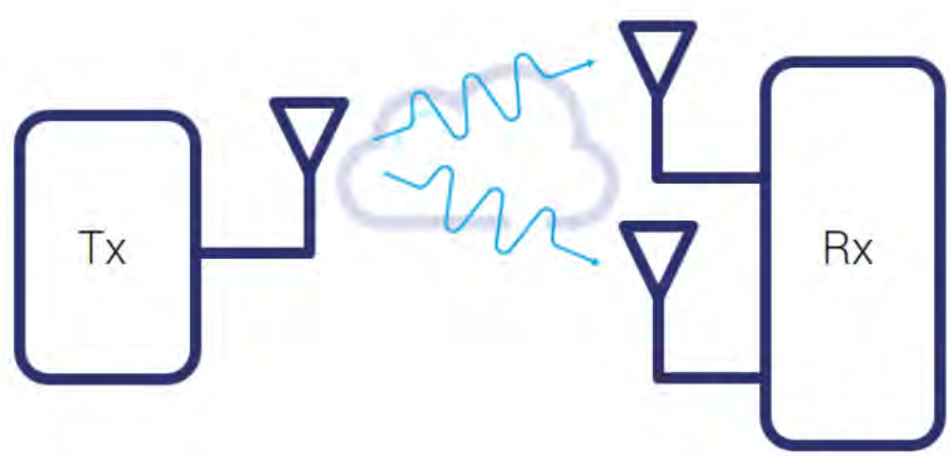

Figure 3.5: SIMO technique with two receiver antennas[6]

3.4 Narrowband and digital communications

The previous Antarctica projects have studied the performance of the digital modulations with frequencies in HF range and using narrowband channel.

The bandwidth used in the Antarctica project is around 2.3 KHz bandwidth which is considered narrowband communications.

The digital communications are based on the modification of one or more parameters of the carrier frequency according to the information bits merely result in different modulations. Specifically in this projects the three principal modulations which are explained below are compared.

Frequency Shift Keying (FSK)

FSK is a digital modulation which modifies the frequency to distinguish different symbols to transmit being the phase and amplitude constants.

It is normally used for low-speed digital applications with modulation order 2. Compared to PSK or QAM, it needs more bandwidth.

Phase Shift Keying (PSK)

PSK is a digital modulations that the carrier frequency is modified by the phase change letting the rest of the carrier parameters constants.

This modulation is benefited by the rise of the modulation index which allow higher bitrates.

Some typical applications are Bluetooth and RFID.

Quadrature Amplitude Modulation (QAM)

This modulation takes the benefit of the PSK modulation but changing also the amplitude. The weak point is the need of the rise of the power due to the noise sensibility in order to keep the same BER[22].

Currently, the project has its best results due to this modulation. It has a lot of applications due to its big immunity agains noise and low probability of error.

3.5 Orthogonal Frequency-Divison Multiplexing (OFDM)

This transmission technique is based on the principle of multicarrier frequency division in which the modulated data in a single carrier, normally with a narrowband modulation as M-QAM or M-PSK, is divided into several subcarriers with narrower bandwidths.

This principle is supported because these subcarriers are orthogonal between them and furthermore, there is a frequency space between each subcarrier letting the maximum amplitude of each subcarrier matches with the null of the adjacent ones, so the transmissions of the OFDM symbols go in parallel without ISI.

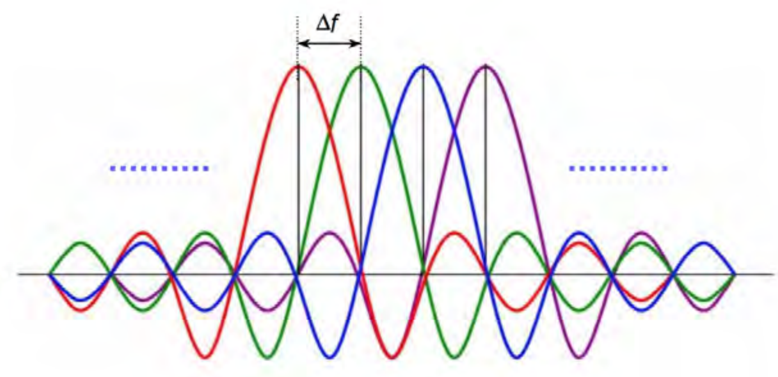

Figure 3.6: OFDM subcarriers assignment[29]

Another benefit is that by taking advantage of the narrow-bandwidth symbols, the channel can be considered constant, for that reason the channel estimation in the reception side is less complex.

This technique has an adaptation for multiple users (multiple access) called OFDMA, which has nowadays a very extended use, especially in the downlink for mobile communications standards, as LTE and recently the fifth generation of broadband cellular network technology, 5G.

3.5.1 Scheme

The next figure shows the process that the bits suffer to reach an OFDM transmission.

Initially, the bits are in serie (one after the other) which are converted to parallel depending the modulation index of the narrowband modulation.

After that, the bits pass by the mapping module (M-QAM or M-PSK) to get the narrowband symbols.

The Inverse Discrete Fourier Transform (IDFT) is applied to these symbols which is used to convert the symbols in the time domain. In the IDFT, the DC null which is used to avoid offset errors and serve as buffers between OFDM resource blocks, is located in the center of the frequency band. and adding the Cyclic Prefix (CP, explained in the next subsection) to finally convert them into serie again. Citar a Matlab

The reception side follows the opposite way with the difference of the use of the Discrete Fourier Transform (DFT) and the channel estimation before the demapping module in order to equalise the symbols.

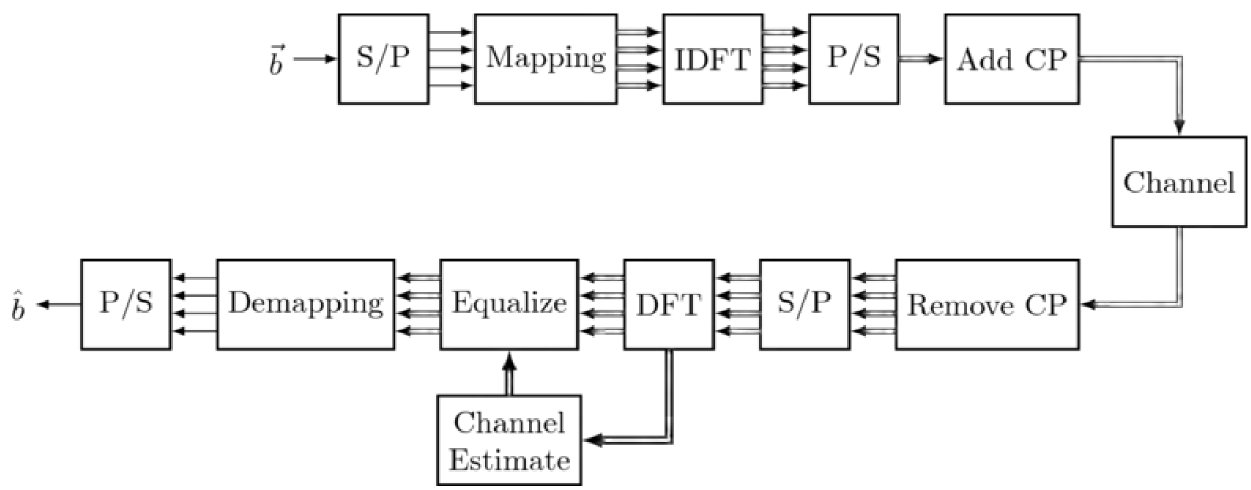

Figure 3.7: OFDM scheme[4]

3.5.2 Cyclic Prefix

The CP is one of the principle powerful advantage of the OFDM. The CP consists in repeating the last part of the OFDM symbol with the aim of combating the multipath effect. The length of the CP is normally the value of the Delay Spread. With that the ISI and ICI are avoided.

3.5.3 Channel estimation and equalization

Some symbols OFDM can be composed by pilot symbols even there are cases where the entire OFDM symbol are pilot symbols.

The insertion of these pilots help to know the channel estimation in the reception side at the cost of losing some efficiency.

In the receiver, the pilots are separated from the information ones, they are compared to the transmitted ones and create a matrix which contains the inverse of the channel which the signal transmitted suffer.

Finally, the resulting matrix multiplies the OFDM symbols, which contain just information. As a consequence of that, the channel effect decreases.

This process is known as equalization, and there are a lot of different techniques. This case refers to the Zero Forcing equalization method.

3.6 Single Carrier Frequency-Domain Equalization (SC-FDE)

Keeping the same analogy with OFDM and OFDMA, the SC-FDMA (Single Carrier Frequency Division Multiple Access) is a multiple users modulation derived from the OFDMA where the main advantage is the mitigation of the well-known problem of OFDMA, PAPR.

It also has a very extended use, but in this case, the main one is the uplink for LTE and 5G standards.

The studied modulation is the SC-FDE which is the version of SC-FDMA without multiple access and compared to OFDM has some differences which are going to be explained in the next point.

3.6.1 Scheme

Despite being almost the same transmission scheme, the IDFT/IFFT is done after the frequency domain equalization improving low SNR caused by the FFT from the OFDM. That means that the transmitter is very simple because it has no complex mathematical operation. The cons here are the computation cost that the receptor has. Furthermore, the equalization for the SC is applied in the frequency domain but is not too easy due to the need to have the noise estimation apart from the channel and it is not possible to use the ZF equalization.

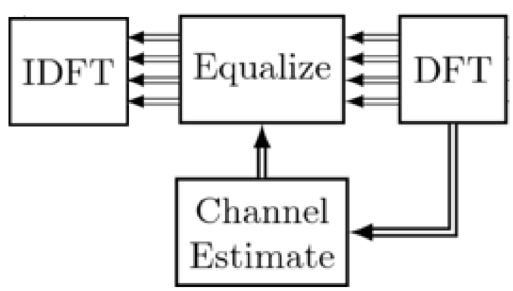

Figure 3.8: FFT and IFFT in the Single carrier reception side[4]

The second difference is that the symbols are spread during the channel bandwidth instead of dividing them into narrow subcarriers. The consequence of that is that Single Carrier takes all the available bandwidth but occupies Nofdmsymbols times less than the OFDM in time-domain.

The SC modulation has three different transmission schemes for subcarrier mapping in order to assign a group of subcarriers to a single user and letting the unused subcarriers with null values. Contrary to OFDM where various subcarriers are assigned for multiple users.

- **DFDMA Distributed FDMA:** In this subcarrier mapping, the subcarriers are over the whole bandwidth [20].
- **LFDMA Localized FDMA:** This scheme batches sequential subcarriers to the same user.

  Several studies have demonstrated that these two schemes present a higher PAPR than the next one [8]. In the next figure, the DFDMA and the LFDMA schemes are shown.

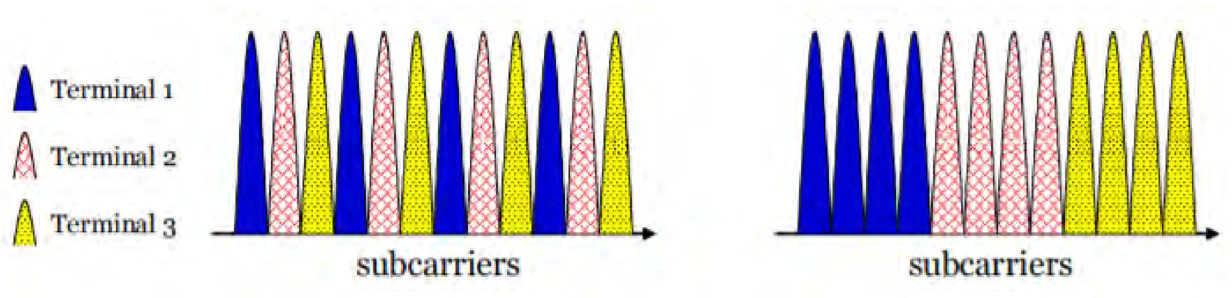

Figure 3.9: DFDMA and LFDMA subcarrier transmission schemes[20]

- **IFDMA Interleaved FDMA:** This last scheme is the chosen one for the uplink in LTE and 5G due to its low PAPR and CFO doesn't affect much. This technique allocates the subcarriers spacing them during the entire bandwidth with an equal distance.

