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NYQUIST MODULATION vs OFDM FOR FIBER-OPTIC COMMUNICATIONS

A Degree Thesis

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Abstract

In nowadays society, the need of fast, reliable communications is growing faster and faster each day. For this reason, there is the need of improving the current communications systems in terms of speed (faster data transmission) and spectral efficiency.

This thesis focus on the study of the Nyquist modulation. This modulation is based on the use of Nyquist pulses conveniently allocated in time in order to make them orthogonal. Due to this fact, in the frequency domain, these pulses are perfectly situated in a finite frequency band. In other words, Nyquist modulation is an Orthogonal Time Division Multiplexing (OTDM) in which the use of Nyquist pulses guarantee that they can perfectly occupy a limited bandwidth in the frequency domain.

The main objective of this thesis is to get results for both an intensity Nyquist modulation and QAM Nyquist modulation and make comparisons between them and with a simple QAM modulation.

Resum

A la societat actual, la necessitat de comunicacions ràpides i fiables esta creixent molt ràpidament. Per aquesta raó, existeix la necessitat de millorar les comunicacions actuals en termes de velocitat i eficiència espectral.

Aquesta tesis es basa en l'estudi de la modulació de Nyquist. Aquesta modulació consisteix en la utilització de polsos de Nyquist convenientment situats en el temps amb l'objectiu de fer que siguin ortogonals entre ells. Al aconseguir col·locar els polsos d'aquesta manera, aconseguim que aquests estiguin perfectament distribuïts ocupant una banda de freqüència limitada. En altres paraules, La modulació de Nyquist és una OTDM (Orthogonal Time División Multiplexing) on la utilització de polsos de Nyquist garanteix que puguin distribuir-se perfectament en un ample de banda limitat.

L'objectiu principal d'aquesta tesis és aconseguir resultats per una modulació d'intensitat utilitzant Nyquist i per una modulació QAM utilitzant Nyquist i poder comparar-les entre elles i amb una modulació QAM simple.

Resumen

En la Sociedad actual, la necesidad de comunicaciones rápidas y fiables está creciendo muy rápidamente. Por esta razón, existe la necesidad de mejorar las comunicaciones actuales en términos de velocidad y eficiencia espectral.

Esta tesis se basa en el estudio de la modulación de Nyquist. Esta modulación consiste en el estudio de pulsos de Nyquist convenientemente separados en el tiempo con el objetivo de hacer que sean ortogonales entre ellos. Al conseguir colocar los pulsos de esta manera, conseguimos que en el dominio frecuencial estos estén perfectamente distribuidos ocupando una banda frecuencial limitada. En otras palabras, la modulación de Nyquist es una OTDM (Orthogonal Time Division Multiplexing) donde la utilización de pulsos de Nyquist consigue que puedan distribuirse perfectamente en un ancho de banda limitado.

El objetivo principal de esta tesis es conseguir resultados para una modulación de intensidad Nyquist y una modulación QAM utilizando Nyquist y poder compararlos entre si y con una modulación QAM simple.



Dedicated to all my dear ones,
thank you for encouraging me and supporting my decisions throughout all these years.



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Table of contents

Abstract.....	1
Resum.....	2
Resumen.....	3
Acknowledgements	5
Revision history and approval record	6
Table of contents	7
List of Figures	9
List of Tables:	11
1. Introduction.....	12
1.1. Thesis Context	12
1.2. State of the art.....	12
1.3. Objectives	12
1.4. Work plan	12
2. State of the art of the technology used or applied in this thesis:.....	14
2.1. OFDM (Orthogonal Frequency Division Multiplexing).....	14
2.1.1. Concept and Definition	14
2.2. Nyquist Modulation	14
2.2.1. Definition and motivation	14
2.2.2. Formal presentation.....	15
2.2.3. Transmitter structure	18
2.2.4. Receiver structure	18
2.2.5. Similarity with OFDM	19
2.3. Nyquist Multiplexing	20
2.3.1. Concept.....	20
2.3.2. Transmitter.....	21
2.3.3. Receiver.....	21
3. Methodology / project development:.....	22
3.1. Introduction	22
3.2. Nyquist Modulation	22
3.2.1. Transmitter.....	22
3.2.2. Receiver.....	24

