EVALUATION OF CROSSTALK ROBUSTNESS OF OPTICAL OFDM

A Degree Thesis

Submitted to the Faculty of the

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by

Sergi Piera Arrufat

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Advisor: Joan M. Gené Bernaus

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Abstract

The OFDM technology has been highly studied/investigated in the telecommunications field but it is still a relatively new term in the optical communications. OFDM has been evaluated in various studies although the tolerance against linear intrachannel crosstalk (XT) remains an open issue. This kind of XT is really relevant in several situations, for example in the multicore fibers (MCF), which is a new kind of fiber that intend to replace the current mono-mode fibers.

Then, by using the VPI Photonics software several simulations will be done in different situations in order to see the effect of the Crosstalk on OFDM signals in a supposedly ideal transmitter-receiver system. To make a complete study, various simulations will be carried out changing the number of subcarriers, the order and the kind of the modulation used.

The Crosstalk will be simulated by an interfering transmitter superposed to the main signal. By using an attenuator, we will be able to control the interference level that produces. The receiver will evaluate the impact of XT in terms of its sensitivity, so that the different cases can be analysed and later make conclusions.

As for the OFDM parameters, we will work with 16, 64, 256 and 1024 subcarriers, and with 4-QAM and 16-QAM modulations.

Resum

La tecnologia OFDM ha estat molt estudiada/investigada en el camp de les telecomunicacions però encara es tracta d'un camp relativament nou pel que fa a les comunicacions òptiques. L'OFDM s'ha avaluat en diversos estudis, tot I això la seva tolerància al crosstalk lineal intracanal (XT) és un tema obert. Aquest tipus de XT és molt rellevat en diverses situacions, per exemple, en el context de les fibres multi-nucli (MCF), un nou tipus de fibres que pretenen substituir les fibres mono-mode actuals.

Així doncs, mitjançant el software VPI Photonics realitzarem un seguit de simulacions en diferents situacions per veure l'efecte del Crosstalk sobre els senyals OFDM en un sistema transmisor-receptor suposadament ideal. Per fer un estudi complet, es realitzaran diferents simulacions variant el nombre de subportadores, l'ordre i el tipus de la modulació emprada.

El Crosstalk vindrà simulat per un transmisor interferent sobreposat al señal principal, que mitjançant un atenuador, podrem controlar el nivel d'interferència que genera. El receptor avaluarà l'impacte del crosstalk en mesures de la seva sensibilitat, per poder analitzar ls diferents casos i treure conclusions posteriorment.

Pel que fa als paràmetres OFDM, treballarem amb 16, 64, 256 i 1024 subportadores, i amb les modulacions 4-QAM i 16-QAM.

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Resumen

La tecnlogía OFDM ha estado muy estudiada/investigada en el campo de las telecomunicaciones pero todavía se trata de un campo nuevo en cuanto a las comunicaciones ópticas. OFDM se ha evaluado en varios estudios, aunque la tolerancia al crosstalk lineal intracanal (XT) es un tema abierto. Este tipo de XT es muy relevante en diversas situaciones, por ejemplo, en el context de las fibras multi-núcleo (MCF), un nuevo tipo de fibras que pretenden substituir las fibras mono-modo actuales.

Así pues, mediante el software VPI Photonics se realizara un seguido de simulaciones en diferentes situaciones par ver el efecto del Crosstalk sobre señales OFDM en un sistema transmisor-receptor supuestamente ideal. Para realizar un estudio completo, se realizaran diferentes simulaciones variando el nombre de subportadoras, el orden y el tipo de la modulacion utilizada.

El Crosstalk vendrá simulado por un transmisor interferente sobrepuesto a la señal principal, que mediante un atenuador, podremos controlar el nivel de interferencia que genera. El receptor evaluará el impacto del crosstalk en medidas de su sensibilidad, para poder analizar los diferentes casos y sacar conclusiones posteriormente.

En cuanto a los parámetros del OFDM, trabajaremos con 16, 64, 256 y 1024 subportadoras, y con las modulaciones 4-QAM y 16-QAM.

This project is dedicated to my family and friends, who have helped me during all these years I have been cursing this engineering grade in the UPC University, especially the ones who have supported me while carrying out my TFG.

Acknowledgements

I would like to thank Joan M. Gené Bernaus, my project supervisor, for all the time he has dedicated to me and his help and advice during all this months I have been carrying out my TFG.

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Name	e-mail
Sergi Piera Arrufat	sergi.piera.arrufat@gmail.com
Joan M. Gené Bernaus	joan.gene@upc.edu

Written by:		Reviewed and approved by:	
Date	20/05/2016	Date	26/06/2016
Name	Sergi Piera Arrufat	Name	Joan M. Gené Bernaus
Position	Project Author	Position	Project Supervisor

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1. Introduction

1.1 Thesis context

Nowadays, society has the necessity of interchanging huge amounts of data in a constant way, and that has implied that the technology evolves as fast as the demand grows.

Optical communications started in 1970 due to the need of higher rates in electrical transmissions (mobile communications, radiocommunications,…). They are based in the transmission of information by sending pulses of light through an optical fiber. Because of its advantages over electrical transmission, optical fibers have largely replaced copper wire communications in core networks in the developed world. This technology covers frequencies from 30 THz to 300 THz, it has a great bandwidth. Thanks to this, optical communications are able to reach transmission rates up to 100 Tb/s. And that is why optical fiber has become in an indispensable method for the current communications in the world.

Apart from that, modulation is the process of conveying a message signal, for example a digital bit stream or an analog audio signal, inside another signal that can be physically transmitted. Some examples of typical digital modulations could be PSK (Phase-shift keying), FSK (Frequency-shift keying), ASK (Amplitude-shift keying), QAM (Quadrature amplitude modulation), etc.

Digital modulations can be divided in single-carrier modulations or multi-carrier modulations. This project will be based in OFDM (Orthogonal Frequency-Division Multiplexing), which is a kind of MCM (Multi-carrier modulation) that has become really popular in the last years in mobile communications as well as in optical communications. This technique has been adopted by many communication standards such as LTE (4G), WLAN or DVB-T because of its high spectral efficiency, robustness against inter symbol interference and its efficient implementation.

So, after introducing these two huge concepts: optical communications and OFDM, this project is based on the study of the combination of these two important technologies. More specifically, the thesis is based in the study of the effect of crosstalk, which is the interference produced between transmitters in a multi-core fiber, in Optical OFDM systems.

Several studies involving both crosstalk tolerance and optical OFDM had been previously carried on the research group of “Departament de Teoria del Senyal i Comunicacions (TSC)”, more precisely, inside the “Grup de Comunicacions Òptiques (GCO)” which expert on the topic is the supervisor of this thesis, Joan M. Gené Bernaus. More concretely, this TFG is the continuation of another thesis from the group with the name “Evaluation of Optical OFDM signals crosstalk tolerance”, made by Adrià Escolano Beltran in 2015.

1.2 Objectives

After giving the context on which this thesis is going to be developed, the objectives of the project are the following:

- See how the number of OFDM subcarriers affect the Optical OFDM system under different crosstalk levels.
- See how the order of the QAM modulation affect the Optical OFDM system under different crosstalk levels.
- See how different combinations of subcarriers and modulations affect the Optical OFDM system under different crosstalk levels.
- Extract conclusions and find which is the best parameter combination to provide the greatest robustness to crosstalk in an Optical OFDM system.

In a more personal point of view, my objective is also to gain a better knowledge and understanding about optical communications and OFDM, as well as provide more information for further research in this telecommunications field.

1.3. Work Plan

The last updated work plan of the project is showed in the following image:

EVALUATION OF CROSSTALK ROBUSTNESS OF OPTICAL OFDM
ETSETB, UPC

Project Lead: Joan M. Gené Bernaus
Start Date: 15/02/2016

WBS	Tasks	Start	End	Duration (Days)
1	**Documentation (100h)**	22/02/16	07/07/16	70
1.1	Project proposal	22/02/16	01/03/16	14
1.2	M1: Project proposal deliver	01/03/16	01/03/16	0
1.3	Critical design review	02/05/16	08/05/16	7
1.4	M2: Critical design review deliver	09/05/16	09/05/16	0
1.5	Group results	09/05/16	29/05/16	21
1.6	Final report redaction	23/05/16	19/06/16	28
1.7	Final report review	13/06/16	19/06/16	7
1.8	M3: Final report deliver	20/06/16	20/06/16	0
1.9	M4: Work Defense	07/07/16	07/07/16	0
2	**OFDM technology investigation (100h)**	29/02/16	17/04/16	42
2.1	Search for OFDM information	29/02/16	20/03/16	21
2.2	Search about optical technology	07/03/16	27/03/16	21
2.3	Study the implementation of optical OFDM	21/03/16	03/04/16	14
2.4	M5: Understand Optical OFDM technology	04/04/16	10/04/16	7
2.5	Study the crosstalk and its main parameters	04/04/16	17/04/16	14
2.6	Learn how the software works	11/04/16	17/04/16	7
3	**WP3: Simulator work (VPI) (50h)**	11/04/16	22/05/16	42
3.1	First simulation tests	11/04/16	24/04/16	14
3.2	Interpretation of the input parameters	11/04/16	24/04/16	14
3.3	Simulation results interpretation	18/04/16	08/05/16	21
3.4	Identify simulation problems and solve them	25/04/16	15/05/16	21
3.5	M6: Identify design's weaknesses	09/05/16	15/05/16	7
3.6	Improve the design	09/05/16	22/05/16	14
3.7	Do advanced simulator tests	16/05/16	29/05/16	14
4	**WP4: Study of simulations (50h)**	16/05/15	12/06/16	28
4.1	Analyse and process the results	16/05/16	29/05/16	14
4.2	Draw conclusions	30/05/16	05/06/16	7
4.3	Further research of the technology	06/06/16	12/06/16	7

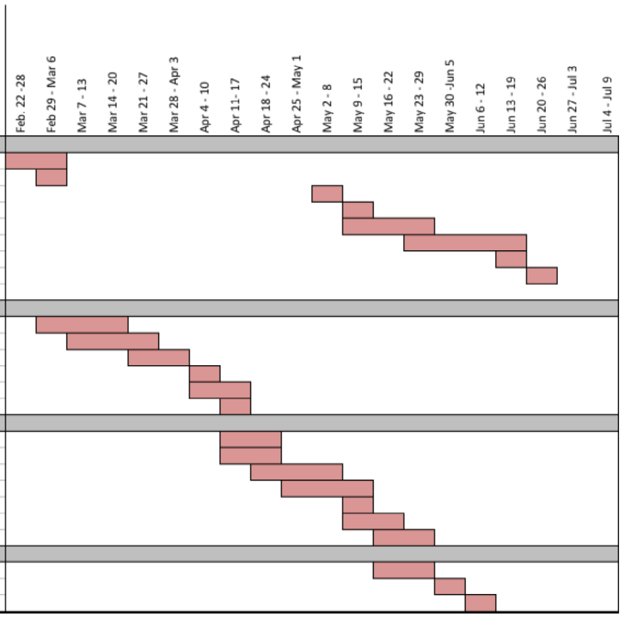


Figure 1: Gantt Diagram

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

In this chapter, we will do a review of all the technology involved in the project in order to give a global view of the most important concepts that will be necessary to understand the body of the thesis.