In the following figure, an example of 4 users and 12 available subcarriers (null subcarriers included) shows how the output data from the of the different subcarriers is distributed for different users.

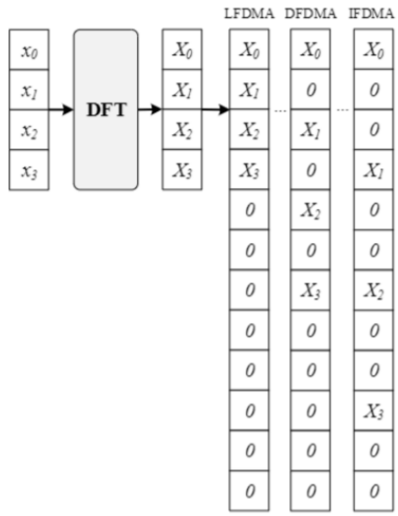

Figure 3.10: Subcarrier mapping[8]

3.6.3 Channel Estimation and Equalization

There are two known FDM pilot schemes, frequency-domain-superimposed pilot technique (FDSPT) and frequency-domain-superimposed(FETs).

The FET technique consists in adding pilots in the frequency-domain between some data symbols. It is more inefficient in terms of spectral bandwidth.

The FDSPT scheme overlays data symbols with pilots. It is more inefficient in terms of BER, and as a result, the power needed to compensate it is about 1.5 dB more. Both techniques make the PAPR increase but not comparable to OFDM [13].

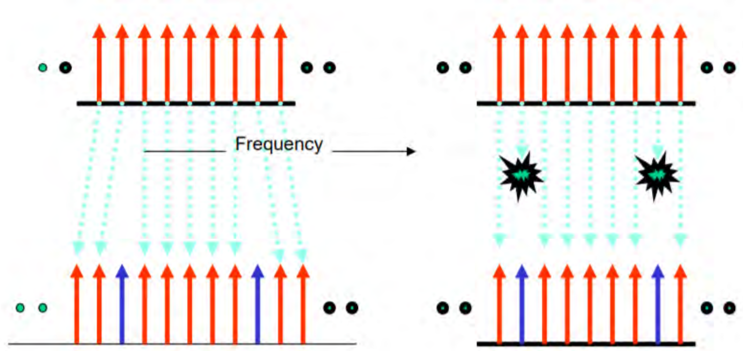

Figure 3.11: FET vs FDSPT

As in OFDM, the frequency domain channel estimation produce inter-carrier interference (ICI) due to the carrier frequency ofset (CFO) caused by the impairment of the transmitter and receiver oscillators[3]. The OFDM suffers the Doppler Shift more than the SC-FDE due to the subcarrier separation[25]. The use of CP helps to SC-FDE to be less sensitive to IBI and ICI.

Despite being the most common and simple, the ZF equalizer reaches a non-good enough channel estimation for this case. In general, this equalizer is used because in most scenarios the CIR is ideally known and is also considered constant during one or two blocks.

For that reason, the MMSE equalizer is better in the case of having a noisy channel because it considers the noise power for channel estimation.

MMSE removes the noise fully at the expense of not reducing the ISI completely.

One thing to keep in mind is that when the equalization is applied, the FFT make the constant pilots null values due to the constant value.

For that reason the pilots take the values of a complex-valued Zadoff-chu sequence which has the characteristic that the values are known and when applied to a signal, gives rise to a new signal of constant amplitude[30].

When the FFT is applied, the pilots have different value but in module are one, and having a constant frequency-domain amplitude. Tahat sequence are called Cazac[10].

Figure 3.12: Zadoff Chu representation

3.7 Comparison between OFDM and SC-FDE

The comparison is made just in a conceptual way. In the next chapter there is a comparison of the OFDM and the narrowband modulations.

The main difference resides in the Peak to Average-Power-Ratio (PAPR) which is the difference between the peak power and the average power. It is known that the weak point of the OFDM is the power consumption needed due to the subcarrier division. That distribution of frequencies forms peaks which produce high peak power, and the average power is sometimes insufficient. For that reason, in the uplink transmissions, the single carrier is often used due to the energy consumption and the no-need to use high-quality and high-cost amplifiers.

Testing both modulations, the results shows that the performance between them is similar, even OFDM can have lowers BER [21] and higher bitrates than SC, but of course the PAPR ratio makes the SC to have a better trade-off.

The second main difference is the distribution of the symbols. In scenarios with Gaussian noise and multipath channel, the signal degradation are similar for both of them, as well as IBI, which is solved with the CP insertion.

The SC is wider in bandwidth, so For the SC the ISI can be a bigger problem. By contrast, the single carrier is more robust than OFDM in terms of Doppler effects due to its subcarriers narrow bandwidths. Both of them can use of guard band in order to reduce ICI.

Previous researches affirm that using multiplex access versions, SC-FDMA using the QPSK modulation, overcomes the OFDMA and that difference decreases rising the modulation order of the symbols.[28].

The Single Carrier needs a MMSE equalization in order to estimate the noise and also helps to have a better spectral efficiency.

The OFDM works fine with ZF equalization which is simpler and is good to avoid interferences.

If we use MIMO techniques, the MMSE equalization seems to have better results due to the noise power reduction and the non-high SNR needed [16].

The next table summarizes all the concepts explained before.

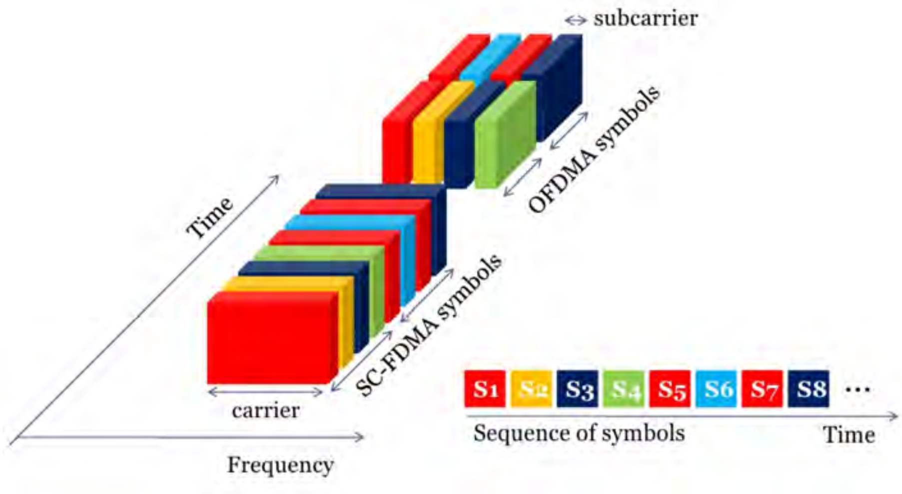

Figure 3.13: Symbols distribution for OFDMA and SC-FDMA[31]

	OFDM	SC
TX	Downlink	Uplink
Robustness against ISI	Good	Bad
Robustness against Doppler Shift	Bad	Good
Robustness against CFO	Bad	Good
PAPR	High	Low
CCI	High	Low
Spectral efficiency	Good	Bad
BER/Bitrate efficiency	High	Moderate
Equalization complexity	Low (ZF)	Moderate (MMSE)
Receiver complexity	Good	Bad

Table 3.1: OFDM vs SC

3.8 Forward Error Correction

Apart from the equalization which estimate the channel behaviour and overcomes the results when demodulating, there are some techniques that avoid errors in terms of bit transmissions called Forward Error Correction (FEC).

FEC or Channel coding

Coding is a technique which consists in adding redundant information in the transmitting signal after the conversion to the digital domain.

This method is very useful, but it causes bitrate loss due to the bits with no information sending.

The steps to code the signal are: convert the signal into digital, then the bits are converted to groups of k bits and this groups are mapped to a code-word of m bits, but taking into account that only 2^k code-words are valid.

In order to detect and correct errors m must be higher than k, so the bitrate must be divided with the factor m/k.

In the transmitting side the received code-word is compared to the multiple options of code-words. If it is equal to one of the possible ones, we can't detect or correct errors, but if the received code-words is not one of the possible ones we can assume that it have errors.

To decode the code-words a bit by bit comparison is done between the received code-word and all the possible ones. The final code-word is the one which has the minimum bits difference if we use the Hard decision method which uses the Hamming distance. There is a Soft decision which is more complex and uses euclidean distances letting to have gains of 2 dB more[26].

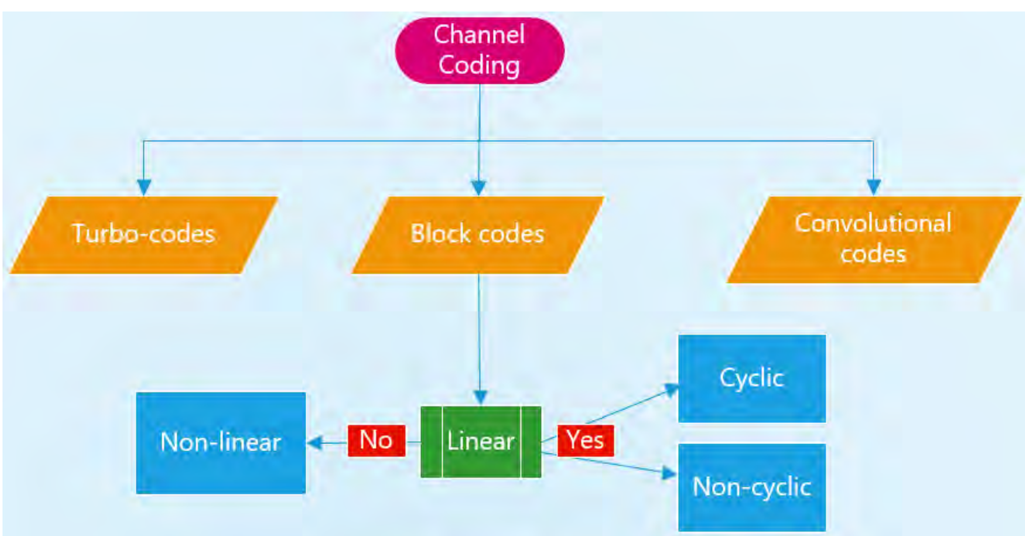

Figure 3.14: Channel Coding types

Interleaving

This technique consists in taking sequences of bits and gives these bits disturbed. This make reducing the burst errors if there are not much errors in a single code-word[1]. The burst errors can be identified due to its dependency with the consecutive bits[5].

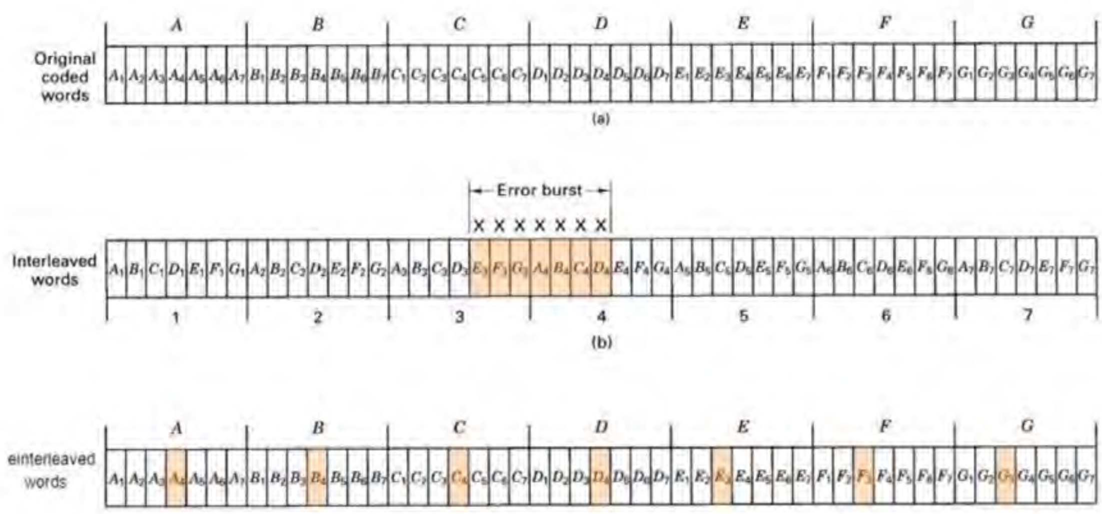

Figure 3.15: Interleaver[26]

Chapter 4

Current platform and implementation

This section explains all the hardware and software which makes possible the NVIS communications and also the changes in the software to do all the tests.