3.2.3. Roll-Off effect	25
3.3. QAM using Nyquist modulation	27
3.4. Interfering Schematics	30
4. Results.....	31
4.1. Intensity Modulation	31
4.2. QAM Nyquist modulation	32
5. Budget	34
6. Conclusions and future development:	35
Bibliography:	37
7. Appendices.....	38
7.1. Rest of Simulations performed during the project development	38
7.1.1. QAM crosstalk comparison	38
7.1.2. 64QAM crosstalk	38
7.1.3. 16QAM crosstalk	39
7.1.4. 4QAM crosstalk	39
7.2. Simulation scripts	40
7.2.1. Crosstalk simulation script.....	40
7.3. Raised cosine Filter	42
7.4. QAM modulation	43
7.4.1. QAM Transmitter	43
7.4.2. QAM Receiver	44
7.4.3. Formal Presentation	45
7.4.4. Simple QAM schematic	46
Glossary	49

List of Figures

Figure 1: OFDM concept	14
Figure 2: OFDM secondary lobes expansion.....	14
Figure 3: Nyquist modulation time domain	16
Figure 4: Nyquist modulation frequency domain.....	17
Figure 5: Nyquist modulation Transmitter scheme	18
Figure 6: Nyquist modulation receiver scheme	19
Figure 7: Comparison between Nyquist modulation and OFDM	20
Figure 8: Nyquist multiplexing frequency domain	20
Figure 9: Nyquist Multiplexing transmitter scheme	21
Figure 10 : Nyquist Multiplexing receiver scheme	21
Figure 11: Nyquist modulation schematic	22
Figure 12: Electric Nyquist modulation. 4 channels overlapped	23
Figure 13: Electric Nyquist modulation. 4 channels overlapped zoom in	24
Figure 14: Electric Nyquist modulation receiver clock signal.....	25
Figure 15: comparison between transmitted and received signal eye diagram	25
Figure 16: Exemplification of the Roll-off effect	26
Figure 17: Exemplification of the Roll-off effect when affecting bandwidth	26
Figure 18: QAM using Nyquist modulation schematic	27
Figure 19: QAM using Nyquist modulation 4 overlapped channels.....	28
Figure 20: QAM using Nyquist modulation 4 overlapped channels zoom in.....	28
Figure 21: QAM using Nyquist modulation. Eye diagram of the 4 channels	29
Figure 22: QAM using Nyquist modulation. Transmitted and received inphase and quadrature eye diagram	29
Figure 23: Optical Nyquist modulation interfering schematic	30
Figure 24: Optical power vs crosstalk using Intensity modulation with different roll-off effects	31
Figure 25: Optical power vs crosstalk using Intensity modulation different subcarriers ..	32
Figure 26: QAM vs Nyquist QAM comparison	32
Figure 27: Nyquist 16QAM with different QAM order interfering	33
Figure 28: Nyquist 4QAM with different QAM order interfering	33
Figure 29: simple QAM crosstalk comparison	38
Figure 30: simple 64QAM with different order QAM interfering.....	38
Figure 31: simple 16QAM with different order QAM interfering.....	39

Figure 32: simple 4QAM with different order QAM interfering	39
Figure 33: raised-cosine filter	42
Figure 34: raised cosine impulse response.....	43
Figure 35: QAM transmitter	43
Figure 36: M transmitter in the Schematic	44
Figure 37: QAM Receiver	44
Figure 38: QAM Receiver in Schematic	45
Figure 39: QAM transmitter scheme	45
Figure 40: QAM receiver scheme.....	46
Figure 41: QAM schematic	46
Figure 42: QAM transmitted and received inphase and quadrature signals	47
Figure 43: QAM transmitted and received inphase and quadrature eye diagram	48

List of Tables:

Table 1: Gantt Diagram.....	13
Table 2: Budget	34
Table 3: Crosstalk results with different QAM interfering	35

1. Introduction

1.1. Thesis Context

The thesis is inside the research work about modulations that is taking place at the “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. The main objective of this thesis is to follow previously done papers on Nyquist modulation by peers Jonathan Rodríguez Casal and Marc Jubany.

One of the optical communications advantages is its huge bandwidth, allowing systems working under these technologies to offer speed levels up to Tb/s. This aspect makes optical fiber an important communication medium, which can also take advantage of other existing data transmission technologies, such as signal multiplexing performed in OFDM.

It should also be said that optical communications are a relatively new communication method so a lot of technology has still to be developed, as well as a lot of electrical components in optical format.

1.2. State of the art

As previously mentioned before, in the Departament de Teoria del Senyal i Comunicacions, for a couple of years some final degree thesis on this subject, the Nyquist modulation, have been developed and are used as a starting point for this thesis. In addition, after some research, it can be said that Nyquist modulation is a topic in which nowadays there is an important research done, as can be seen in the bibliography part where a couple of articles related to the topic developed in this thesis are named.