OFDM plays a significant role in the modem telecommunications for both wireless and wired communications. The history of frequency-division multiplexing (FDM) began in 1870s when the telegraph was used to carry information through multiple channels. The fundamental principle of orthogonal FDM was proposed by Chang as a way to overlap multiple channel spectra within limited bandwidth without interference. Since then, many researchers have investigated and refined the technique over the years and it has been successfully adopted in many standards such as WiFi, LTE (4G), UWB, DVBT.

Although OFDM has been studied in RF domain for over four decades, the research on OFDM in optical communication began only in the late 1990s and it has been in the focus of the research since then. With the advent of coherent detection technologies, optical multicarrier techniques, mainly OFDM has become an attractive candidate for high-speed optical transmission especially at the emerging rates of 100 Gb/s to 1Tb/s.

2.1. OFDM

Orthogonal Frequency-Division Multiplexing (OFDM) is a special class of multi-carrier modulation (MCM) in which data is transmitted through low rate subcarriers. This concept of subcarrier transmission is an attractive and efficient way to increase the data transmission rate by using a large number of closely spaced orthogonal subcarriers, each one modulated with a conventional modulation scheme (such as QAM) at a low symbol rate.

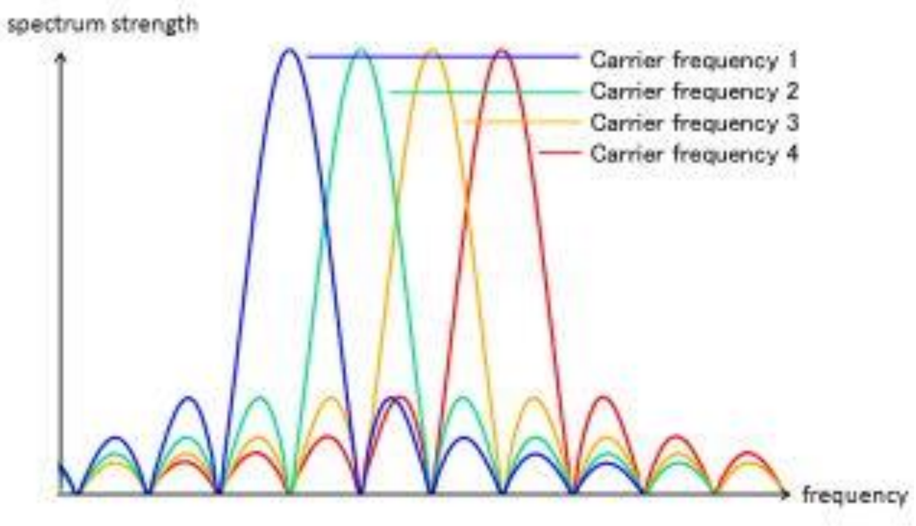


Figure 2: OFDM spectrum

OFDM Fundamentals

The structure of a complex multiplier (IQ modulator/demodulator), which is commonly used in MCM systems is shown at **Figure 3**. The key distinction of OFDM from general multicarrier transmission is the use of orthogonality between the individual subcarriers.

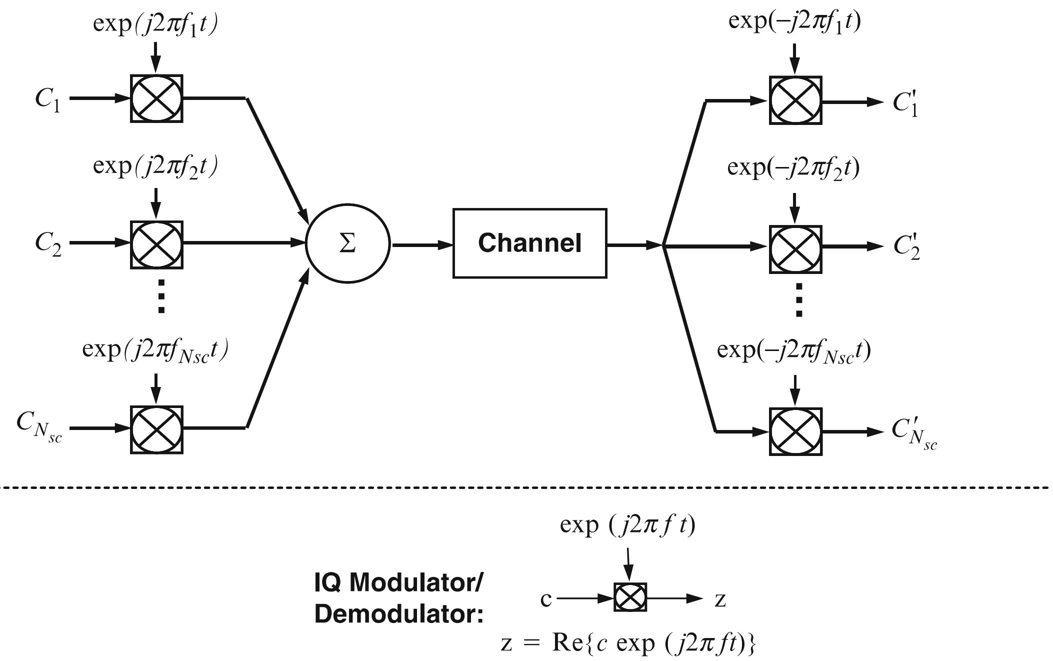


Figure 3: Multi Carrier Modulation scheme

Orthogonality between OFDM subcarriers

The MCM transmitted signal s(t) is represented as:

$$s(t) = \sum_{i=-\infty}^{+\infty} \sum_{k=1}^{N_{sc}} c_{ki} s_k(t - iT_s)$$

$$s_k(t) = \Pi(t) e^{j2\omega f_k t}$$

$$\Pi(t) = \begin{cases} 1, & (0 < t \leq T_s) \\ 0, & (t \leq 0, t > T_s) \end{cases},$$

where c_{ki} is the ith information symbol at the kth subcarrier, s_k is the waveform for the kth subcarrier, N_{sc} is the number of subcarriers, f_k is the frequency of the subcarrier, and T_s

is the symbol period. The optimum detector for each subcarrier could use a filter that matches the subcarrier waveform, or a correlator matched with the subcarrier. Therefore, the detected information symbol c_{ik} at the output of the correlator is given by:

$$c'_{ki} = \frac{1}{T_s}\int_0^{T_s} r(t \quad iT_s)s \quad _k \mathrm{d}t = \frac{1}{T_s}\int_0^{T_s} r(t \quad iT_s)\mathrm{e} \quad ^{j2\omega f_k t}\mathrm{d}t,$$

where r(t) is the received time-domain signal. The classical MCM uses non-overlapped band-limited signals, and can be implemented with a bank of large number of oscillators and filters at both transmitter and receiver. The major disadvantage of MCM is that it requires excessive bandwidth. The OFDM key is that it works by employing overlapped signals to reduce the bandwidth used. These signals would create interference between them if they were not orthogonal. If we see the correlation between two consecutive subcarrier signals,

$$\begin{aligned}\delta_{kl} &= \frac{1}{T_s}\int_0^{T_s} s_k s \quad _l \mathrm{d}t = \frac{1}{T_s}\int_0^{T_s} \exp\left(j2\Delta\left(f_k \quad f_l\right)t\right)\mathrm{d}t \\ &= \exp\left(j\Delta\left(f_k \quad f_l\right)T_s\right)\frac{\sin\left(\Delta\left(f_k \quad f_l\right)T_s\right)}{\Delta\left(f_k \quad f_l\right)T_s}.\end{aligned}$$

it can be seen that if the following condition,

$$f_k \quad f_l = m\frac{1}{T_s}$$

is satisfied, then the two subcarriers are orthogonal to each other.

This means that if subcarriers are spaced at a multiple of the inverse of the symbol rate, they can be recovered by the receiver with no inter-carrier interference (ICI), although these signals are overlapped in frequency.

Discrete Fourier Transform Implementation of OFDM

We rewrite the OFDM signal expression shown before for one OFDM symbol as:

$$\tilde{s}(t) = \sum_{i=0}^{N \quad 1} A_i \exp \quad j2\omega\frac{i}{T}t \quad , \quad 0 \quad t \quad T,$$

which is the complex form of the OFDM baseband signal. If we sample the complex signal with a sample rate of N/T, and add a normalization factor 1/N, then

$$A_i = \sum_{i=0}^{N \quad 1} R_n \exp \quad j2\Delta\frac{i}{N}n \quad , \quad n = 0, 1, \ldots, N \quad 1,$$

where Sn is the nth time-domain sample. This is exactly the expression of inverse discrete Fourier transform (IDFT). It means that the OFDM baseband signal can be implemented by IDFT. The pre-coded signals are in the frequency domain, and the output of the IDFT is in the time domain.

There are two fundamental advantages of DFT/IDFT implementation of OFDM. First, they can be implemented by (inverse) Fast Fourier Transform (FFT) algorithm, where the number of complex multiplications is reduced from (N/2)·log(N).

Second, a large number of orthogonal subcarriers can be modulated and demodulated without the need of using a complex set of RF oscillators and filters. This leads to a relatively simple architecture for OFDM implementation when large number of subcarriers is required.