4.1 Hardware

There are 6 different components, but the main components are: Red Pitaya and Raspberry. In Figure 4.1 we can see a scheme with all the components:

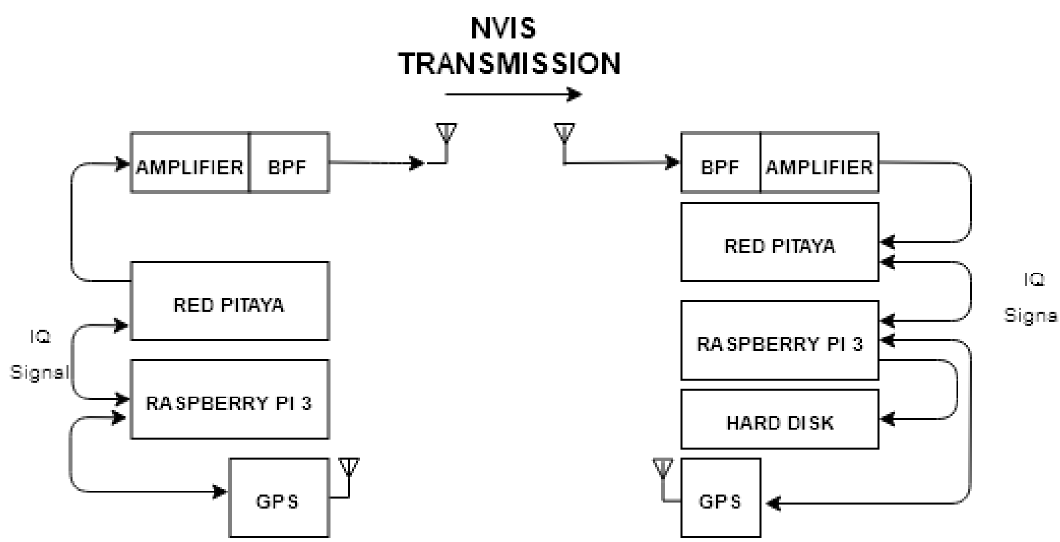

Figure 4.1: Current platform scheme[19]

4.1.1 GPS

The first component is just a GPS which is used for synchronization of the transmitter and the receptor. With the time synchro the Raspberry sends a signal to the Red Pitaya to start transmitting/receiving.

4.1.2 Raspberry

Raspberry Pi is conected with the Red Pitaya through Ethernet and has two main goals: one is sending signals to Red Pitaya to start the demodulation and the second one is controlling all the peripherals. It has a Linux Operating System (OS).

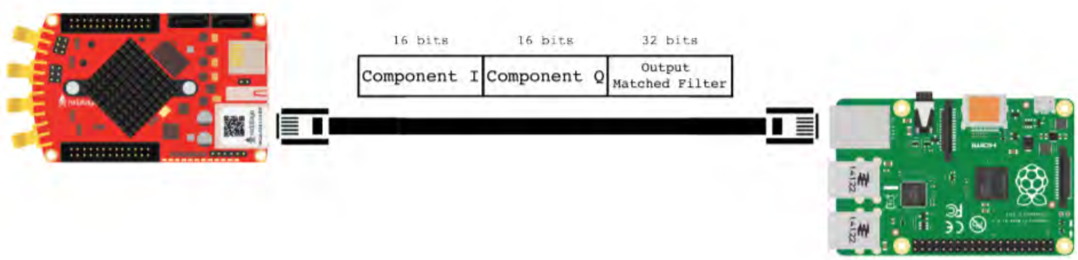

Figure 4.2: Connection between Raspberry and Red Pitaya[19]

4.1.3 Red Pitaya

The Red Pitaya STEMLab 125-14 is a system composed by a Dual core ARM Cortex A9+ including an Operating System (SO) and a Xilinx Zynq 7010 SOC FPGA[7].

The FPGA helps with all related points of the signal processing making use of the converters Analog-to-digital (ADC) and Digital-to-Analog (DAC) with 14 bits of resolution and sample frequency of 125 MSPS. The Red Pitaya has two channels, for that reason the MIMO technique is being studied, but the DAC has only one converter so in [25] was taken into account in the platform design.

For the project purpose are needed two Red Pitayas, one for the transmitter where the frequency rises by the Digital Up Converter (DUC) and the other for the receptor which does the opossite job through the Digital Down Converter (DDC).

4.1.4 Preamp and amplifier

For transmitting signals with powers as 54 dBms the RF output of the Red Pitaya is connected to an amplifier with the frequency limits that NVIS uses.

The chosen model for the project is the Bonn BLWA 0103-250 which has a operating frequency between 1.5 MHz and 30 MHz.

In the reception side, the received power needs an amplification of 30 dB before the packets being processed so a Low Noise Amplifier (LNA) is used.

4.1.5 Filter

A filter is needed in order to reduce the interferences as maximum. A bandpass filter (BPF) between 2 and 7 MHz avoid that around the frequency that we used (5.4 MHz)[18].

4.1.6 Antenna

The antenna is one essential component for the study and must be as much portable as possible.

The inverted-V dipole is a variation of the horizontal dipole which consists in tilting both dipoles, being the main advantage the use of a single mast[12] but in addition the range frequency is excellent for our purpose.

4.2 Software

As explained before, Matlab is used to configure all the parameters of the narrowband and the multicarrier modulations.

4.2.1 Frame Format

The designed frame was previously designed to avoid the maximum of signal degradiation that the channel can produce.

All the frames are composed by a tone of 600 Hz and a PN to correct some critical effects produced by the ionosphere transmissions.

Initially, the transmissions start with 20.000 samples of null information to give a margin to power on the amplifier when the transmitter and receiver are working, and also to have a very extense estimation of the noise. In the receiver side this value is very useful to calculate the EbNo.

After that, each modulation frame composed by a tone and PN sequence are transmitted.

In the next figure we can see the real part of the first transmitted modulation (PSK) and then the tone and the PN sequence concepts will be clarify.

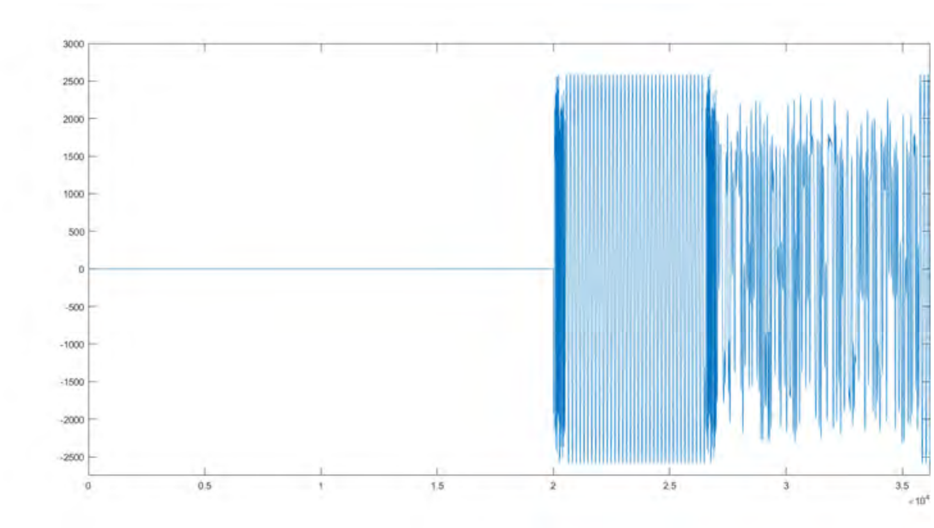

Figure 4.3: Frame beggining with PSK modulation

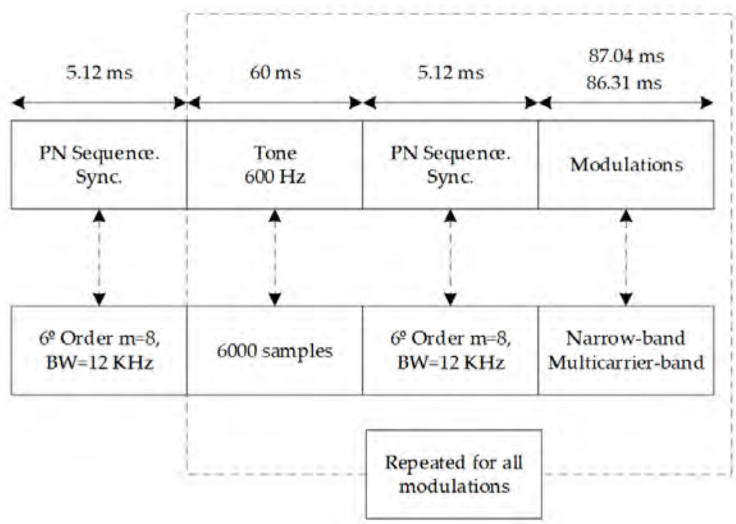

Figure 4.4: Frame design

4.2.2 Tone

6000 samples are used for sending a tone of 600 Hz that has as main goal the correction of the doppler shift effect which is around 50 Hz. The ionosphere does not produced a doppler of this type being 10 Hz in the worst case. 50 Hz is produced by the clocks of the Red Pitaya that they are not very accurate. The tone is moving around 550 Hz and 650 Hz, so with a tone of 600 Hz with 60 ms length, the effect can be corrected in 33 cycles.

4.2.3 PN-sequence

The PN sequence allows the synchronization in time, as well as the channel estimation. Is it used a 6th PN sequence with a resampling of 8 with a bandwidth of 12 KHz. The duration of the PN is 5 ms and goes as a header of all the packets in order to detect the correlation peak with means the packet beginning.

The next figure schematizes the current frame that is used in the project. Notice that the multicarrier-band modulation is a little bit wider in time than the narrow-band modulations. That is because of the resampling. The OFDM depends on the IFFT points and for the narrow-band modulations is just a multiplying factor.

4.3 Test design

The tests are organized as follows: the transmissions start in the minute 5 each 10 minutes and lasts 5 minutes where the modulation order increases each 1 minute. When the first 5 transmissions ended the transmission power increases by the double, starting in 3W and finishing in 100w.

Modulation Order	Peak Power	Minutes
2, 4, 8, 16, 32	3W	05, 06, 07, 08, 09
2, 4, 8, 16, 32	6W	15, 16, 17, 18, 19
2, 4, 8, 16, 32	12W	25, 26, 27, 28, 29
2, 4, 8, 16, 32	25W	35, 36, 37, 38, 39
2, 4, 8, 16, 32	50W	45, 46, 47, 48, 49
2, 4, 8, 16, 32	100 W	55, 56, 57, 58, 59

Table 4.1: Test design

4.4 OFDM code

The code shows directly the process to obtain the OFDM frames. Some variable declarations are not shown.