1.3. Objectives

The main objectives of this thesis are:

1. Accomplish to be spectral efficient.
2. Take maximum profit of the given bandwidth.
3. Get to take measures of Crosstalk in different scenarios.

In a more personal point of view, my objective is to get to know better how the Nyquist modulation works, how it is its implementation in the optical field and try to better understand QAM modulation, also used in this paper.

1.4. Work plan

No changes were applied on the work packages defined at the beginning of this project. Some modifications to the Gantt diagram were done and were taken into consideration in the Critical Design Review. From that point to the present moment, again, some minor modifications were done, basically due to the fact that some schematics were not working properly and taking results was harder than first expected.

In the Gantt diagram below, in red are when the tasks were firstly planned. In green, the modifications they suffered before the critical design review. Finally, in blue, the last

modifications that the diagram suffered between Critical Design Review and the delivery of this paper.

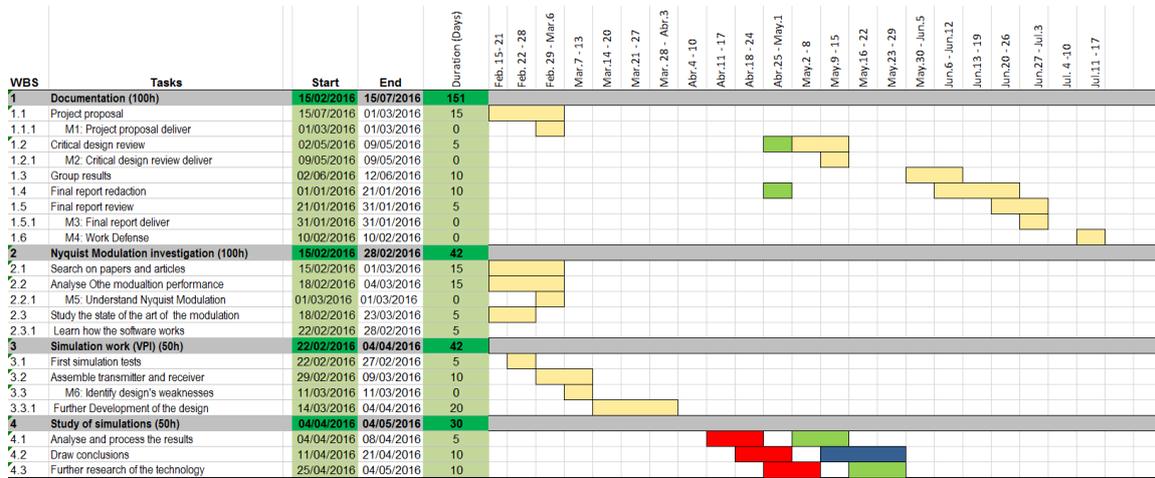


Table 1: Gantt Diagram

2. Background:

2.1. OFDM (Orthogonal Frequency Division Multiplexing)

2.1.1. Concept and Definition

OFDM is one of the most used and popular modulation systems in communications nowadays. It is widely used in different current services like 4G, wireless Networks, digital television...

It is mentioned and briefly explained in this section due to the fact that it keeps a close relationship with Nyquist modulation as it is going to be explained later.

OFDM is a multicarrier transmission system which allows multiplexing a group of symbols in a group of orthogonal subcarriers. The objective is to multiplex N complex symbols in a total bandwidth B .

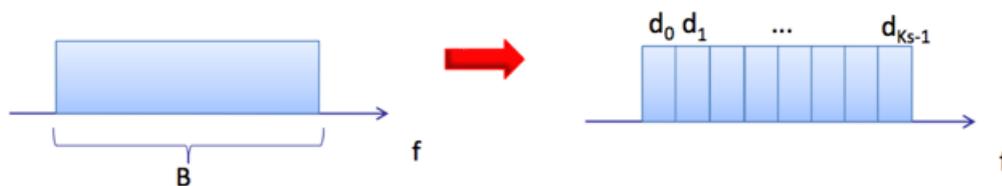


Figure 1: OFDM concept

To do so, the carriers, which are Nyquist pulses, are precisely situated in the frequency domain in order to be orthogonal. However, one problem may appear in OFDM, that is, that the secondary lobes of the Nyquist pulse may affect adjacent frequency channels and generate some spectral inefficiency, as it can be seen in the image below.