Cyclic Prefix

Due to the multipath propagation, inter symbol interference (ISI) will be generated at the receiver side. To deal with ISI, a guard time must be introduced between symbols. In OFDM, it is used the so-called cyclic prefix. It consists on inserting a cyclic extension of the OFDM symbol into the guard interval Δg. This is done by adding at the beginning of the OFDM symbol, the last samples of the same symbol. In order to be effective, the length of the cyclic prefix must be at least equal to the length of the multipath channel impulse response. Thanks to the insertion of the cyclic prefix, the orthogonality of the different subcarriers is preserved.

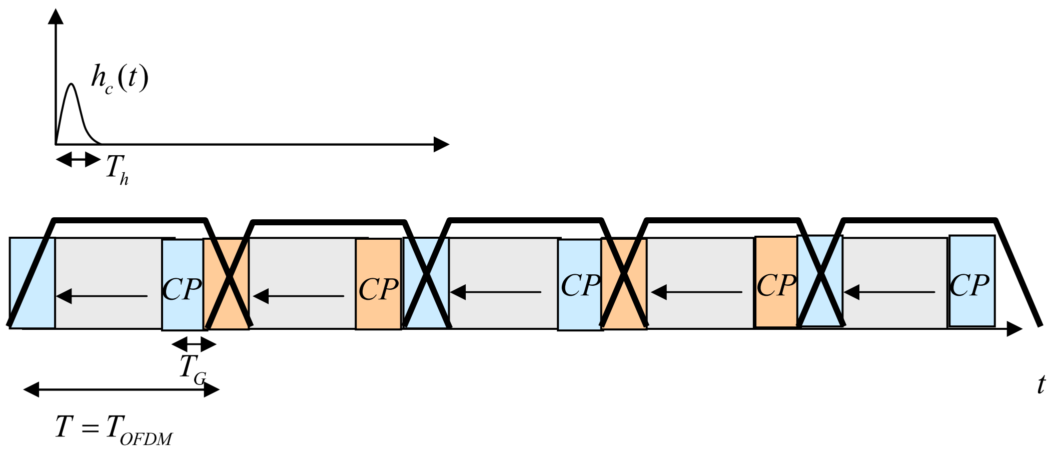


Figure 4: Cyclic Prefix implementation

In **Figure 5** we can appreciate the block diagram of an OFDM system with all the different parts involved explained before:

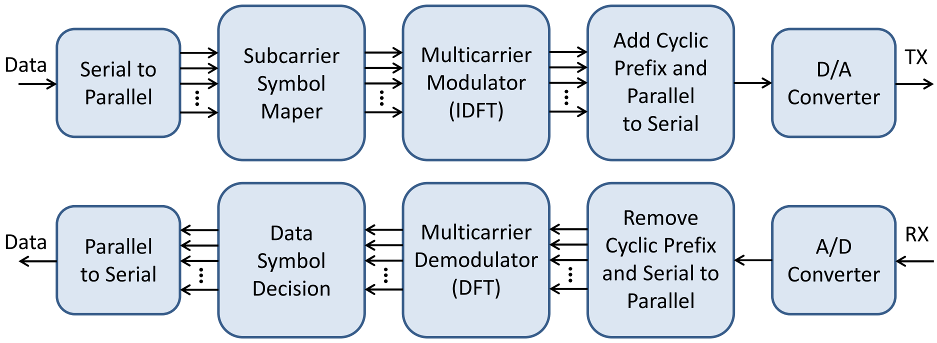


Figure 5: OFDM block diagram

2.2. Coherent Optical OFDM

As this project is focused on the OFDM technology in the optical field, it is necessary to talk about how is this kind of MCM implemented in the optical domain.

There are mainly two ways to build an optical OFDM system: coherent detection and direct detection, according to their underlying techniques and applications. While direct detection has been the most used technique for optical communications over the last two decades, the recent progress in forward-looking research has clearly pointed to the trend that the future of optical communications is the coherent detection.

When these two technologies, OFDM and coherent detection are fused, the system is able to provide a high spectral efficiency, robustness to chromatic dispersion and polarization-mode dispersion and high receiver sensitivity.

The block diagram of a typical CO-OFDM system is the one shown in **Figure 6**:

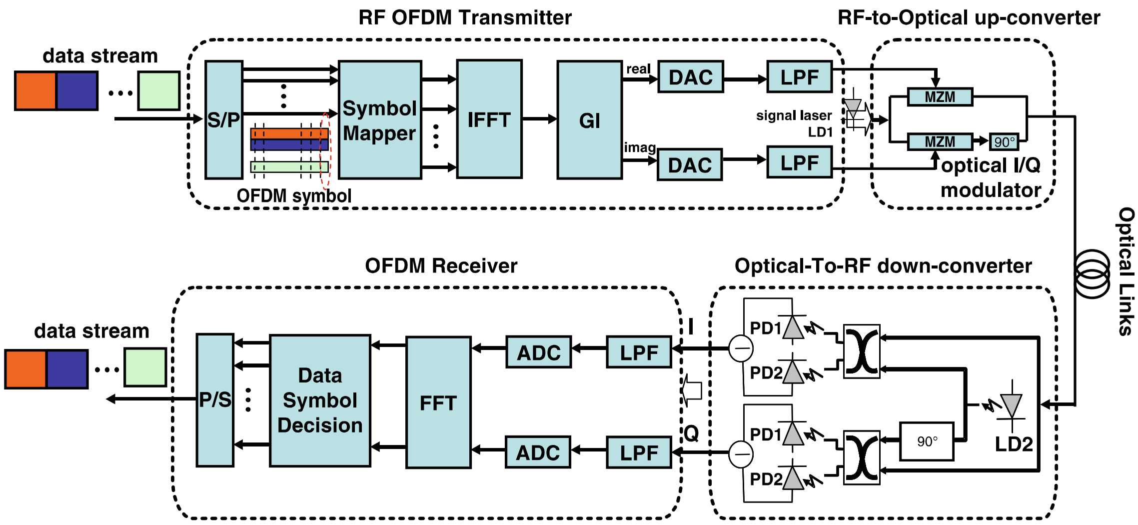


Figure 6: Coherent Optical OFDM block diagram

It contains five basic functional blocks: RF OFDM signal transmitter, RF to optical (RTO) up-converter, Fiber links, the optical to RF (OTR) down-converter, and the RF OFDM receiver.

In the RF OFDM transmitter, the source data is first split into multiple parallel branches. This is so-called “serial-to-parallel” conversion. The number of the multiple branches matches the number of loaded subcarrier. Then the converted signal is mapped onto a modulation format, such as PSK, QAM, etc. The IDFT will convert the mapped signal from frequency domain to time domain. The cyclic prefix is inserted to avoid ISI. Digital-to-Analog converters (DACs) are used to convert the time-domain digital signal to analog signal. A pair of electrical low-pass filters is used to remove the alias sideband signal. At the RTO up-converter, the baseband OFDM signal is converted into the optical domain using an optical I/Q modulator, which is comprised by two Mach–Zehnder modulators (MZMs) with a 90º optical phase shifter.

After the optical link, in the OTR down-converter, the I/Q components of the OFDM signal are recovered by using a digital coherent receiver consisting of a 90º optical hybrid and two photodetectors. After that, the inverse process of the transmitter stage is performed in order to obtain a final data stream as the original one.

2.3. Crosstalk

Crosstalk (XT) is a phenomena produced when more than one signal is transmitted simultaneously in the same communication channel (or adjacent). It produces interferences between signals, as well as degradation of the main signal.

It is calculated as:

$$XT(dB) = 10\log\left(\frac{P_I}{P_{Ref}}\right)$$

Where Pi is the power of the interfering signal and Pref is the power of the desired signal that will suffer the crosstalk effects. Both expressed in W or mW.

As it seems logical, we are interested in the minimum crosstalk level under any circumstances, although it depends on many factors such as modulation format, environment, materials, transmission power...

One important example where XT appears is, indeed, in Multi-core Fibers, where every independent core transmission affects and interferes on the other cores.

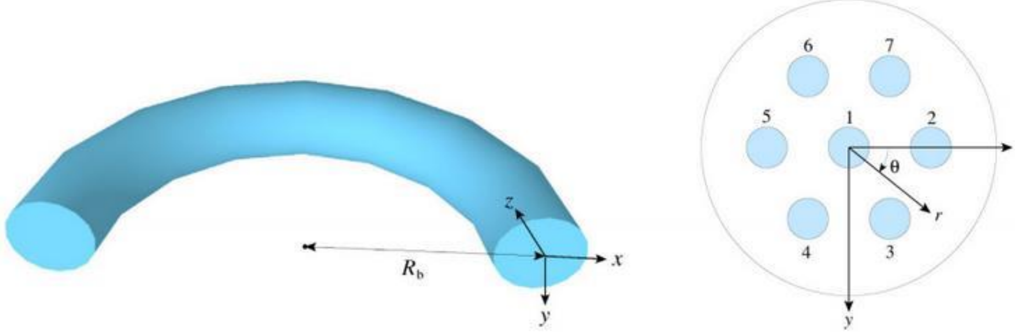


Figure 7: Multi-core fiber section

3. Methodology / project development:

In order to carry out the investigations proposed, the VPI Photonics software is the main tool that will be used to run the corresponding simulations. This software is a powerful application that contains a great set of optical and electrical modules to perform different kind of communication schemes and simulate their behaviour.

Specifically, the development of the schematics is made using the VPI Tranmission Maker, and the graphical simulation results can be shown in the VPI Photonics Analyzer, which are two tools from the VPI software set.

However, some of the simulations will be done by using a simulation script that allows getting some parameters that cannot be obtained by simply using the VPI Photonics Analyzer.

In this section, we will see the different schematics implemented to run the simulations. The first one used is the Coherent Detection Optical OFDM scheme, which will be the basic structure on which the rest of the schematics will be based. After that, some scenarios will be implemented in order to evaluate the crosstalk effect in different situations.

To do a more exhaustive study, apart from the different scenarios, the different simulations have been done varying some representative parameters to see their effect in crosstalk terms:

- OFDM subcarriers
- QAM bits per symbol
- Crossed cases (different parameter order between TX and RX)

More detailed information about this can be found in chapter 4.