OFDM creation

A loop of 50 iterations (number of packets) is needed. We generate the bits randomly depending the modulation order. After that, the data passes through the encoder, and the inverleaver.

```
for pak=1:system.param.mod.paquetsondeig
    % Random generation of bits
    rng(1);
    bitsoriginal = randi ([0 1],1,bitslengthor);

    % Encoder
    if (encoderactive == 1)
        txBitsEncoded = convenc(bitsoriginal,trellis);
    else
        txBitsEncoded = bitsoriginal;
    end

    txBitsEncodedi=txBitsEncoded;

    % Interleaver
    if(interleaveractive == 1)
        txBitsEncodedi = [txBitsEncodedi zeros(1,delay)];
        txBitsEncodedInter = convintrlv(txBitsEncodedi,nrows,slope);
        %txBitsEncodedInter = txBitsEncodedInter((delay+1):end);
    else
        txBitsEncodedInter = txBitsEncodedi;
    end

    % Zero Padding
    if (encoderactive == 1)
        bitsZP = zeros(1,bitslengthZP);
        bits = [txBitsEncodedInter bitsZP];
    else
        bits=txBitsEncodedInter;
    end
```

Figure 4.5: 50 iterations Loop and bits generation

Once we have the bits depending on the modulation order, the bits are separated by having groups of k (number of bits used for the modulation order).

After that, the symbols are converted to decimal letting the MSB (Most Significant Bit) to the left side in order to have the symbols and we modulate with QAM or PSK.

```
% Bits organized by symbols
symbolsbits = reshape(bits,system.param.mod.k,[])';

% Bits to symbols
txsymbols = bi2de(symbolsbits,'left-msb');

% Modulation
if(system.param.mod.M==8)
    txmod=pskmod(txsymbols,system.param.mod.M);
else
    txmod = qammod(txsymbols,system.param.mod.M);
end
```

Figure 4.6: Symbols mapping

The symbols are divided into the number of subcarriers and we concatenate the pilots and the DC null. (The concatenation is possible due to our pilot design).

```
%Symbols divided into subcarriers
ofdmsymbols = reshape(txmod,[],nsubcarriersdatos);
[y_ofdmsymbols,~]=size(ofdmsymbols);

%Pilots and DC null added
dc_null=zeros(y_ofdmsymbols+1,1);%  DC null
pilot = 1+1i;
pilotstx=(repelem(pilot,1,length(ofdmsymbols)));

ofdmsymbolspdc=[pilotstx;ofdmsymbols];
ofdmsymbolspdc=horzcat(dc_null,ofdmsymbolspdc);
```

Figure 4.7: Pilots and DC null addition

Zeros in the middle of the matrix are added, in order to rise the points of the IFFT and doing the upsampling in the same mathematical expression. After that, the IFFT is applied to the resulting matrix.

```
% IFFT
ofdmsymbolspdc_pad=zeros(length(Y),(floor(system.param.Fm*length(X)/BWmod))...
    -length(X));
ofdmsymbolsup=horzcat(ofdmsymbolspdc(:,1:round(length(X)/2)),...
    ofdmsymbolspdc_pad,ofdmsymbolspdc(:,round(length(X)/2)+1:end));

ofdm = ifft(ofdmsymbolsup,length(ofdmsymbolsup),2);
```

Figure 4.8: IFFT

After the IFFT, the Cyclic Prefix is inserted for then be converted into series forming one packet. This entire process is repeated 50 times to fill the 50 packets of the OFDM and the loop finish.

```
    % CP insertion
    for n = 1:length(Y)
        ofdminterp(n,:) = [ofdm(n,end-round(system.param.Fm*tcp)+1:end) ofdm(n,:)];
    end

    % OFDM symbols organized in serie
    ofdmtemporal = reshape(ofdminterp.',[],1);

    ofdmtemporal=ofdmtemporal.';
    % Each group of 6 OFDM symbol is saved in one packet
    Ofdm7paq(pak,:)=ofdmtemporal;

end
% 50 packets organized in serie
OFDM_Rm=reshape(Ofdm7paq.',[],1);
```

Figure 4.9: CP insertion and 50 packets creation

The IBO is done as follows: Getting the maximum and the minimum values of the OFDM signal for real and imaginary parts, then the IBO divides these maximum and values, and then a loop runs over each sample diving its value by the IBO.

```
% IBO calculation
edge_real_max=max(max(real(OFDM_Rm)));
edge_real_max=edge_real_max/(10^(IBO/20));
edge_imag_max=max(max(imag(OFDM_Rm)));
edge_imag_max=edge_imag_max/(10^(IBO/20));

edge_real_min=min(min(real(OFDM_Rm)));
edge_real_min=edge_real_min/(10^(IBO/20));
edge_imag_min=min(min(imag(OFDM_Rm)));
edge_imag_min=edge_imag_min/(10^(IBO/20));

for i=1:length(OFDM_Rm)

        if real(OFDM_Rm(i))>edge_real_max
            OFDM_Rm(i)=edge_real_max+1i.*imag(OFDM_Rm(i));
        end

        if imag(OFDM_Rm(i))>edge_imag_max
            OFDM_Rm(i)=real(OFDM_Rm(i))+1i.*edge_imag_max;
        end

         if real(OFDM_Rm(i))<edge_real_min
            OFDM_Rm(i)=edge_real_min+1i.*imag(OFDM_Rm(i));
        end

        if imag(OFDM_Rm(i))<edge_imag_min
            OFDM_Rm(i)=real(OFDM_Rm(i))+1i.*edge_imag_min;
        end

end
```

Figure 4.10: IBO code

To scale the signal, the maximum of the absolute value of all the samples of the OFDM (real and imaginary) divides all the signal and then is multiplied by the scale value.

```
%OFDM Scale
OFDM_Rm=(OFDM_Rm/max(abs(OFDM_Rm))).*Esc;

ofdm_max=max(abs(max(real(OFDM_Rm))),abs(min(real(OFDM_Rm))));

if ofdm_max ~=0
    OFDM_Rm=real(OFDM_Rm).*(Esc./ofdm_max) + (1i.*imag(OFDM_Rm));
end

ofdm_max=max(abs(max(imag(OFDM_Rm))),abs(min(imag(OFDM_Rm))));

if ofdm_max ~= 0
    OFDM_Rm = 1i.*imag(OFDM_Rm).*(Esc./ofdm_max) + real(OFDM_Rm);
end
```

Figure 4.11: OFDM scale

The OFDM is divided into packets to be inserted into the total frame.

```
%OFDM is divided into packets
OFDM_Rm_=reshape(OFDM_Rm,[],system.param.mod.paquetsondeig).';
```

Figure 4.12: OFDM divided into packets

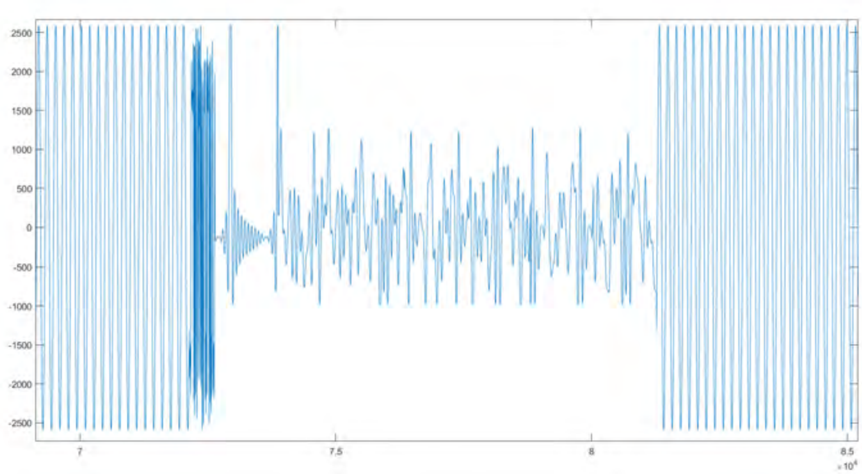

Figure 4.13: OFDM packet with IBO=3 dB

To know the PAPR, there are some conversion calculations, the peak value and the average.

```
voltage_ofdm=OFDM_Rm./system.param.PowerRef;
peak=max(abs(voltage_ofdm).^2)/50;
mean=mean(abs(voltage_ofdm).^2/50);
PAPR=10*log10(peak/mean);
```

Figure 4.14: OFDM PAPR

OFDM demodulation

The received OFDM signal is encapsulated in 50 packets, so another loop is needed to treat each packet. Then, the Cyclic Prefix is removed and the FFT is applied removing the zero padding which was inserted for the upsampling. Also, the DC null is removed.

```
    % Loop
for npaquet=1:system.param.mod.paquetsondeig
    demod_ofdm_cp=data_demod;
    demod_ofdm_cp=reshape(demod_ofdm_cp,[],system.simbolsofdmtx+1).';

    % CP removal
    tcp=0.003;
    cp=tcp*system.param.Fm;
    demod_ofdm_sincp=demod_ofdm_cp(:,cp+1:end);

    % FFT
    demod_ofdm_fft=fft(demod_ofdm_sincp,length(demod_ofdm_sincp),2);

    % FFT padding removal
    demod_ofdm_fft_sinzp=horzcat(demod_ofdm_fft(:,1:round(system.nsubcarrierstotales/2))...
        ,demod_ofdm_fft(:,end-round(system.nsubcarrierstotales/2)+1:end));

    % DC_null removal
    demod_ofdmsymbols=demod_ofdm_fft_sinzp(:,2:end);
```

Figure 4.15: CP, FFT and DC null removal

The first row corresponds to the received pilots, so they are divided by the known pilots to create the matrix which contains the channel estimation. After that, the information data is also divided by this matrix, and the pilots are removed.

```
pilotsrx=demod_ofdmsymbols(1,:);

% Channel estimation
H=pilotsrx./system.pilotstx;

H_interp=[H;H;H;H;H;H;H];

% Data is multiplied by the channel estimation
demod_ofdmsymbols_eq = demod_ofdmsymbols./H_interp;

% Pilots removal

rx_symbols=demod_ofdmsymbols_eq(2:end,:);
```

Figure 4.16: Equalization and pilots removal

From high modulation orders as 16 or 32, a scale must be imposed in order to precise the values of the symbols constellations. An example of 16-order is shown.

```
if(system.param.mod.M==16)

    rx_real=real(rx_symbols);
    rx_imag=imag(rx_symbols);


    for a=1:6
        rx_real(a,:)=(rx_real(a,:)/(max(abs(rx_real(a,:)))).*3);
    end


    for a=1:6
        rx_imag(a,:)=(rx_imag(a,:)/(max(abs(rx_imag(a,:)))).*3);
    end


    rx_symbols=complex(rx_real,rx_imag);

end
```

Figure 4.17: OFDM symbols scale

The last steps are undoing all the processes following the scheme. Starting in undoing the modulation, converting the symbols into bits, then organize them in series, padding removal and remove the interleaver and the encoder.

The received bits are compared to the original transmitted and the BER is calculated.

```
    % Modulation undo
    rx_demod = qamdemod(rx_symbols,system.param.mod.M);
    %rx_demod = pskdemod(rx_symbols,system.param.mod.M);

    % Symbols to bits
    rx_bits_p=de2bi(rx_demod,system.param.mod.k,'left-msb');

    % Bits organized in series
    rx_bits_s = reshape(rx_bits_p.',1,[]);

    % Padding undo
    rx_bits_s=rx_bits_s(1,1:length(ofdmbitsoriginal));

    % Interleaver undo
    if (interleaveractive == 1)
        rx_bits_inter = [zeros(1,delay) rx_bits_s];
        rx_bits_enc = convdeintrlv(rx_bits_inter,nrows,slope);
        rx_bits_enc = rx_bits_enc((delay+delay+1):end);
    else
        rx_bits_enc = rx_bits_s;
    end

    % Encoder undo
    if (encoderactive == 1)
        rx_bits = vitdec(rx_bits_enc,trellis,7,'trunc','hard');
    else
        rx_bits = rx_bits_enc;
    end
    clearvars H_interp;
end
```

Figure 4.18: Bits demodulation

Chapter 5

Simulation and results

5.1 BER/EbNo simulation

The first test had the the goal of seeing how OFDM behaves against noise and multipath effect depending on the modulation order.

The simulation scenario was done with a sweep of white Gaussian noise with powers in relation to the input signal from 24 dB to -5 dB. The second scenario is the same as before, but adding the multipath effect which consists in two paths being the first one a normal path without power lose, and the second path delayed 250 milliseconds and a power lose of 3 dB.