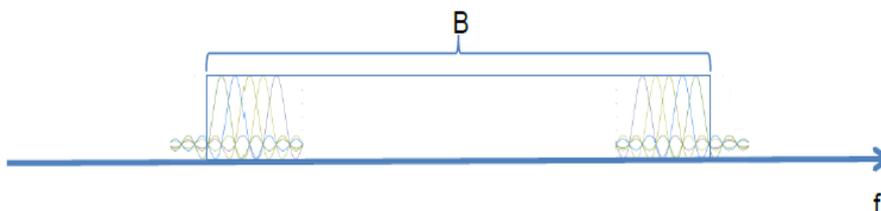


Figure 2: OFDM secondary lobes expansion

2.2. Nyquist Modulation

2.2.1. Definition and motivation

The Nyquist Modulation is a particular case of OFDM in which Nyquist pulses are precisely allocated in the time domain in order to guarantee orthogonality between them

with the objective that all different channels are perfectly distributed in a limited bandwidth in the frequency domain.

There is a real need in optical communications to take maximum advantage of the bandwidth, or in other words, to be spectrally efficient due to the limitations that electrical components have. In addition, as optical communications are a relatively new way of communicating, it is necessary to find a modulation that really is spectral efficient.

For this reason, Nyquist modulation is studied. As can be seen in the OFDM modulation, some interference is produced due to the expansion of the secondary lobes of the sinc function to neighbour frequency bands. Thus, the idea is to move the perfect orthogonal division into the time domain so perfect rectangular channels are found in the frequency domain.

2.2.2. Formal presentation

The main idea of Nyquist modulation is having N complex symbols, $d_0 d_1 d_2 \dots d_N$ and allocate them in time slots of T_s/N , where T_s is the Symbol Time and N is the number of channels. To do so, the main idea is that the signal will be formed by sincs with a main lobule amplitude of $2T_s/N$ and with a separation between them of T_s/N as can be seen in the formula below, where the generic expression for the transmitted signal is presented. The $1/T_s$ is a scaling factor used to have a power value of 1 in the frequency domain. The separation between sincs, as will be explained in this same chapter, is to keep them orthogonal.

$$x(t) = \sum_{l=0}^{N-1} d_{l,0} \frac{N}{T_s} \text{sinc} \left(\frac{t}{\frac{T_s}{N}} \right) * \delta \left(t - l \frac{T_s}{N} \right)$$

In the following image, we can appreciate the time slots representation in the time domain.

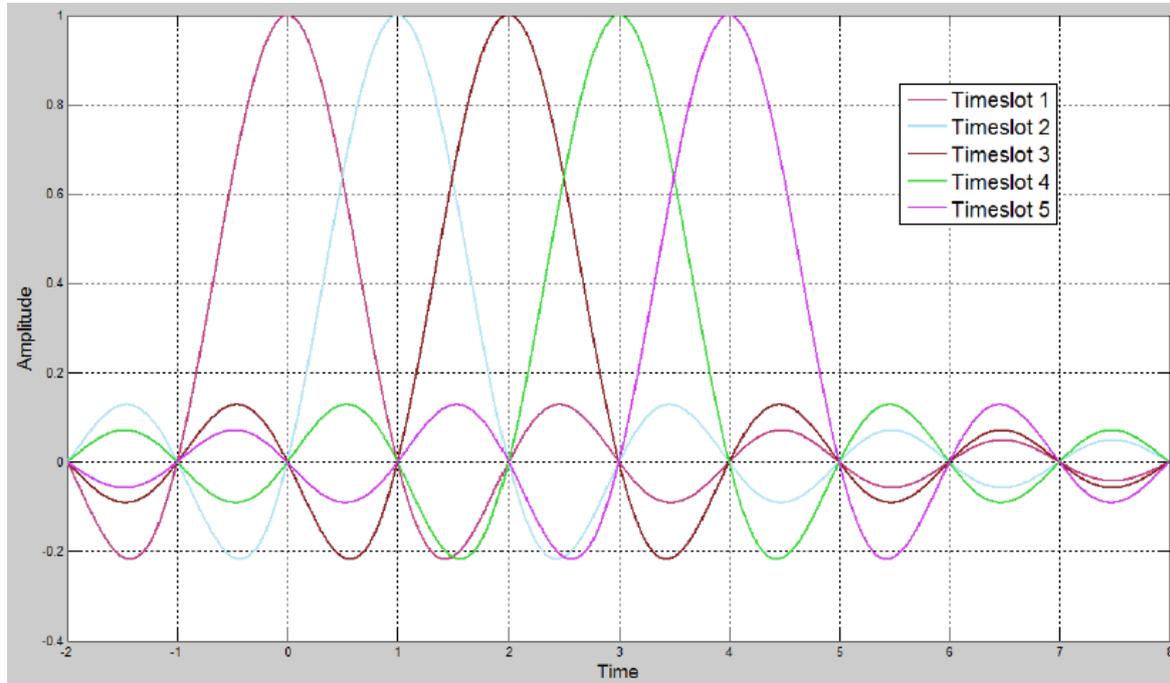


Figure 3: Nyquist modulation time domain

Now, changing into the Frequency domain, by applying fourier Transformation into the Transmitted signal, we can appreciate that the signal is a group of N sinusoids limited into a Bandwidth of $N \cdot F_s$ where $F_s = 1/T_s$ as it can be appreciated in the formula below.