3.1. Coherent Optical OFDM

The first step of the study is to design the Coherent detection Optical OFDM scheme, as it will be the basic structure for the rest of the simulation scenarios, so we need to prove that the transmitted signal is correctly recovered by the receiver after the electrical to optical conversion and vice versa.

A generic CO-OFDM system includes five basic functional blocks: OFDM transmitter, electrical to optical up-converter, optical link, optical to electrical down-converter, and OFDM receiver. This schematic does not have any optical link (optical fiber) connected between the transmitter and the receiver because the main goal of this thesis is to test the effect of the crosstalk in terms of the receiver sensitivity, without taking into account external effects such as the fiber attenuation, dispersion, or other parameters that could influence the results.

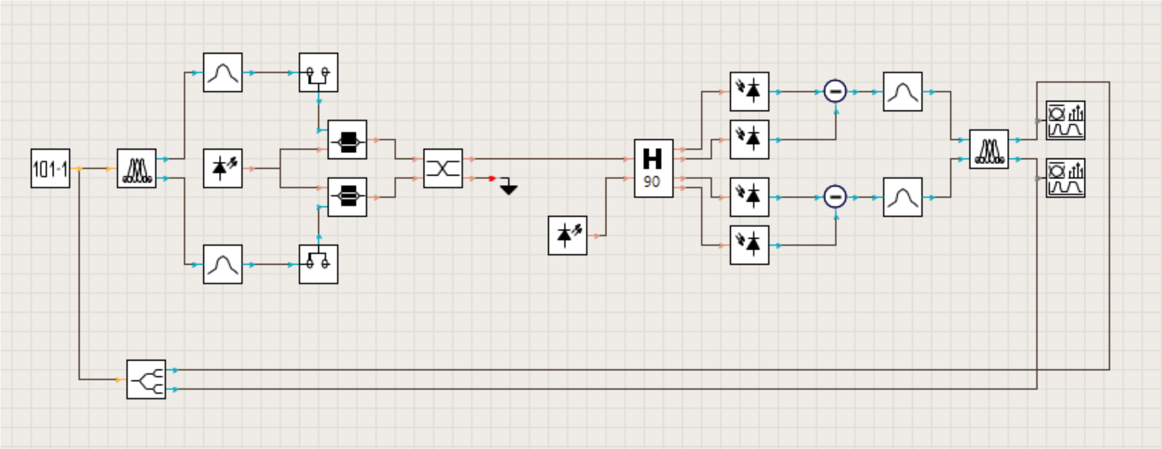


Figure 8: Coherent Optical OFDM schematic

As it can be seen in **Figure 8**, we can distinguish two basics stages, the OFDM transmitter and the OFDM receiver.

The transmitter stage is formed by a pseudorandom sequence generator, an OFDM coder, which generates two signal blocks corresponding to the In-Phase and Quadrature of the OFDM signal, and a low pass filter, in our case a raised cosine filter, which is the most optimal filter to reduce the ISI. The conversion to the optical domain is performed by two Mach-Zender modulators using a laser source, and two laser drivers placed just before the modulators in order to adjust the electrical signal in the lineal zone of the modulator transfer function. After that, a coupler is used to sum both Quadrature and In-Phase OFDM signals.

At the receiver side, we can see the general structure of a coherent detection system formed by a 90º optical hybrid fed by a laser source and four photo-detectors to recover both I and Q parts of the transmitted signal.

Finally, we add two signal analyzers at both I and Q branches, also linked with the output of a QAM coder using the same bit sequence generator so that we are able to compare both signals and check if the OFDM system is working correctly.

We will make the performance for two modulation formats, 4-QAM and 16-QAM. These will be the two symbol constellations used for all simulations in order to compare the effect of the number of bits per symbol used in the modulation.

4-QAM

As a first test, we used a 4-QAM and 16 subcarriers in the OFDM modulation, and these were the results obtained:

In **Figure 9** we can appreciate both In-Phase and Quadrature components of the OFDM signal are correctly received.

Figure 10 represents the eye diagram of both branches to see all the transitions between the symbols of the 4-QAM constellation.

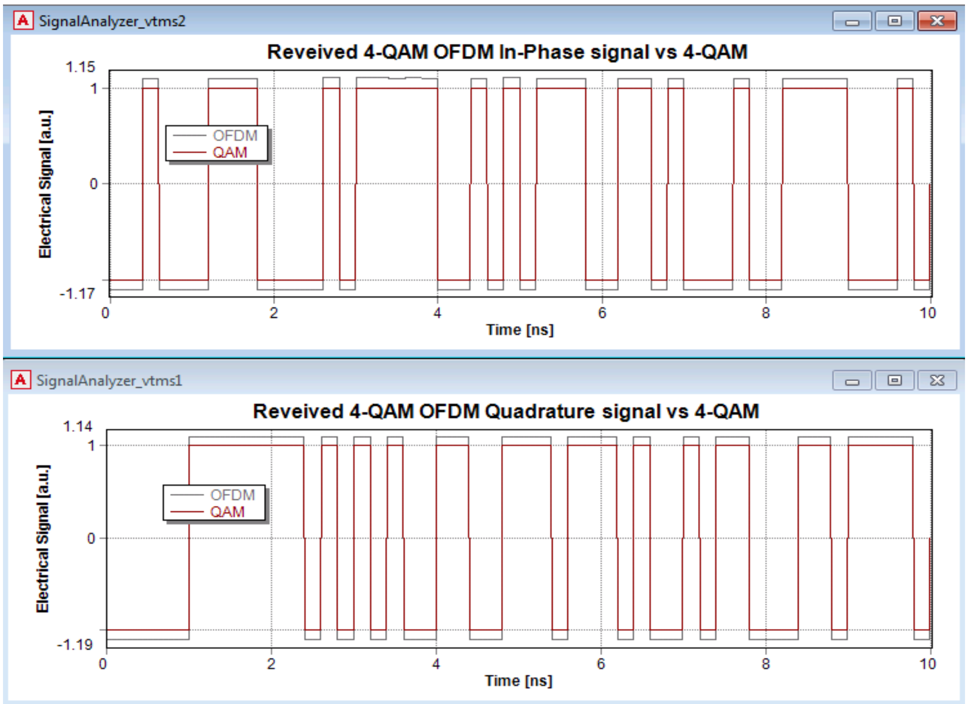


Figure 9: In-Phase and Quadrature parts of the received OFDM and 4-QAM signals

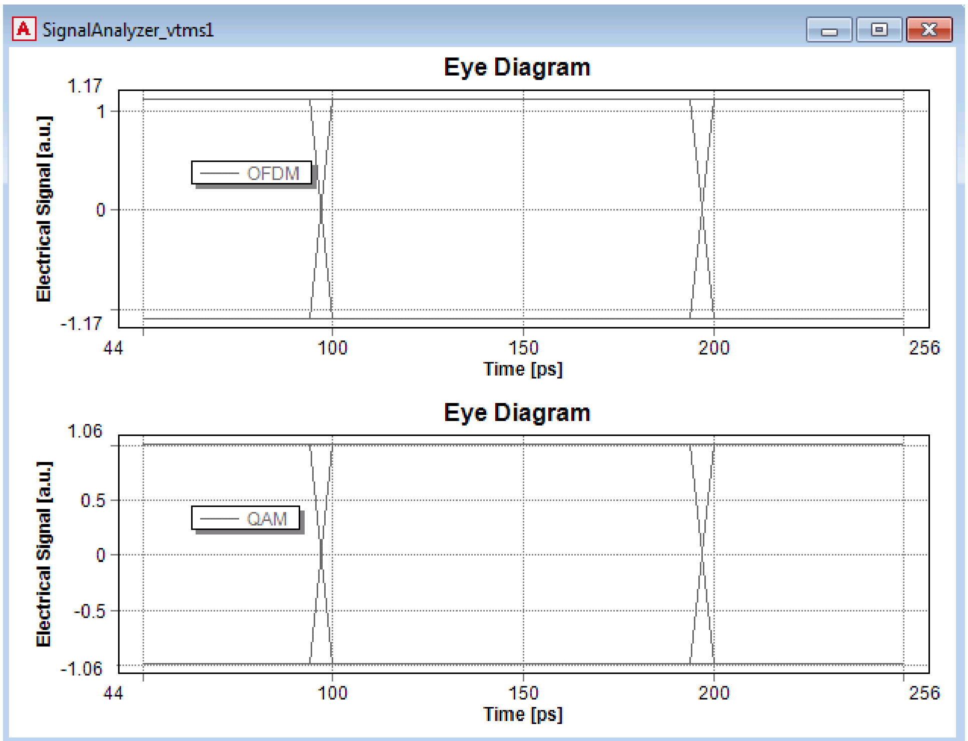


Figure 10: Eye diagram of the In-Phase and Quadrature parts of the 4-QAM OFDM received signal

16-QAM

The same was done for the 16-QAM case. In **Figure 11,** the 4 signal levels for each I and Q of the 16-QAM can be appreciated. In **Figure 12** there is represented the eye diagram of the In-Phase and Quadrature parts of the 16-QAM OFDM received signal.