The simulated tests give BER/EbNo graphs because its fast analysis of the modulations in terms of performance, but the information giving is not enough to affirm the better modulation.

The Figure 5.1 shows that in scenarios with the presence of noise but without multipath, the OFDM does not overcomes the PSK or the QAM, but has similar results to PSK. These results are reasonables taking into account that the average power of the OFDM is less than any other modulation in comparison. For that reason the noise affects more to OFDM.

By contrast, in figure 5.2 we can see a scenario with the presence of a multipath effect where the OFDM overcomes the results due to the multipath.

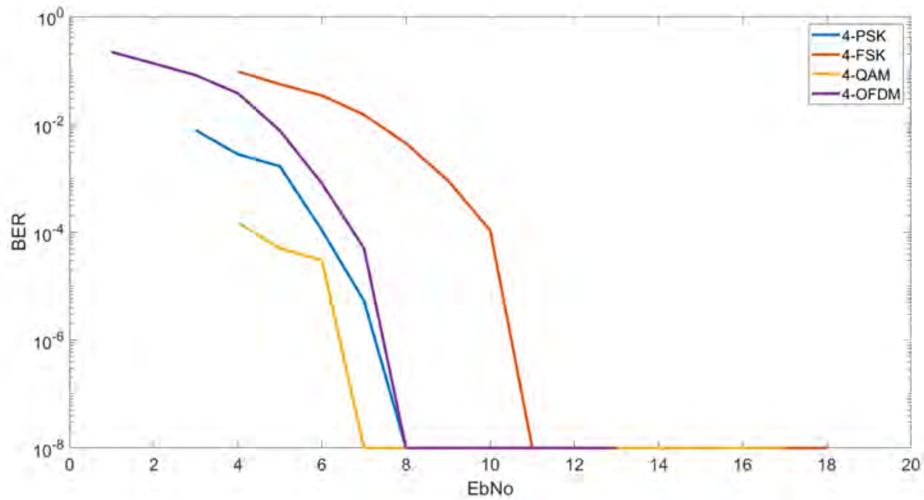

Figure 5.1: M=4 modulations comparison in presence of noise

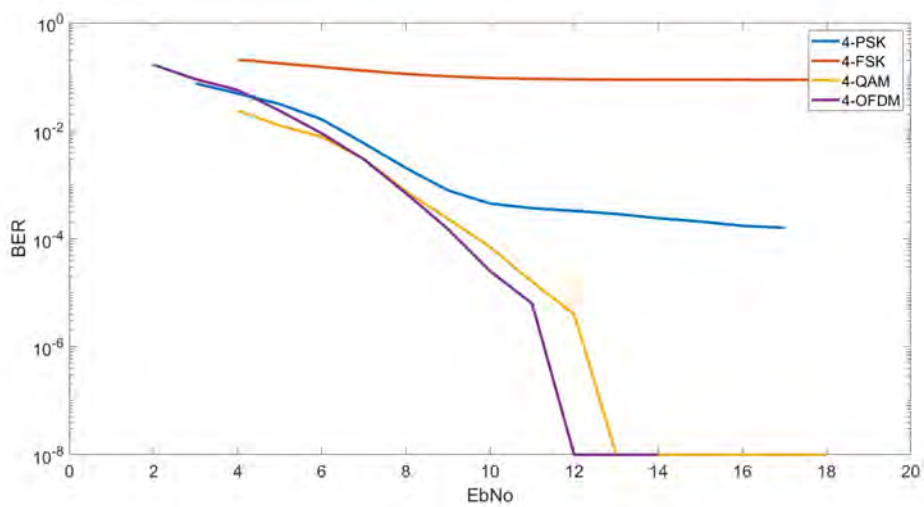

Figure 5.2: M=4 modulations comparison in presence of noise and channel

Rising the modulation order, the results start to have a bigger difference in presence of multipath effect. In figure 5.4 the OFDM shows very good result due to the Cyclic Prefix avoiding the multipath effect.

Also is true that the EbNo is divided into all the different subcarriers, so more power is needed.

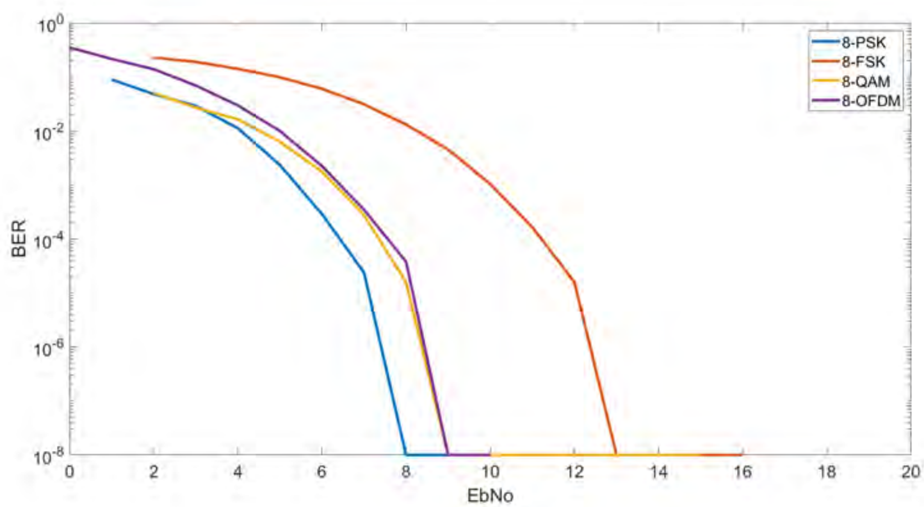

Figure 5.3: M=8 modulations comparison in presence of noise

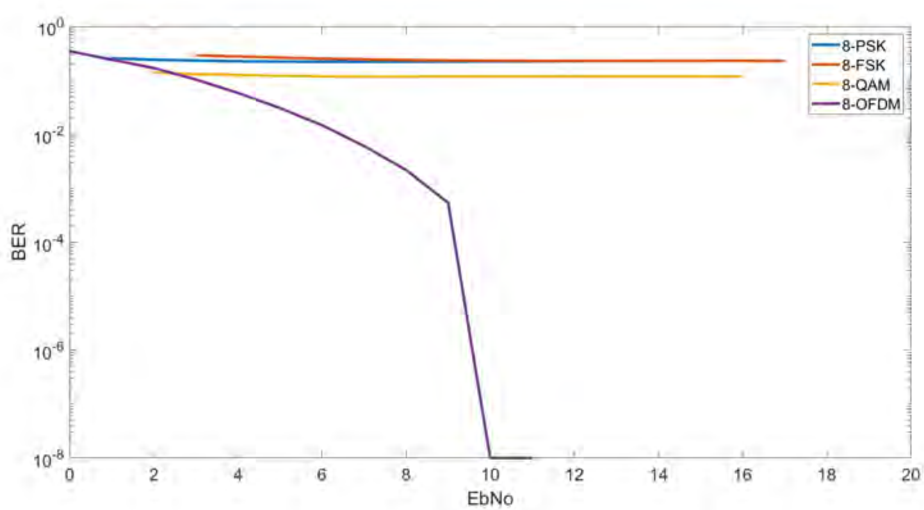

Figure 5.4: M=8 modulations comparison in presence of noise and channel

16-order which is a high order shows good results for the OFDM but the comparison is not so fair taking into account several parameters.

The multipath and the noise affect the other modulations a lot, because there is a situation where the OFDM has a better performance due to the Cyclic Prefix which doesn't sense the multipath a lot.

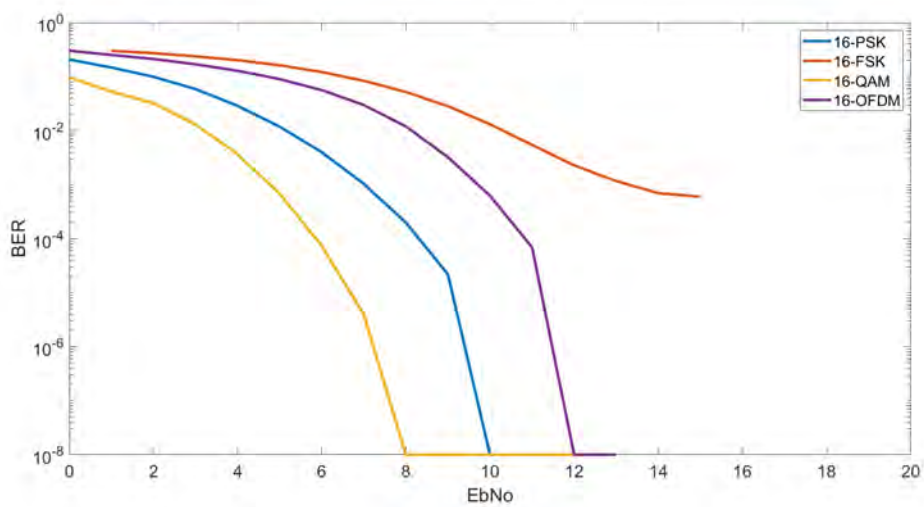

Figure 5.5: M=16 modulations comparison in presence of noise

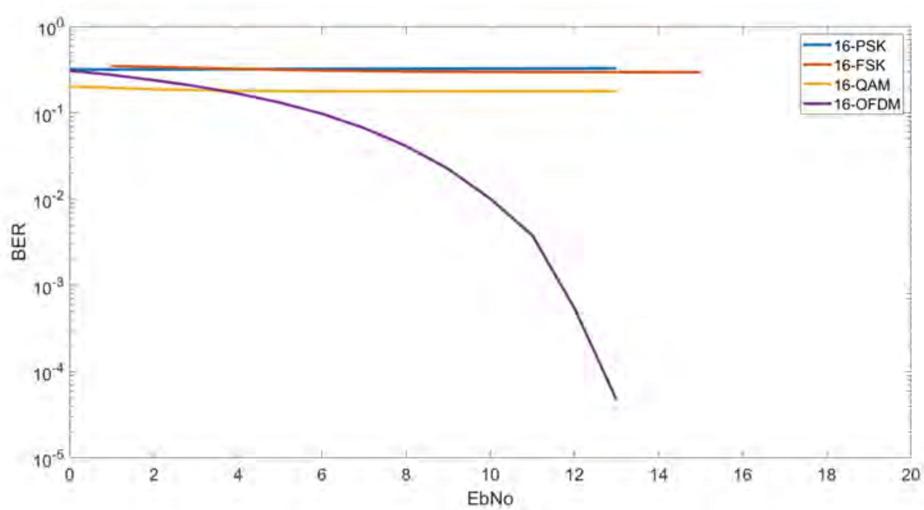

Figure 5.6: M=16 modulations comparison in presence of noise and channel

OFDM is not as robust as QAM in front of noise, so we rise the modulation order to see OFDM limit.

In order 32 it still has good results. M=64 has still enough BER (9x10^{-3}) to have a good transmission, but we need to see how many possibilites of having an EbNo of 14 dB.