$$X(f) = \sum_{l=0}^{N-1} d_{l,0} \text{rect} \left(\frac{f}{N F_s} \right) e^{-j2\pi l \frac{T_s}{N} f}$$

In the image we can appreciate the sinusoids limited into a bandwidth of $N \cdot F_s$.

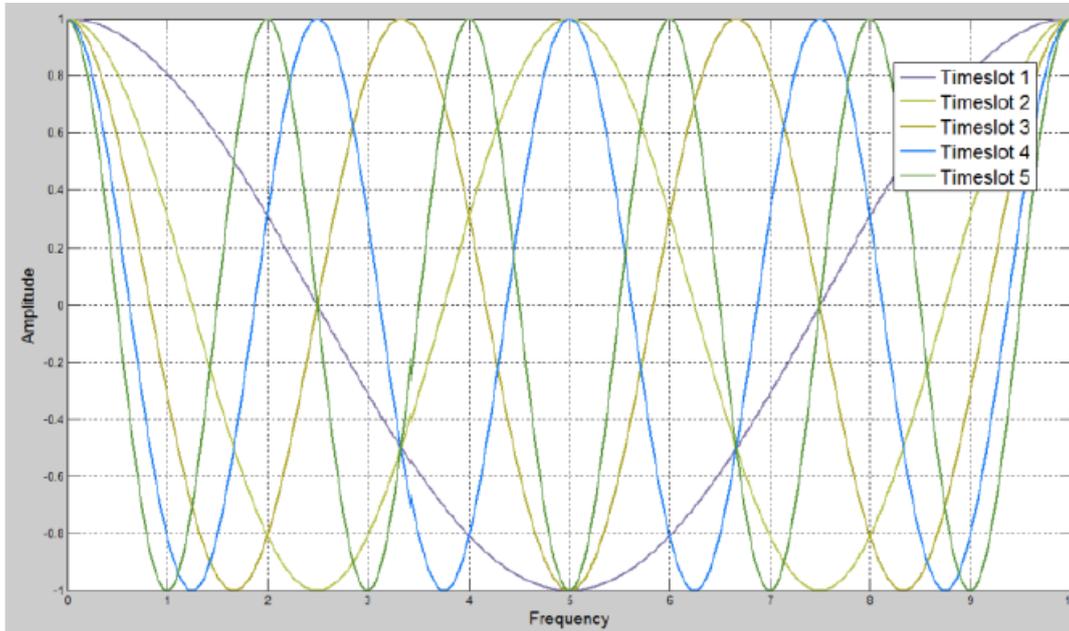


Figure 4: Nyquist modulation frequency domain

A brief explanation on why the Nyquist pulse are orthogonal is going to be presented. First, we are going to introduce generic representations of the Nyquist pulse both in the frequency and time domain.

Frequency domain	Time Domain
$rect\left(\frac{z}{Z}\right) = \begin{cases} 1 & \text{for } z < \frac{Z}{2} \\ 0 & \text{else} \end{cases}, \quad sinc\left(\frac{z}{Z}\right) = \begin{cases} 1 & z = 0 \\ \frac{\sin(\pi z/Z)}{\pi z/Z} & z \neq 0 \end{cases}$	

When calculating the correlation between two generic subcarriers, and after some mathematics done, the result found is that both in the time and frequency domain, the result is a delta, meaning that, when the subcarriers are different, the result is 0, and that when the we are talking about the same subcarrier, the result is 1. As can be seen below.

$$\frac{1}{Z} \int_{-Z/2}^{+Z/2} e^{j2\pi m z/Z} e^{-j2\pi m' z/Z} dz = \delta_{mm'} \quad \text{for } m, m' \in \mathbb{Z}$$

$$\frac{1}{Z} \int_{-\infty}^{+\infty} sinc\left(\frac{z}{Z} - m\right) sinc\left(\frac{z}{Z} - m'\right) dz = \delta_{mm'} \quad \text{for } m, m' \in \mathbb{Z}$$

2.2.3. Transmitter structure

in the Scheme below the structure of a Nyquist transmitter is presented. The idea is the following: we have the generic sinc, with a main lobule of width $2T_s/N$, and in every branch we delay it the correspondent amount of time. Moreover, in every branch, we multiply the Nyquist pulse by the symbol to transmit. Finally, we add all the branches.