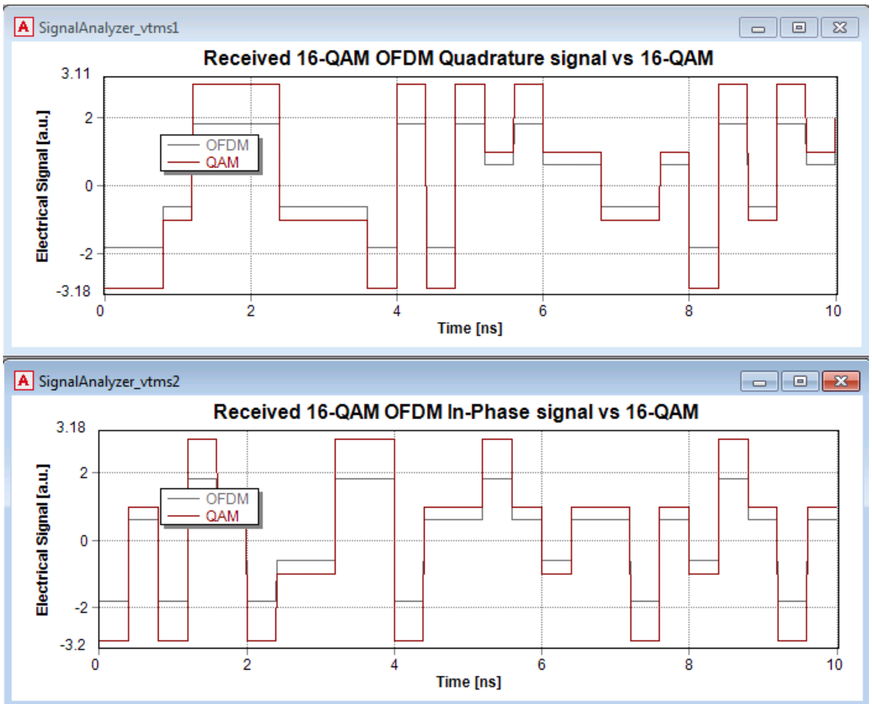


Figure 11: In-Phase and Quadrature parts of the received OFDM and 16-QAM signals

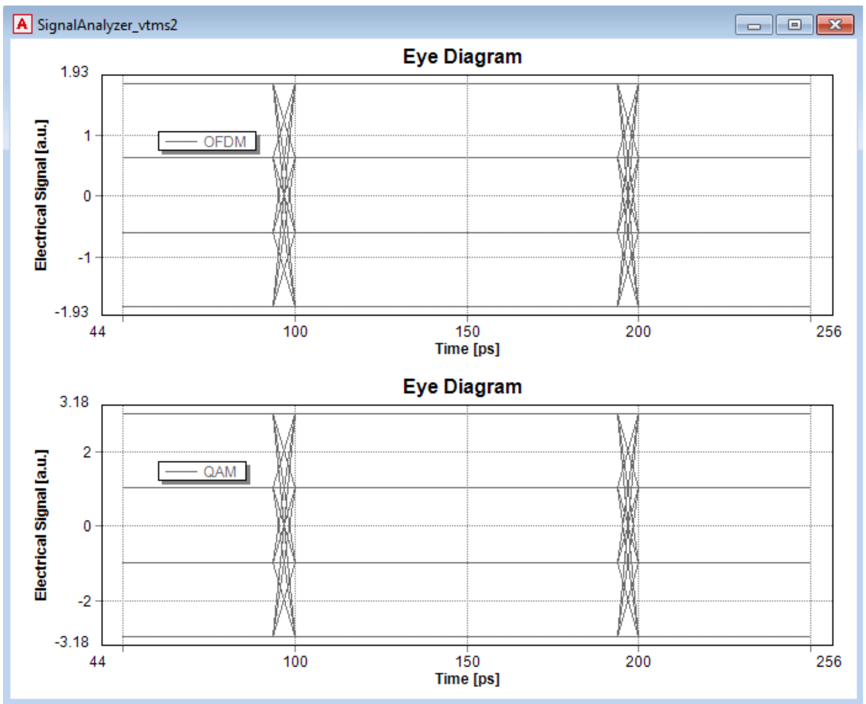


Figure 12: Eye diagram of the In-Phase and Quadrature parts of the 16-QAM OFDM received signal

3.2. OFDM with OFDM interferer

In order to start evaluating the crosstalk effect, a new schematic was constructed with another OFDM transmitter interfering the original one.

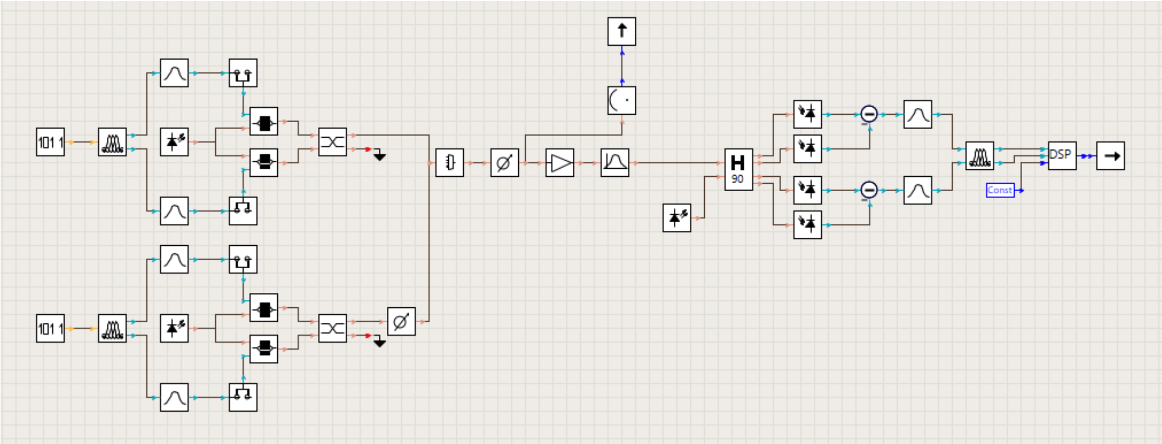


Figure 13: Coherent Optical OFDM schematic with one OFDM interferer

As we can see, this interferer is exactly the same as the original transmitter. Now an optical amplifier and an optical filter have been added between the transmitter and the receiver in order to simulate the noise added to the receiver. Also, two attenuators have been included to the schematic. The first one (ATT1) is placed at the end of the interferer branch and it will represent the crosstalk level for every simulation run. The second attenuator (ATT2) is placed at the receiver input and it is used to simulate the channel attenuation. Moreover, a power meter is placed just after the second attenuator in order to get the receiver optical power needed to get a certain bit error rate. And finally, a DSP module is added at the output of the OFDM decoder to extract the BER obtained for every simulation run.

The main goal of the thesis, as said before, is to see the impact of the crosstalk in the received signal, and that will be evaluated basically by the receiver sensitivity, under the condition of obtaining a BER smaller than 10^-3.

In order to do that, a simulation script was used. The function of this script is the following: A simulation run is done for every crosstalk level (ATT1) from 0 to 40 dB. For each crosstalk level, the ATT2 value starts at 40 dB, but this value is iterated in a range from 0 to 80 dB until the minimum optical power needed to get a BER of 10^-3 is found.

This script will be used in every simulation scenario to get results, compare them and finally make conclusions.

3.3. OFDM with QAM interferer

This module is done in order to test the crosstalk effect having as interferer a different modulation rather than the OFDM original one.

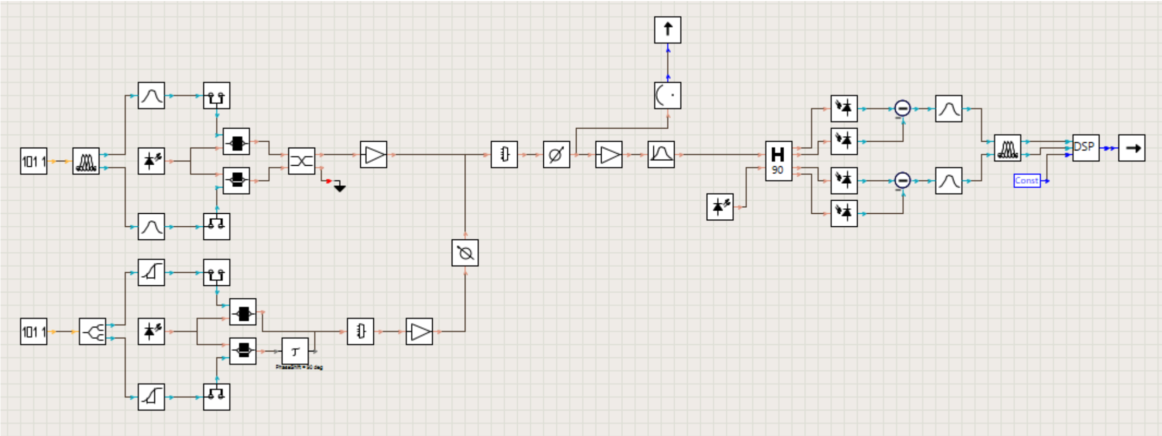


Figure 14: Coherent Optical OFDM schematic with one QAM interferer

Following the same structure as the previous schematic, now we changed the OFDM coder of the interferer for a QAM coder. As the modulations now are different, both transmitter signals have different power at their output and it is difficult to adjust the transmission parameters of both branches to obtain the same optical power at their output. So, in order to control that, an optical amplifier is placed at the output of both transmitters to adjust both output powers at the same level.

4. Results

In this chapter all the simulation results will be presented and analyzed.

The simulations will follow the same order as the schematics shown in chapter 3.

For every simulation scenario, the impact of the number of subcarriers used in each OFDM transmitter will be studied. Finally a general comparison with all the simulated variations will be shown.

We divide the simulations presented in the following way:

- Both TX and INT using the same number of subcarriers
    - 4-QAM
    - 16-QAM
- TX and INT using different number of subcarriers (16-QAM)
    - TX using 16 subcarriers
    - TX using 1024 subcarriers
- TX and INT using different modulation (OFDM vs QAM)
    - 4-QAM
    - 16-QAM

4.1. OFDM with OFDM interferer using the same number of subcarriers

In this case, we will use the schematic presented in 3.2, which consisted in a system formed by an OFDM transmitter, an OFDM receiver and another OFDM transmitter interfering.

4-QAM

In this case, we used a 4-QAM modulation for both OFDM transmitters. We used the simulation script and ran different simulations changing the number of subcarriers used in each transmitter. In this case, the number of subcarriers was the same for each transmitter, and simulations were done for 16, 64, 256 and 1024 subcarriers to have a global view of how subcarriers affect the receiver sensitivity in terms of crosstalk.