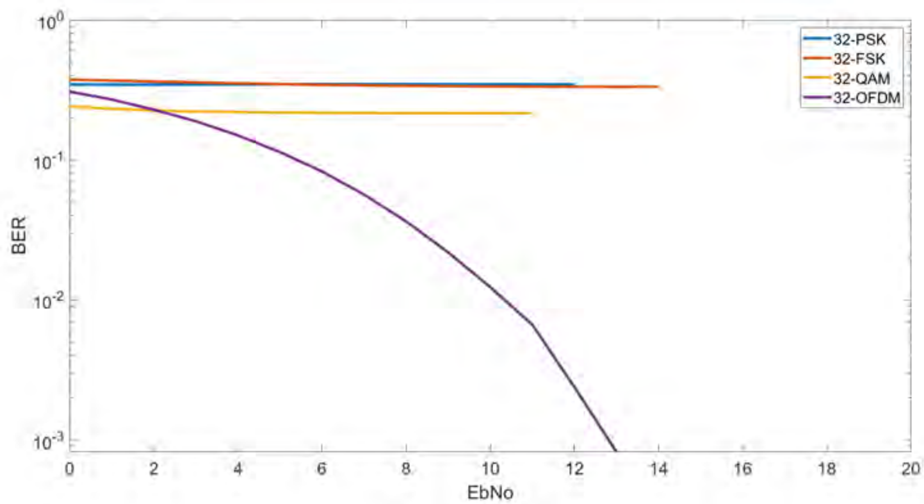

Figure 5.7: M=32 modulations comparison in presence of noise and channel

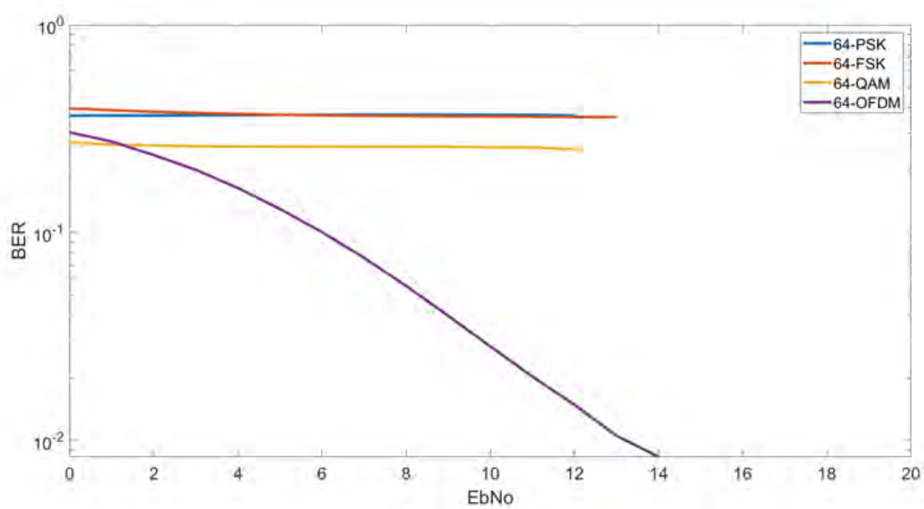

Figure 5.8: M=64 modulations comparison in presence of noise and channel

5.2 Real scenarios tests

The real tests were done between Barcelona (La Salle Bonanova) where the transmitter is installed and Cambrils (Tarragona) where there are two receiver antennas.

The radio-link works with NVIS for a distance of 100 Km approximately making use of the test design previously explained.

5.2.1 BER/EbNo

As expected, compared to the simulated scenario, the results are worst, but the OFDM modulation is still better because the real channel have multipath with more than two paths.

The BER/EbNo shows the behaviour in terms of wrong bits having a specific EbNo. In next figure, we can see that QAM needs 3-4 dB more of EbNo to have the same BER.

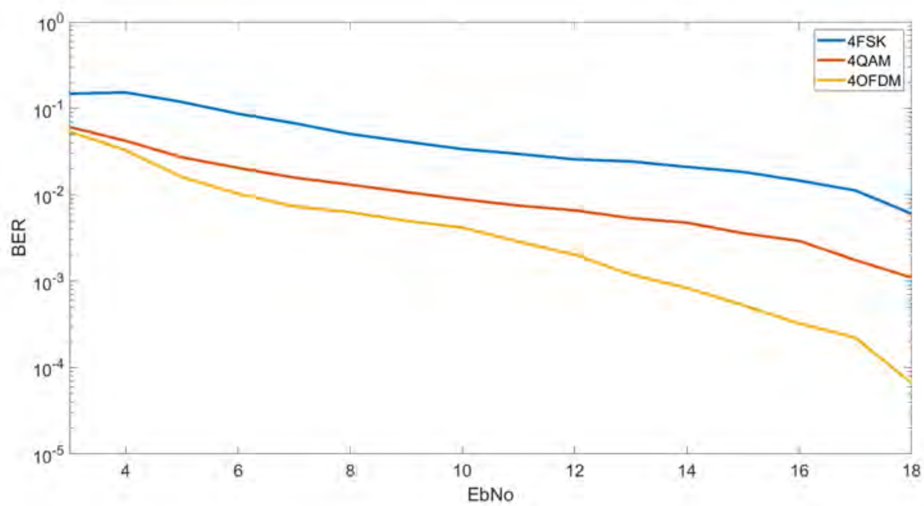

Figure 5.9: M=4 modulations BER/EbNo

Rising the modulation order we can see that results are worst in terms of BER. Comparing the EbNo and the BER the difference with the 4-order are less than 1 dB of EbNo which is not much, but the main fact here is that the final EbNo are pretty lower (almost 4 dB less of EbNo).

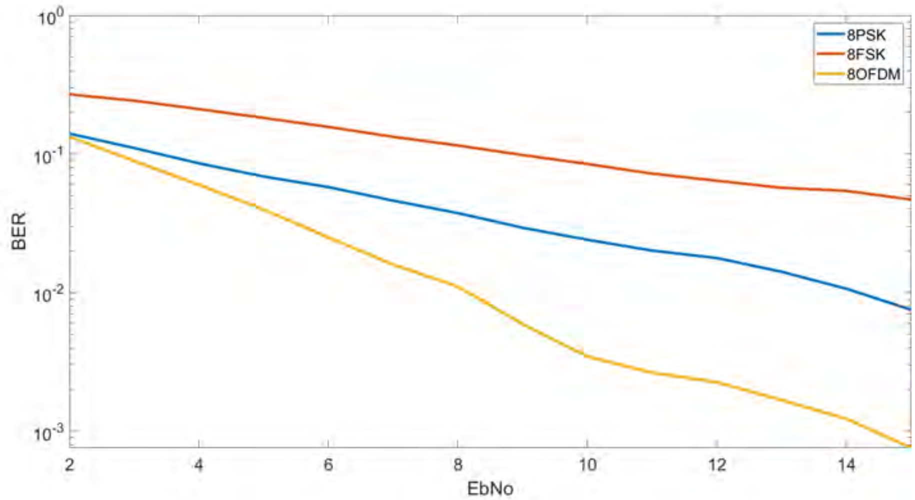

Figure 5.10: M=8 modulations BER/EbNo

16-order are very similar than the 8-order but having higher BERs. Depending the scenario, the transmissions can be inviable.

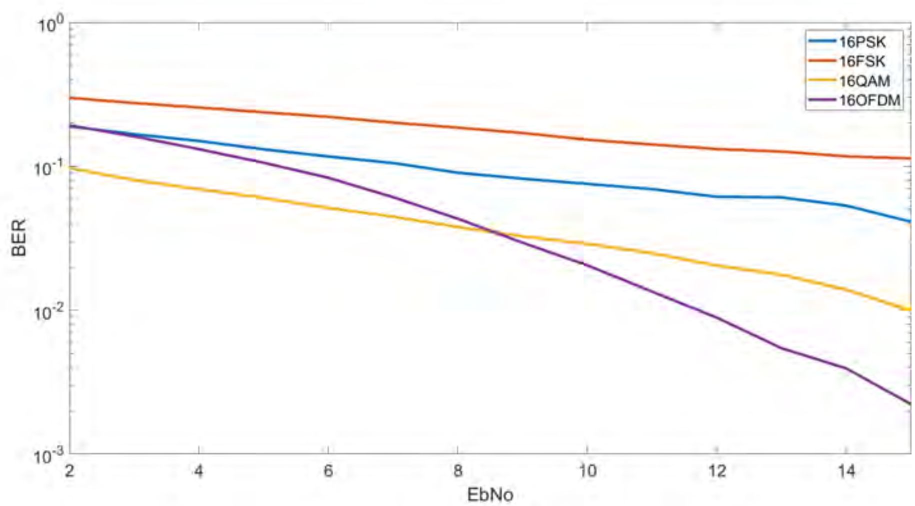

Figure 5.11: M=16 modulations BER/EbNo

5.2.2 BER CDF

CDF figures shows the probability of having a specific value. In that case we compare the probability of having a specific BER with a specific EbNo value.

EbNo=5 dB

In the next two figures, we can see that 4-QAM is slightly better than 4-OFDM, but 8-OFDM overcomes 8-PSK. That mans that the results of BER/EbNo previously explained mean that they are not always available.

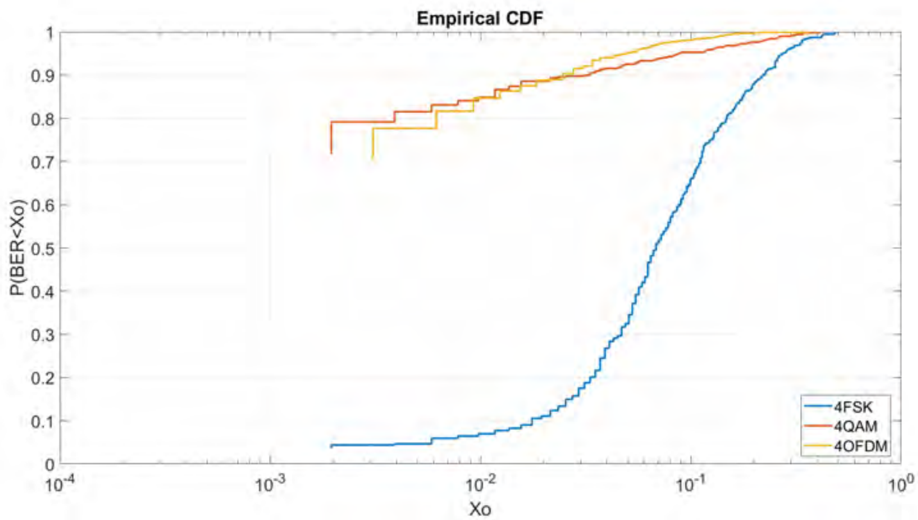

Figure 5.12: M=4 modulations CDF

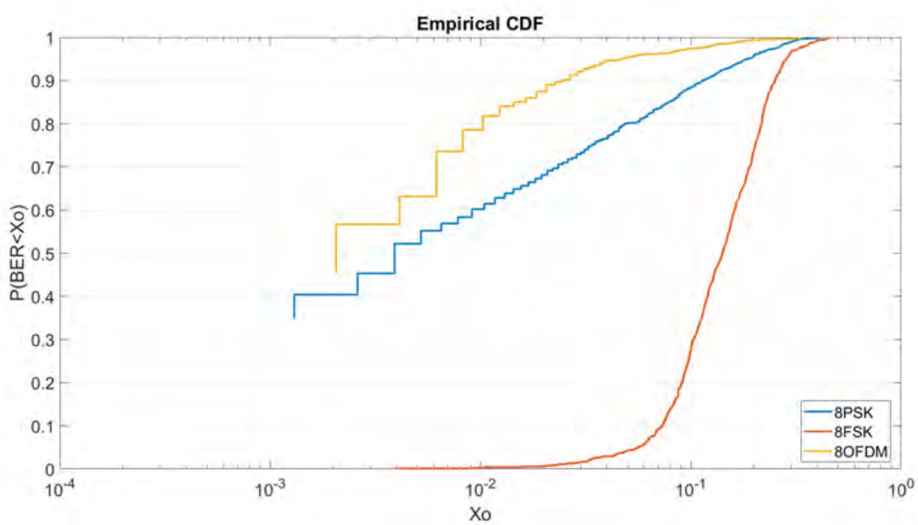

Figure 5.13: M=8 modulations CDF

16-order shows that the probabilities of having a BER under 10^{-2}, are almost null for the OFDM, being the QAM which has the better results but more power is needed.