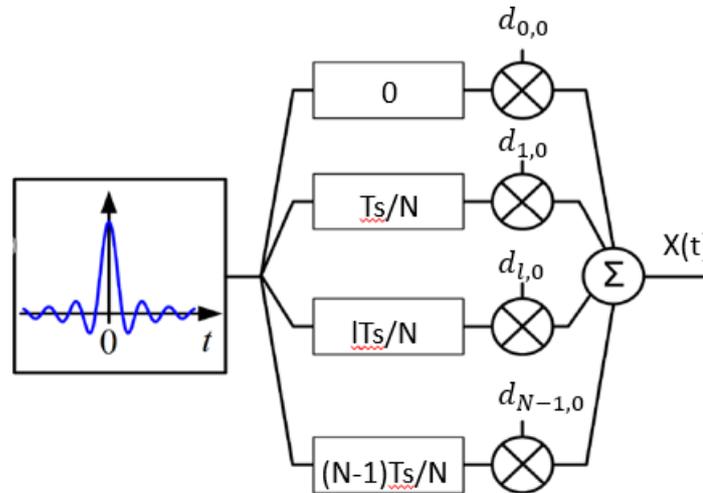


Figure 5: Nyquist modulation Transmitter scheme

Later on in this paper, it is going to be deeply explained how this transmitter was implemented in the actual schematics.

2.2.4. Receiver structure

The same type of explanation as the transmitter is going to be made for the receiver. As it can be seen in the schematic below, first we got the received signal, which in every branch the first thing done is to delay it the same amount of time than in the transmitter, but negative.

In addition, in the receiver, in order to recover the signal, some operations must be done, as can be seen in the following development:

$$X(f) = \left(\text{rect} \left(\frac{T_s}{N} f \right) e^{-j2\pi l \frac{T_s}{N} f} e^{j2\pi k \frac{T_s}{N} f} \right) * H(f) = \frac{T_s}{N} \int_0^{\frac{N}{T_s}} \text{rect} \left(\frac{T_s}{N} f \right) e^{-j2\pi l \frac{T_s}{N} f} e^{j2\pi k \frac{T_s}{N} f} \partial f$$

$$= \frac{T_s}{N} \int_0^{\frac{N}{T_s}} e^{-j2\pi(k-l) \frac{T_s}{N} f} \partial f = d_{l,0}$$

Where $H(f)$ is the expression of the matched filter in the frequency domain:

$$H(F) = \frac{T_s}{N} \text{rect} \left(\frac{T_s}{N} f \right),$$

Doing the inverse DFT we get:

$$x(t) = \frac{N}{T_s} \text{sinc}\left(\frac{t}{T_s/N}\right) * \delta\left(t - k\frac{T_s}{N}\right) * \delta\left(t + l\frac{T_s}{N}\right) \cdot h(t) = \frac{N}{T_s} \text{sinc}\left(\frac{t}{T_s/N}\right) \text{sinc}\left(\frac{t}{T_s/N}\right)$$

Only when $k=l$, the system recovers the original signal. If k is different from l , the signal is delayed a multiple of T_s/N that as explained in the orthogonality part the product of the signal is 0.

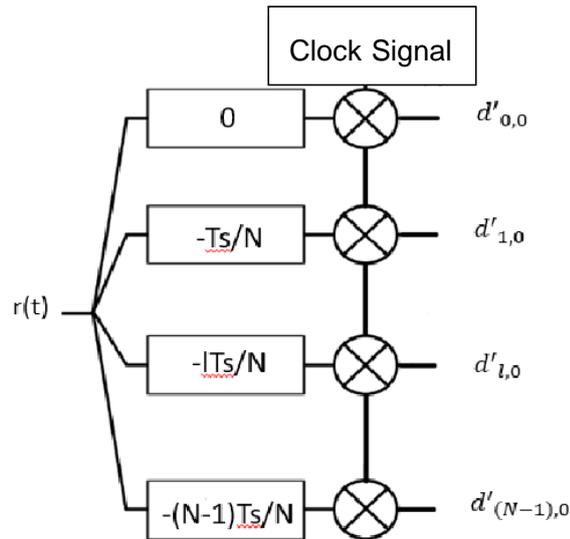


Figure 6: Nyquist modulation receiver scheme

2.2.5. Similarity with OFDM

Nyquist modulation concept has a close correlation with OFDM. Both try to fit Nyquist pulses in a way that they are orthogonal in a domain in order to have a perfect rectangular distribution on the other domain.