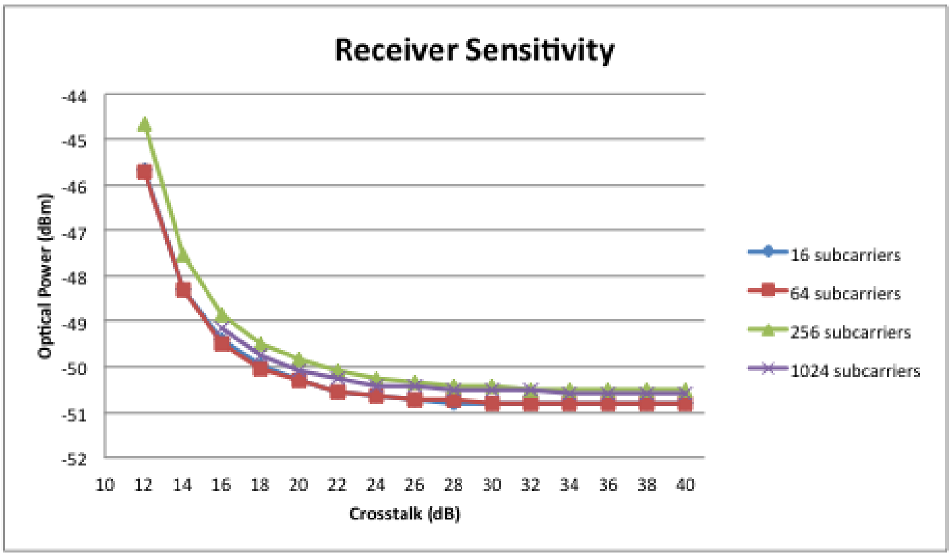


Figure 15: Receiver sensitivity in function of XT for different number of subcarriers.
4-QAM OFDM interfered with 4-QAM OFDM

As it can be seen in **Figure 15**, the receiver sensitivity decreases as the crosstalk level increases. Also, the optical power needed for the receiver to achieve a BER of 10^-3 tends to -50 dBm approximately. If we see the different graphs obtained, we notice that the number of subcarriers used does not have much effect in the receiver sensitivity. However, we get a little improvement in the sensitivity when using a smaller number of subcarriers in both OFDM transmitter and interferer.

16-QAM

The same procedure was done for a 16-QAM modulation

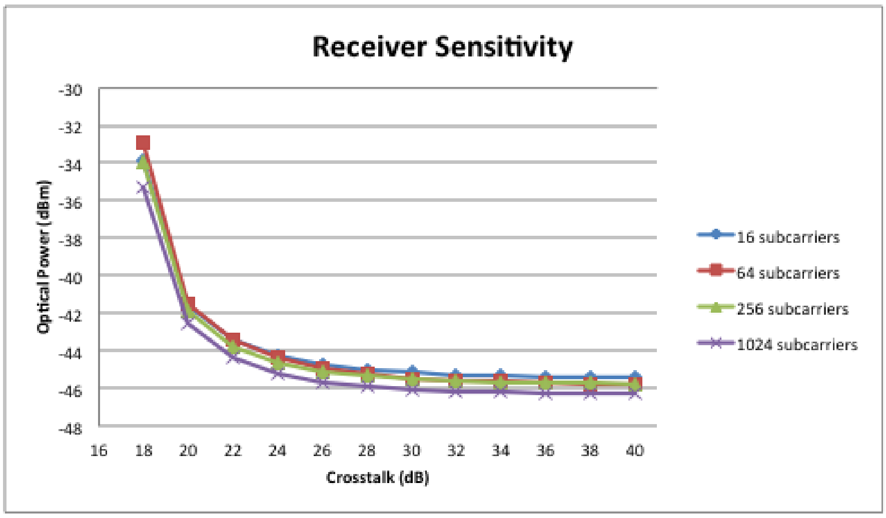


Figure 16: Receiver sensitivity in function of XT for different number of subcarriers.
16-QAM OFDM interfered with 16-QAM OFDM

In the 16-QAM case, we see the same behaviour as the 4-QAM case. After seeing both graphics, we can say that when using the same number of subcarriers in both transmitter and interferer, changing the subcarriers used will not modify significally the receiver sensitivity.

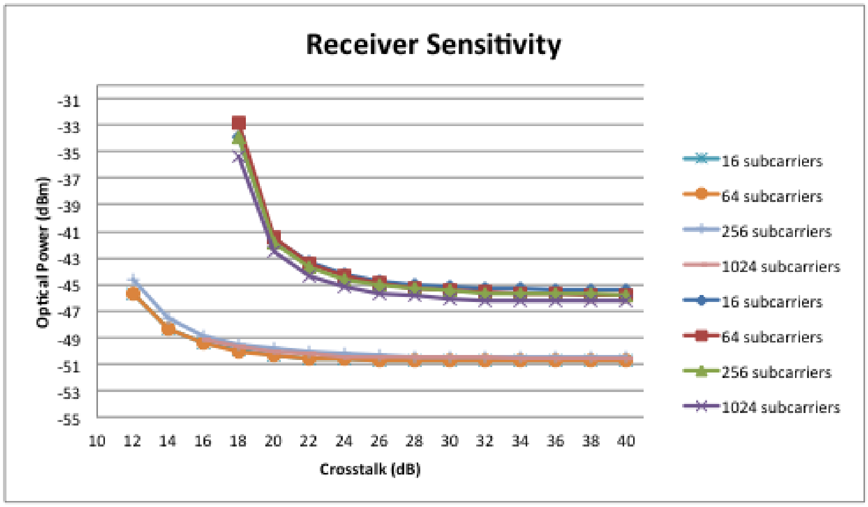
However, if we show the results for 4-QAM and 16-QAM in the same chart we can appreciate significant differences.

Figure 17: Receiver sensitivity in function of XT for different number of subcarriers.
4-QAM OFDM interfered with 4-QAM OFDM.
16-QAM OFDM interfered with 16-QAM OFDM.

In **Figure 17** we can notice that the 4-QAM case achieves a better sensitivity than the 16-QAM's one. Moreover, it presents a higher tolerance to crosstalk because it is able to find a BER smaller than 10^-3 when the signal receives a higher level of interference. Conversely, the 16-QAM case is not able to find the sensitivity for crosstalk levels above 18 dB.

If we want to see a better comparison, we can calculate the OSNR Penalty, which is not more than subtracting the optical power needed when the Crosstalk level is maximum, that is when the sensitivity curve gets flat. This allows us to have a global view of the crosstalk effect, regardless of the modulation influence in the sensitivity.

In **Figure 18** the OSNR Penalty is shown for both 4 and 16-QAM modulations. Now, only the 16 subcarriers case is shown.



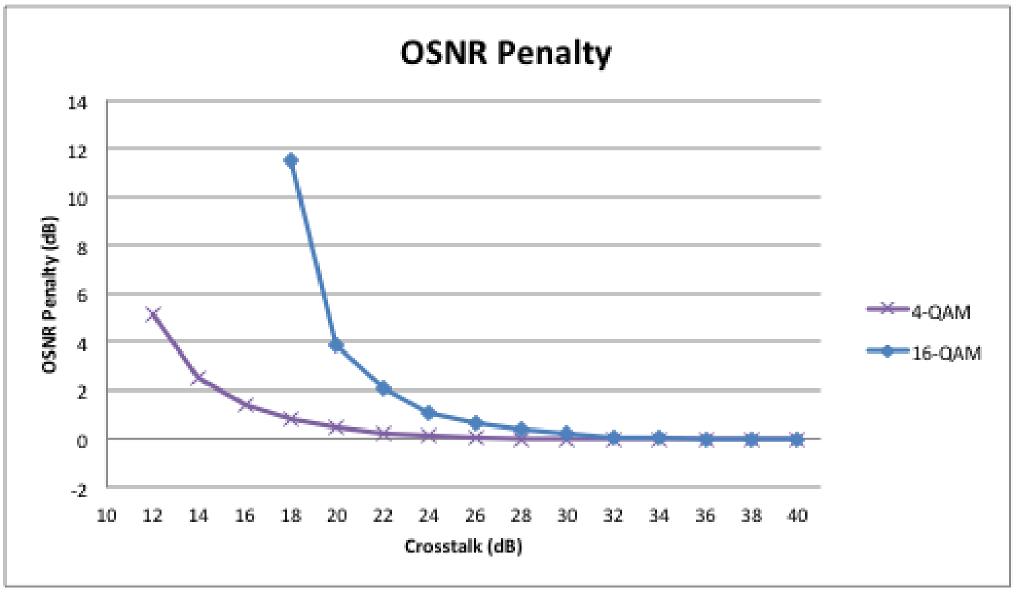


Figure 18: OSNR Penalty in function of XT. 4-QAM OFDM interfered with 4-QAM OFDM. 16-QAM OFDM interfered with 16-QAM OFDM.

As we could guess from **Figure 17**, the 4-QAM case tends to get a 0 dB OSNR penalty faster than the 16-QAM case.

The 4-QAM has a 1-dB penalty of 17 dB, while the 16-QAM has a 1-dB penalty of 24 dB.

So after analysing the previous results, we can confirm that the tolerance to crosstalk is higher when the number of bits per symbol used in the simulation is lower.

4.2. OFDM with OFDM interferer using different number of subcarriers

In this section, more simulations were performed using the same scheme as the one used before. Now, the two OFDM transmitters (original TX and interferer TX) do not use the same number of subcarriers as the previous section. Therefore, in order to see the impact of subcarriers, two tests were done: one when the transmitter uses 16 subcarriers, and another one when the transmitter uses 1024 subcarriers. In both extreme cases, we ran several simulations changing the number of subcarriers used by the interferer. Now, only the 16-QAM modulation was used.

<u>**Receiver Sensitivity with 16-QAM 16 subcarriers OFDM Transmitter**</u>

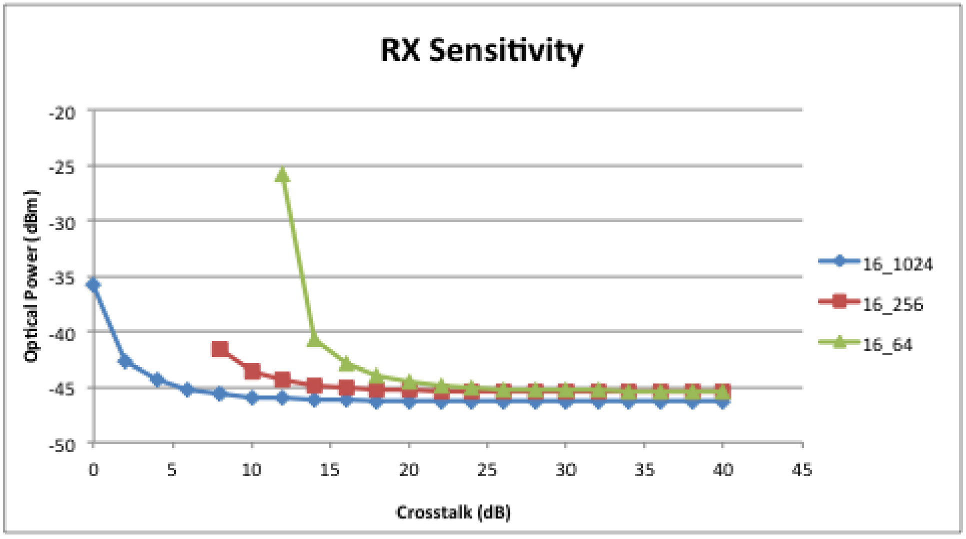


Figure 19: Receiver sensitivity in function of XT for different number of subcarriers. 16-QAM OFDM interfered with 16-QAM OFDM.