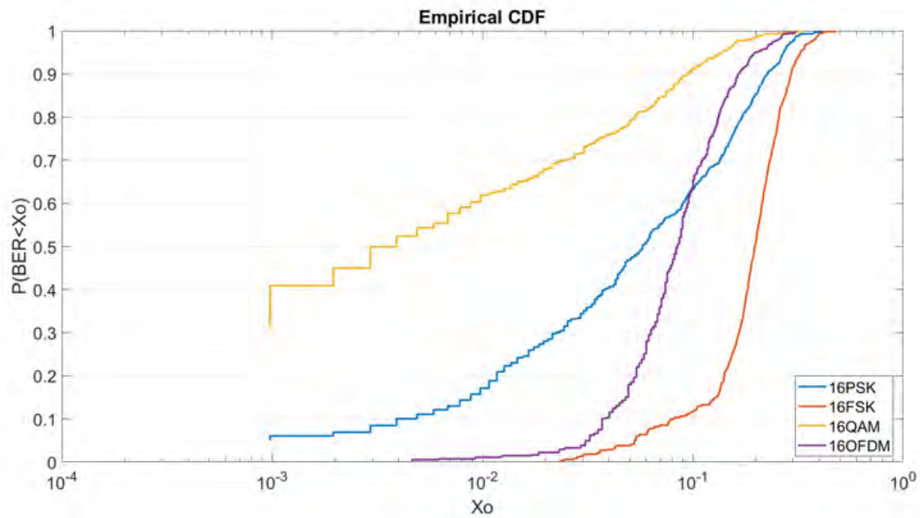

Figure 5.14: M=16 modulations CDF

EbNo=8 dB

3 dB more of power means excellent results for OFDM and QAM and here the OFDM is slightly better.

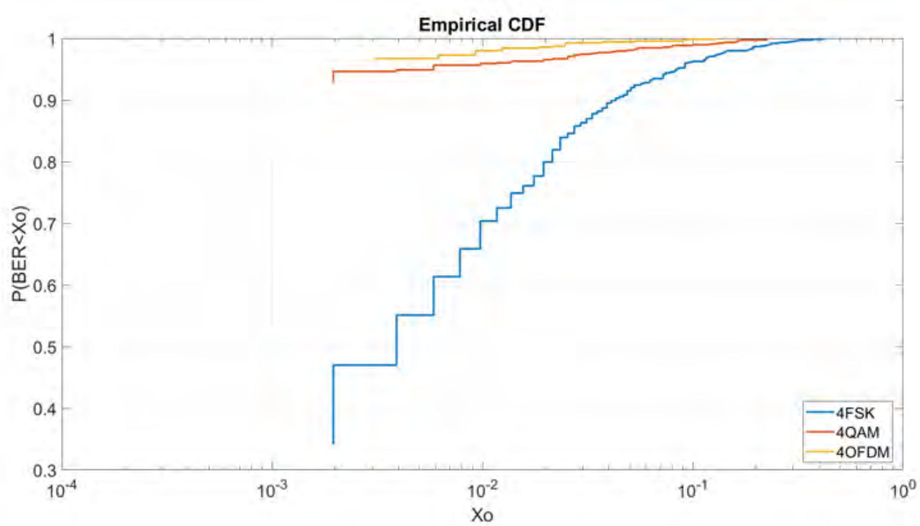

Figure 5.15: M=4 modulations CDF

For M=8 OFDM is still better, but now it has higher probabilities than the case of having an EbNo of 5 dB.

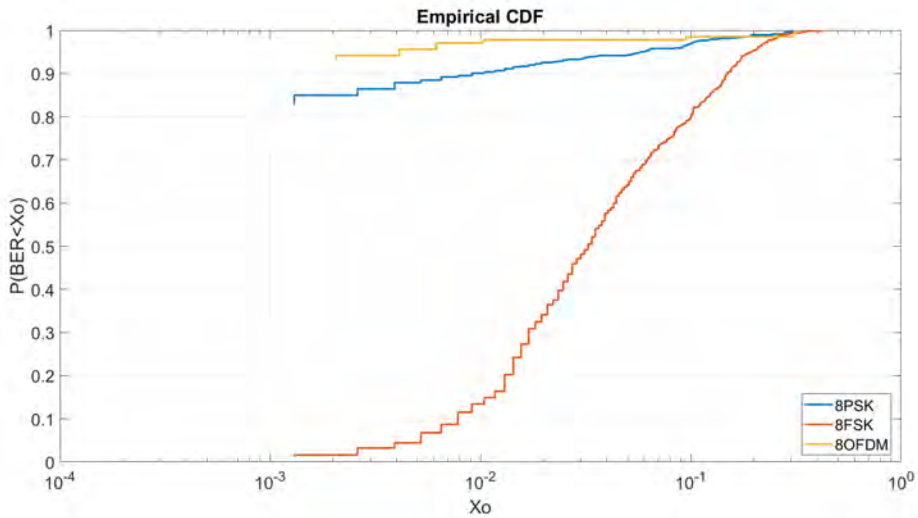

Figure 5.16: M=8 modulations CDF

For M=16 the high need of EbNo in high orders for the OFDM subcarriers are therefore very bad results for OFDM.

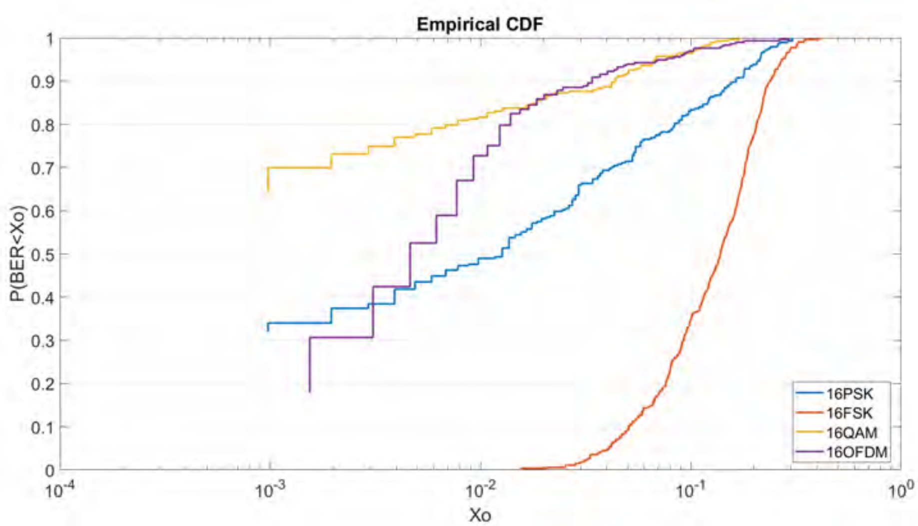

Figure 5.17: M=16 modulations CDF

5.2.4 Power CDF

If we compare the results, the conclusion is that OFDM with a mapping of 4-QAM is the best option for M=4, and for M=8, the OFDM with a mapping of 8-PSK is again the best modulation.

In the previous results, the peak power was considered, but the fair comparison is by taking into account the average power.

In the next figure, we can see that the power transmissions are: 4QAM=4.7W, 8PSK=5.1W, 4-OFDM=3.4W and 8-OFDM=3.7W.

The difference of power between QAM and OFDM make a significant difference of BERs. In addition, if we see the behaviour of the 8-OFDM taking into account that the power difference between 4-OFDM and 8-OFDM are almost negligible, make the OFDM with null probabilities a decent BER.

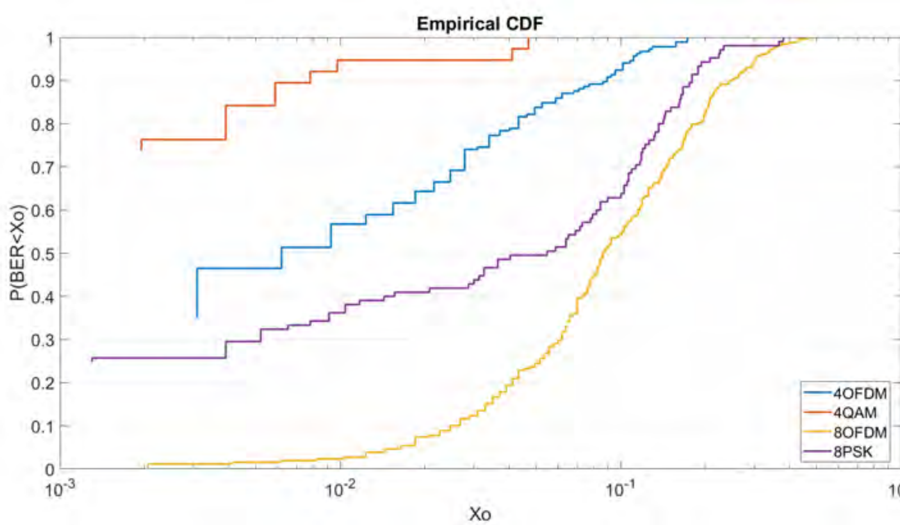

Figure 5.18: 4-order vs 8-order

5.3 IBO

The optimization of the average power of the OFDM resides in the Input Back Off (IBO) which consists in cutting the modulated signal to limit the peaks produced by the subcarrier assignation with the aim of reducing the PAPR.

In the next figure, the two signals on the right are: raw OFDM and OFDM with IBO=6 dB is shown.

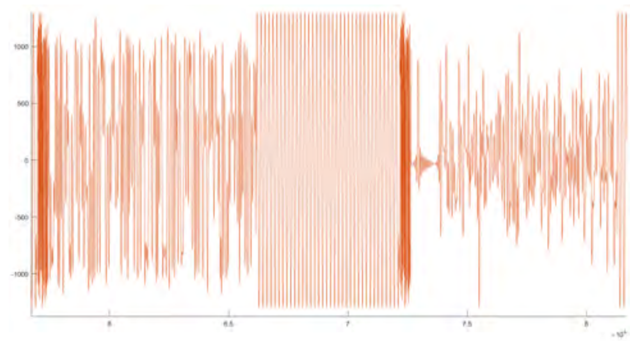

Figure 5.19: IBO= 0 dB.

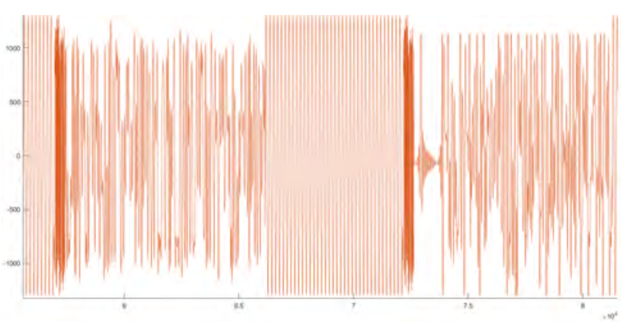

Figure 5.20: IBO= 6 dB.

An IBOs sweep was done to find the ideal design for the OFDM. The tests follow the same structure as always, but in this case, we change the IBO value fixing the transmission power.

The next table summarize the BER results in relation of the IBO instead of rising the peak power transmissions and the next figure shows the results graphically.

IBO [dB]	BER
0	0.0863
3	0,0494
4,5	0,0404
6	0,0331
7,5	0,0284
9	0,0273
10	0,0267
12	0,0295
15	0,0377
18	0,0448
21	0,0497
24	0,0554
27	0,0639

Table 5.1: IBOs sweep simulation.

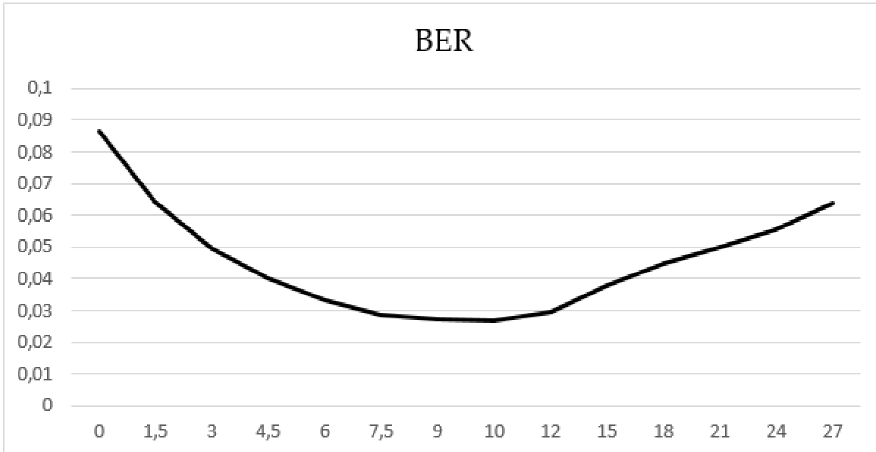

Figure 5.21: IBOs evolution

Notice that having an IBO of 3 dBs reduces the BER to the half in relation to not having IBO being the optimum value around 9 and 10 dBs which reduces the BER more than 3 times (taking into account that these tests are in simulated scenario). From this value, the BER starts to decrease again until 21 dB where the BER is the same of having 3 dB of IBO.