As can be seen in the image below, OFDM allocates the Nyquist pulse precisely distributed to keep orthogonality in the frequency domain obtaining a perfect rectangular distribution on the time domain. This is the contrary of what has been explained about Nyquist modulation.

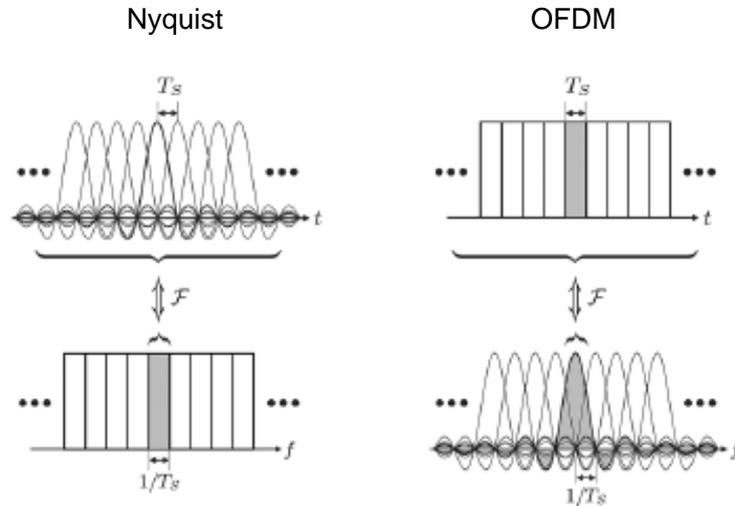


Figure 7: Comparison between Nyquist modulation and OFDM

2.3. Nyquist Multiplexing

2.3.1. Concept

Nyquist Multiplexing consists on sending different data channels at different optical frequencies but in the same time slot. The pulses used in the time domain are sincs so for this reason, as it was seen in previous chapters, they will be rectangular pulses in the frequency domain.

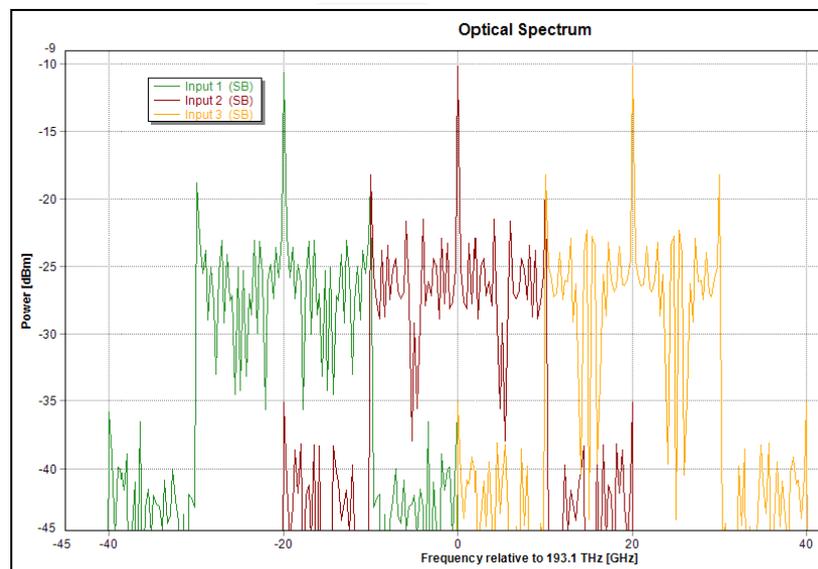


Figure 8: Nyquist multiplexing frequency domain

In the image above it can be seen the different channels in the frequency domain. It is easy to see that they are not overlapped.

2.3.2. Transmitter

In every branch we have a pulse generator that generates pulses every T_s . These pulses have an amplitude of $A = 2T_s/N$. After that, this pulses go through a cosine raised filter that gives them the form of a sinc. Finally, every signal is modulated by a laser into the optical domain and multiplexed with the rest of the branches.