In **Figure 19** it can be seen that when the transmitter is using a small number of subcarriers (16 in that case), the receiver sensitivity improves when the interferer uses a higher number of subcarriers. Also, when the interferer is using 64 subcarriers, the receiver is not able to find the optical power needed when the crosstalk level is above 12 dB, while for the 256 and 1024 cases yes. So, when the transmitter uses 16 subcarriers, the systems presents a better tollerance to crosstalk when the interferer has a higher number of subcarriers (1024 in that case).

It is important to emphasize that the “blue” case (16 subcarriers signal, 1024 subcarriers interferer) is the only one that is able to reach a sensitivity level for a BER under 10^-3 when the crosstalk level is 0 dB (worst case, higher interference).

<u>Receiver Sensitivity with 16-QAM 1024 subcarriers OFDM Transmitter</u>

Now, let’s see what happens when the transmitter uses a high number of subcarriers, for example 1024.

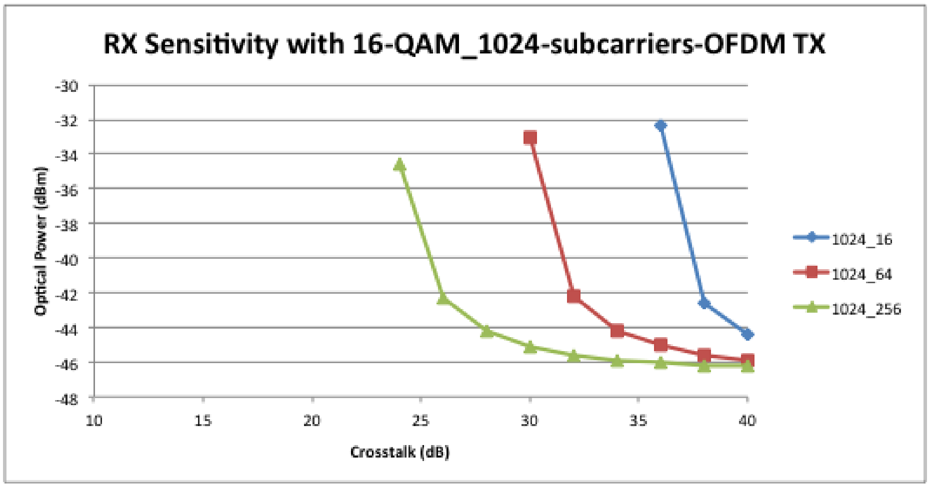


Figure 20: Receiver sensitivity in function of XT for different number of subcarriers. 16-QAM OFDM interfered with 16-QAM OFDM.

This case looks as the opposite of the previous one. Now, the receiver is not able to find a BER below 10^-3 for crosstalk levels above 24 dB. However, the sensitivity obtained when the presence of interference is lower is -46 dBm, similar to the one obtained in the previous simulations.

So after comparing the previous results, we can say that when the transmitter uses a low number of subcarriers, the system presents a greater robustness to crosstalk.

However, if we see the effect that is produced to the interfering transmitter, who is also another transmitter, we see that it generates the opposite behavior in robustness against crosstalk. In **Figure 21** we can appreciate three representative cases when two transmitters have different number of subcarriers. In that example, the “blue” case is when the transmitter uses 16 subcarriers and the interferer 64, the red case is the opposite, when the transmitter uses 64 subcarriers and the interferer 16, and the green one when using the same numbers of subcarriers (16 subcarriers in that case, although there is not much difference in the cases when both transmitters use the same number of subcarriers).

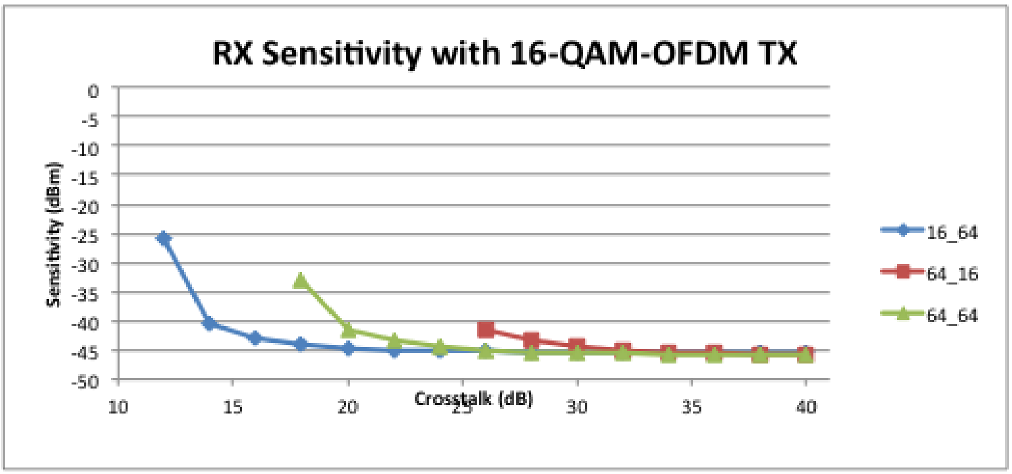


Figure 21: Receiver sensitivity in function of XT for different number of subcarriers. 16-QAM OFDM interfered with 16-QAM OFDM.

As we saw in the last figure, now the case when the transmitter uses the major number of subcarriers presents a higher robustness to crosstalk. The sensitivity when crosstalk is reduced is -45 dBm for the three situations.

We have to notice that the gain produced in tolerance to crosstalk for one transmitter in respect to the case when both TXs use the same number of subcarriers, is lost for the other transmitter that uses less subcarriers. In **Figure 21** we can see that for a sensitivity level of -42 dBm, there is a difference of 10 dB crosstalk tolerance between the two transmitters using 16 and 64 subcarriers respectively. The case when both TXs use the same is just in the middle of the other two cases.

So, as a conclusion, is not a good deal to implement a system with various transmitters working with different subcarriers, because while the transmitter with a greater number of subcarriers will gain some tolerance to crosstalk, the other transmitters with less subcarriers will lose the same tolerance level.

4.3. OFDM with QAM interferer

As a last test, it was intended to prove what was the crosstalk effect when having an OFDM signal against a single QAM interferer. In order to make the simulations, we used the schematic shown in 3.3, which consisted on the same structure, but changing the OFDM interferer for a QAM interferer.

In particular, simulations were done for 4-QAM and 16-QAM modulation formats, as well as for 16 and 1024 subcarriers. The results are shown in **Figure 22**.

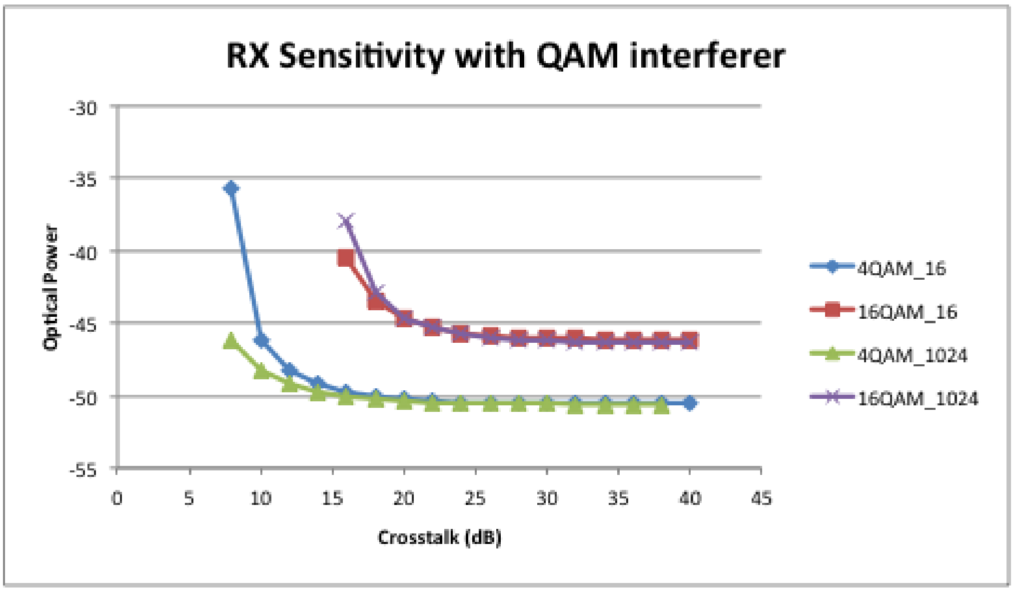


Figure 22: Receiver sensitivity in function of XT for different number of subcarriers.
4-QAM OFDM interfered with 4-QAM.
16-QAM OFDM interfered with 16-QAM.

As we can observe, the system is more tolerant to crosstalk when the modulation order is lower. Also the 4-QAM case is better than the 16-QAM in sensitivity terms. As for the same crosstalk level, for example 20 dB, in the 16-QAM case the receiver needs -46 dBm, while in the 4-QAM the receiver only needs -50 dBm.

Talking about the number of subcarriers, we still cannot see an important impact on the receiver sensitivity. However, in the 4-QAM case, we get a better sensitivity when the OFDM signal uses 1024 subcarriers instead of 16.