Apart of finding the ideal IBO to optimise the OFDM performance in terms of PAPR, the rise of the average power increases the possibilities of having more EbNo and better BERs, but the consumption is getting higher too.

IBO [dB]	PAPR [dB]	Average Power
4.5	10.3	2.3 W
6	9.1	2.9 W
7.5	8.1	3.7 W
9	7.2	4.6 W
4.5	6.7	2.5 W
6	5.8	3.1 W
7.5	5.0	3.7W
9	4.4	4.3W

Table 5.2: OFDM average power in relation to IBO

5.3.1 BER CDF against IBO

The main goal for this purpose is to use this communication technology for sensors so 12 W is enough for this purpose.

In order to modify the performance of the OFDM we try different configurations of IBOs and different powers between 6 and 12 W.

The next figure shows that the best options are 9 dBs of having for the 12 W and 7.5 dBs, but taking into account that the power consumption is the central point of the IBO study we conclude that 7.5 dB is enough. It has a similar result of having 9 dBs of IBO, but the average power increases, so it has no sense to select 9 dB.

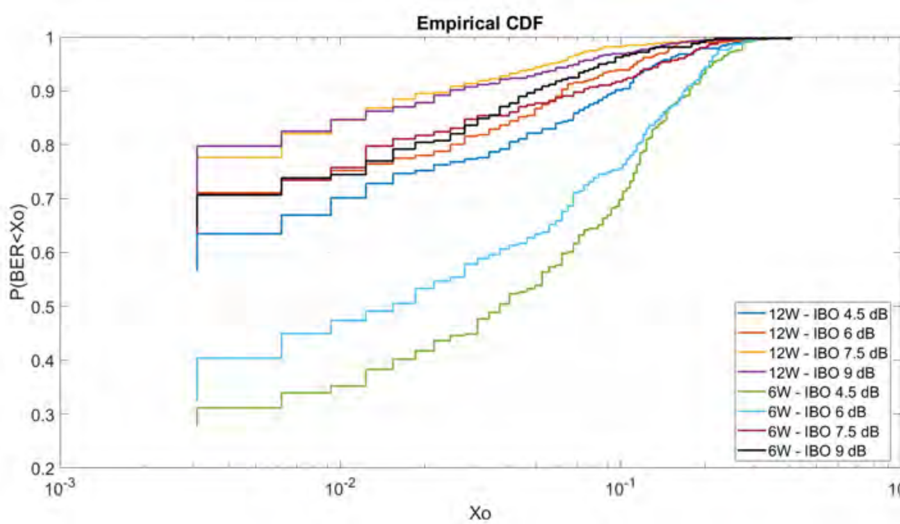

Figure 5.22: BER CDF having different IBOs

5.4 SIMO technique

Evaluating the results testing a 12 W OFDM using an IBO of 9 dB, the CDF gives very good results, taking into account that the ordinary one has an 80 % of probabilities of having a BER lower than $3{\cdot}10^{-2}$.

With the second antenna deployment in the receiver side, using the Equal Gain Combining the results are just improved just 2 % of probabilities. This techniques are used when both waves have very good results. In this case, the extraordinary wave doesn't have bad results at all, but there's a huge difference between the ordinary and the extraordinary one.

With Selection Combining method this result is improved 7 % doing a selection of the best BER in both waves. Almost 90 % of probabilites of having very good transmissions.

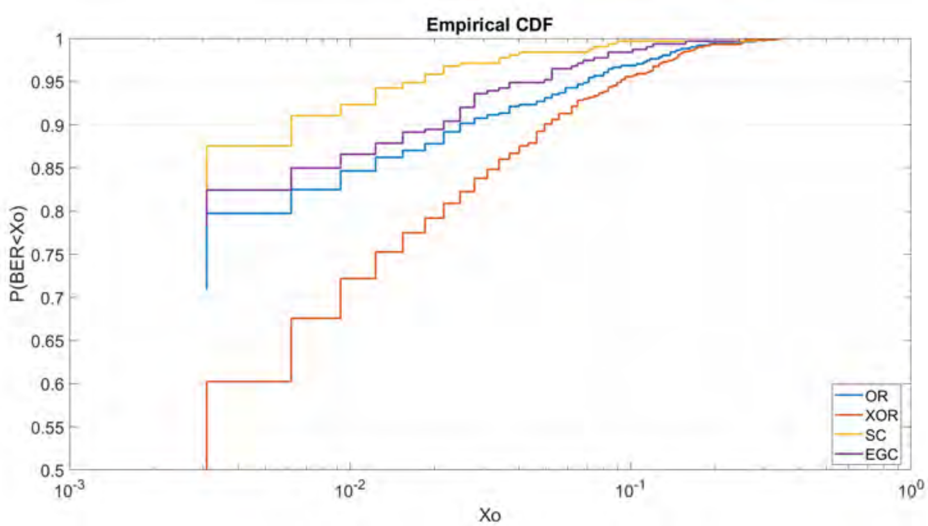

Figure 5.23: SIMO technique

Chapter 6

Work Plan

6.1 Time-cost

This project started in February and was divided into several parts.

First of all, reading all the documentation of previous Antarctica projects carefully took around one month.

Once the documentation reading was ended, the coding part started. The first code was a modular and robust code for the OFDM modulation which was explained in 4.4. Then, it had to be integrated into the code where the transmissions frames are configured.
In this part there are some divisions:

- **CreateIQData:** This Matlab code is used for configuring and creating the transmission frames which was adapted to have the OFDM code integrated.
- **DemodTrama:** This code consists in demodulating all the received files and giving parameters results as BER, EbNo. It works just for a single file.
- **MassiveDemodTrama:** This code runs the DemodTrama repeatedly and save the results for all the files in a Matlab Matrix.
- **MassiveGrafiques:** This code read the Matlab Matrix and shows all the results graphically.

Once, the codes were finished, the results of simulation environment were done, so the next step was the trips to Cambrils to allow us testing all the developed system in a real scenario. The transmitted data was saved in two USBs of 128 Gb each one so the data collection it can't be done by a VPN due to the limitations of our current link, so there were many trips just for collecting data.

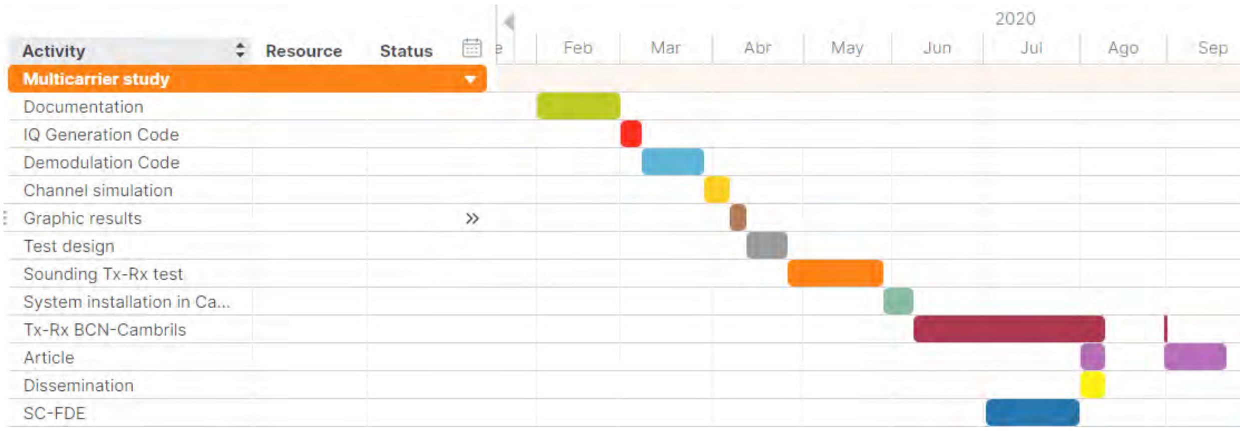

Figure 6.1: Gantt diagram

6.2 Economical-costs

The needed costs in order to develop the platform running are broken down as follows:

Hardware	Price
2 x Red Pitaya 125-14 (Starter Kit)	319 €
2 x Raspberry Pi3	39.99 €
Adafruit Ultimate GPS Breakout v3	53.02 €
PCB BPF and components	60€
Bonn BLWA 0103-250	5000 €
3 x Antenna and Balun	60 €
RF cables	100 €
2 x USB 128 Gb	26.39 €
Matlab	69 €
Travel and daily substance allowance	644.48 €
Total	**1817.26 €**

Table 6.1: Economical costs

Chapter 7

Conclusions

The completion of this Master's dissertation shows the virtues of the multicarrier modulations.

Different tests have been done in order to find the optimum modulation for different scenarios. As we can see in the results, 12 W power is the best option for low-power systems and efficiently speaking the modulation order 4 overcomes any of the other orders.

We can conclude that in some scenarios OFDM modulated with 4-QAM and 12 W with NVIS technology is totally viable for the purpose that we exposed, due to its good performance against multipath having a CP of 300 samples.

First of all, the robustness was tested comparing the BER/EbNo in simulation and real scenarios. Taking into account several tests, OFDM overcomes the narrow-band modulations in almost all scenarios, as BER/EbNo with all the modulation orders or BER/CDF with high EbNo. This is because of the Cyclic Prefix which avoids the multipath effect with 2.75 ms delayed paths.

In contrast, without multipath or having lower EbNo the QAM shows better results as in figure 5.12. The need of a bigger EbNo for the OFDM is due to the division into subcarriers.

IBO had a very deep study where overcomes the results optimising the OFDM for low-power systems as we can see in figure 5.22 making the comparison with narrow-band modulations fairer specially with IBO of 7.5 and 9 dBs which reduce the PAPR significantly. Also, the SIMO technique helped to have more robust results and a very small improvement in the bitrate. The SC method achieved almost 90 % of probabilities of having very good transmissions as in figure 5.23.

Finally, depending on the multipath, the solar radiation and other parameters decide which modulation gives a better solution, and we can conclude that having a modulation technique as OFDM with modulation order 4 and transmission power 12 W is a good option for sensors data gathering making use of the SIMO technique with SC and having an IBO of 9 dB.

Having a modular code, helped me to integrate the OFDM code and some small improvements. It was a scheme that i couldn't finish the Single Carrier code because it could have been an interesting comparison between both multicarrier modulations.

I want to conclude saying that the realization of this project was totally successfully for the personal and work environment and I want to keep growing up doing that.

Chapter 8

Future Work

This research represents a good progress for the entire project, but there are still a lot of tests that needed to be tested. Some points are explained as follows:

- **SIMO:** The phasing box to do the SIMO technique must be implemented in a digital way making use of the FPGA.
- **MIMO:** MIMO technique would be a good improvement for the project because the bitrate is going to be the double with two antennas in the transmitter.
- **Multiple frequencies:** This improvement is the most interesting due to the wide range of the availability of the ionosphere. In the near future, a system with artificial intelligence could be learn the behaviour of the ionograms to choose the best frequency to transmit.
- **Single Carrier:** This modulation was explained conceptually but is going to be the next test because we have detailed the advantages against OFDM most essentially the power consumption.
- **Components power control:** The consumption of the components is an important handicap for our project. The use of batteries make hard the design of our system, for that reason, the sleep-mode for some components can be implemented. Also the power consumption of different amplifiers could be tested due to the non-need of linearity for some modulations.
- **Errors correction:** Despite errors correction were coded the transmissions weren't done with that methods, so these results could be improved using the coder and interleaver.
- **Equalizations:** Just test different methods to equalize the modulations.

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