4.4. General comparison

To see a final view of the study done, a chart comparing the different simulated situations is shown in **Figure 23**. In that graphic there are represented the following cases:

- 4-QAM transmitter / 4-QAM interferer
- 16-QAM transmitter / 16-QAM interferer
- 4-QAM OFDM transmitter / 4-QAM interferer
- 16-QAM OFDM transmitter / 16-QAM interferer
- 4-QAM OFDM transmitter / 4-QAM OFDM interferer
- 16-QAM OFDM transmitter / 16-QAM OFDM interferer

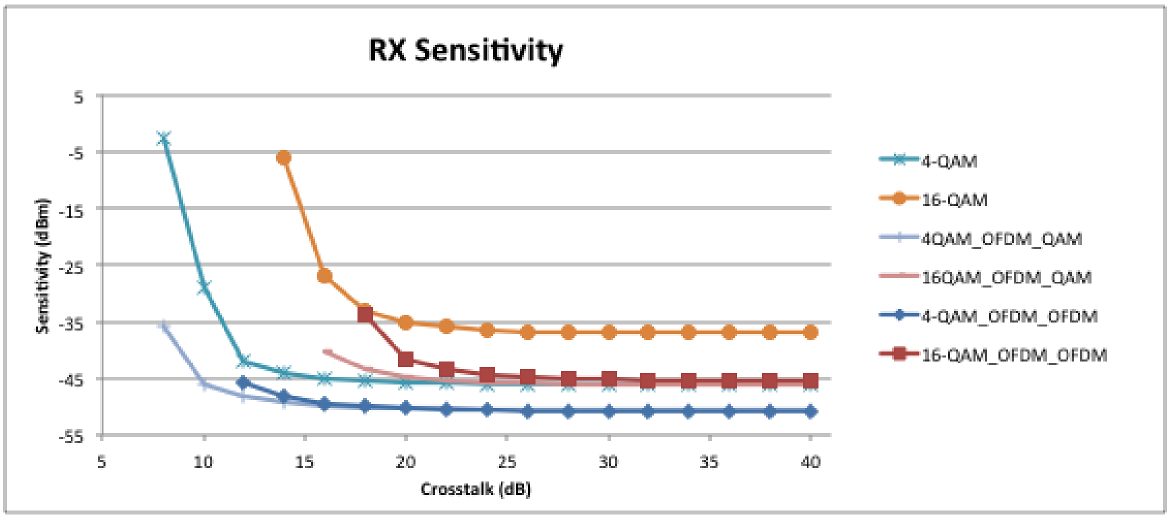


Figure 23: Receiver sensitivity in function of XT for different number of subcarriers. General comparison

We took the results obtained in the Adrià Escolano's TFG to represent the receiver sensitivity when both transmitters use a QAM modulation, without implementing OFDM. So now we have a general comparative of the QAM and OFDM implementations when using 2 and 4 bits per symbol in the constellation.

As we see, the cases that present a higher tolerance to crosstalk are the ones using a 4-QAM constellation. If we focus on the sensitivity level achieved, the best cases would be the 4-QAM OFDM transmitter with a 4-QAM interfering, and 4-QAM OFDM transmitter with another 4-QAM OFDM interfering.

After seeing all the results, the case which achieves a better robustness to crosstalk as well as the lowest receiver sensitivity is the one implemented with a 4-QAM OFDM transmitter with a 4-QAM (no OFDM) interferer.

5. Budget

CONCEPT	DETAIL	NUMBER OF HOURS	COST/HOUR	FINAL COST
Documentation (redaction and review)	Project Proposal	10	8€/h	80 €
	Critical Design Review	10	8€/h	80 €
	Results analysis	30	8€/h	240 €
	Final Report	40	8€/h	320 €
	Thesis Presentation	15	8€/h	120 €
Investigation about the topic (Optical OFDM)	Documentation about topic	15	8€/h	120 €
	State of the art	10	8€/h	80 €
	OFDM modulation performance	10	8€/h	80 €
	Crosstalk implementation	15	8€/h	120 €
	Learning about software	10	8€/h	80 €
Programming of the simulations	First simulation tests	15	8€/h	120 €
	TX/RX structure design	20	8€/h	160 €
	Optical OFDM implementation	10	8€/h	80 €
	Crosstalk simulations	40	8€/h	320 €
Software costs	Software license	1 license	500€/license	500 €
	Software amortization (5%)	-5%	-25 €	-25 €
Study of results	Result analysis	35	8€/h	280 €
	Draw conclusions	10	8€/h	80 €
	Further Research	10	8€/h	80 €
TOTAL		305		2.915 €

Table 1: Project Budget

6. Conclusions and future development:

After showing and analyzing all the results obtained during the development of the thesis, we can make the following conclusions:

- The number of subcarriers used in the transmitters has an almost negligible effect on the receiver sensitivity as well as the tolerance to crosstalk.
- The system is more tolerant to XT and presents a better sensitivity when the order of the modulation is lower. That is, the 4-QAM case is better than the 16-QAM case.
- When both transmitters use different number of subcarriers, the one that has a lower number of subcarriers obtains a greater tolerance to XT, while the one with more subcarriers worsens its tolerance in respect with the case with both transmitters using the same number of subcarriers. So it is not a good practice to use different subcarriers for different transmitters, as the gain obtained for one transmitter is lost for the other one.
- When an OFDM transmitter is interfered with a QAM interferer (without implementing OFDM), the sensibility at the point where the interference is higher improves between 1 and 5 dB compared with the case with an OFDM TX interfering. Moreover, it presents from 2 to 4 dB improvement in tolerance to crosstalk.
- The system obtains a better sensibility when it uses OFDM rather than when using the simple QAM modulation (without implementing OFDM).
- The case which presents a higher robustness to crosstalk, and therefore tolerates a higher level of crosstalk as well as presenting a better sensibility at the receiver, is the case when the 4-QAM OFDM transmitter is interfered with a 4-QAM transmitter (without implementing OFDM). The second best case, which presents similar results to the one before, is the case when a 4-QAM OFDM transmitter is interfered with another 4-QAM OFDM transmitter, equal to the original one.

After seeing these results, we can guess what the following steps could be. We could, for example, take into account losses introduced by either connectors or cables, as well as adding optical fiber between the transmitter and the receiver. Also it could be studied what happens if we add more than one interfering transmitter when we are using either QAM modulation or OFDM. It could also be interesting to study how a different kind of modulation is affected by crosstalk. There are lots of parameters that affect the behavior of the transmitter-receiver structure that could be taken into account in future studies.

In particular we had some problems when working with the OFDM transmitter using 64-QAM symbols, so it could be an interesting line of study in the future.

Apart of that, we did all the simulations under an ideal point of view, supposing all the elements used on the schematics to be ideal. That is something that could be changed in future simulations and we could see how these changes affect its behavior against crosstalk.

Finally, some other phenomena could be taken into study, such as:

- The effect of cyclic prefix on OFDM signals
- The effect of correlation between the seeds of the PRBS
- Noise effect on the lasers
- Roll-off factor effect on the optical filters (Raised cosines)
- Non-lineal effects on the transmitted signal
- Parameters from the digital/analog (DAC) conversors
- Phase shift on the signals
- Different modulations
- More interfering transmitters

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[11] Evaluation of optical OFDM signals crosstalk tolerance. Adrià Escolano. TFG ETSETB. 2015.

[12] Investigation on crosstalk tolerance of OFDM optical systems. Ferran Garin. PFC ETSETB. 2015.

7. Appendices (optional):

Crosstalk simulation script:

```
set all "C:/Users/pfc_jgene4/Desktop/Simulacions_X/"
append all "all.txt"
set potencia "C:/Users/pfc_jgene4/Desktop/Simulacions_X/"
append potencia "potencia.txt"
set CROSSTALK "C:/Users/pfc_jgene4/Desktop/Simulacions_X/"
append CROSSTALK "CROSSTALK.txt"
set CHANNEL_ATT "C:/Users/pfc_jgene4/Desktop/Simulacions_X/"
append CHANNEL_ATT "CHANNEL_ATT.txt"
set ATT1 0;
set inc 2
set BER 0
set power 0
set BER_fnd 0

while {$ATT1 <= 40} {
	setstate Attenuator_vtms1 Attenuation $ATT1;
	set Error 1.0
	set MaxATT 80.0
	set MinATT 0.0
	set ATT2 40.0
	while {$Error > 0.05} {
		setstate Attenuator_vtms2 Attenuation $ATT2;
		run 1
		wrapup
		set BER  [statevalue PostValue_vtms2 InputValue];
		if {[expr $BER > 1.0e-3]} {
			set MaxATT $ATT2;
			set ATT2 [expr ($MaxATT + $MinATT)/2];
		}

		if {[expr $BER < 1.0e-3]} {
			set MinATT $ATT2;
			set ATT2 [expr ($MaxATT + $MinATT)/2];
			set BER_fnd 1;
		}

		set Error [expr $MaxATT - $MinATT]
	}

	run 1
	wrapup
	setstate Attenuator_vtms1 Attenuation $ATT1;
	setstate Attenuator_vtms2 Attenuation $ATT2;
	set BER  [statevalue PostValue_vtms2 InputValue];
	set power [statevalue PostValue_vtms1 InputValue];

	set result [open $all a]
	puts $result "---"
	puts $result "---"
	puts $result "Atenuacio 2 (canal) (dB):"
	puts $result $ATT2
	puts $result "Atenuacio 1 (Crosstalk) (dB):"
	puts $result $ATT1
	puts $result "Potencia Optica (dBm):"
	puts $result $power
	puts $result "BER:"
	puts $result $BER
	puts $result "BER trobada:"
```

```
    puts $result $BER_fnd
    puts $result "--"
    puts $result "--"
    close $result

    set result2 [open $potencia a]
    puts $result2 $power
    close $result2

    set result3 [open $CROSSTALK a]
    puts $result3 $ATT1
    close $result3

    set result4 [open $CHANNEL_ATT a]
    puts $result4 $ATT2
    close $result4

    set ATT1 [expr $ATT1 + $inc]
}
```

Figure 24: Crosstalk simulation script

Glossary

TX: Transmitter

INT: Interferer

QAM: Quadrature Amplitude Modulation

I: In-Phase

Q: Quadrature

OFDM: Orthogonal Frequency-Division Multiplexing

CO-OFDM: Coherent Optical OFDM

BER: Bit Error Rate

XT: Crosstalk

ISI: Inter Symbol Interference

OSNR: Optical Signal-to-Noise Ratio

MCM: Multi Carrier Modulation

MCF: Multi-core fiber

RF: Radio Frequency