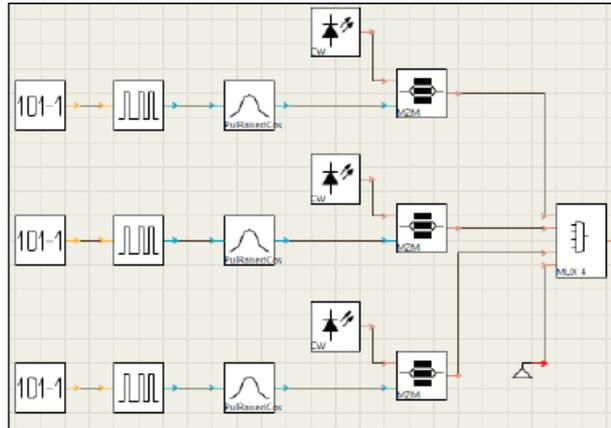


Figure 9: Nyquist Multiplexing transmitter scheme

2.3.3. Receiver

First, we des-multiplex the signal and transform every branch from the optical to the electric domain. Thanks to the de-multiplexer and that the signals of every branch are in different frequencies there is no need for having a recovery clock signal.

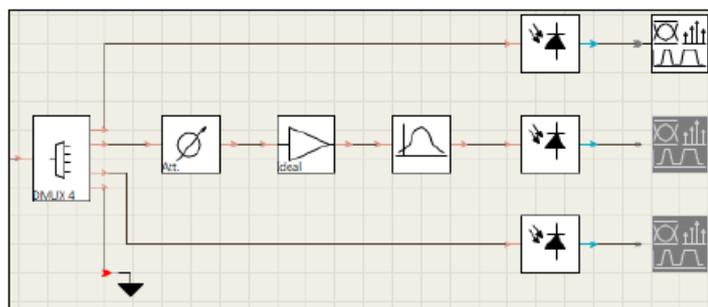


Figure 10 : Nyquist Multiplexing receiver scheme

3. Methodology / project development:

3.1. Introduction

During the development of this paper VPI Transmission Maker, from VPI photonics, was used. VPI is a powerful software that allow us to carry on simulations both in the optical and electrical domain and in different scenarios.

In this thesis, the main point was to observe how Nyquist modulation behaves in the optical world. However, in order to fully understand how the Nyquist modulation works simpler schematics were designed. In this part of the thesis, we are going to present the different schematics used during the process in order to understand Nyquist modulation and the final schematics from where the results were taken. To begin with, a brief explanation on which are the main parameters to bear in mind while using this software is presented.

Firstly, the TimeWindow, sets the period of real time that is represented as a block of data. It also sets the spectral resolution. Secondly, the SampleRateDefault. It used by default in all modules as a sample rate parameter. However, each module can have his own sample rate. Finally, the BitRateDefault, is used by default by all modules as a bit rate parameter. Each module however, can set a different bit rate.

These parameters were set differently depending on if a QAM modulation was used or not. In order to have the same number of symbols when using a QAM modulation or one simpler TimeWindow and SampleRateDefault were multiplied by the number of bits used in that specific modulation.

3.2. Nyquist Modulation

In order to set a start point, the first and simplest module studied was the Nyquist modulation. In this section, we are going to deeply explain how we implemented the different parts of a Nyquist Modulation system that will be used in other schematics in the future. In the image below the VPI schematic can be seen.

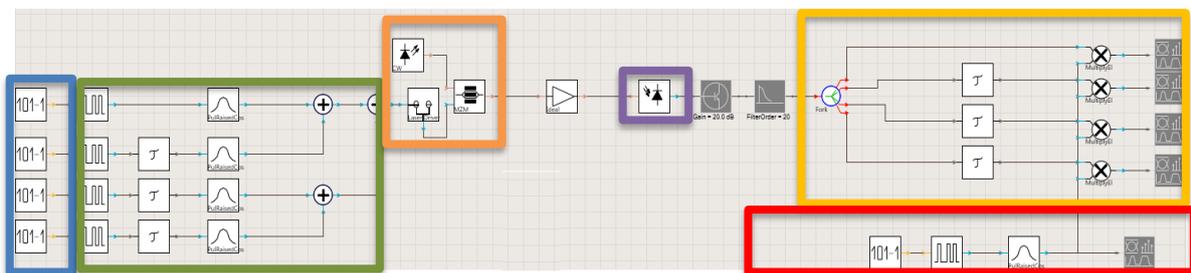


Figure 11: Nyquist modulation schematic

3.2.1. Transmitter

The Transmitter block is formed by the blue and green boxes on the image above. The first module, inside the blue rectangle, is the data transmitter. It generates many types of pseudo random data sequences.

The second box, the green one, is where the Nyquist encoder is set. modules on the left of this box are the coders. These modules generate a sampled RZ (Return to Zero) coded signal defined by a sequence of bits at its input. The next modules are delayers. They delay the signal in order to maintain the orthogonality explained in the second part of this paper. In order to calculate the delay, first we have to know the main lobe width of the Nyquist pulse. For this reason, the next module it is going to be presented. This module generates a Nyquist response from an incoming electrical impulse. Finally, the 4 channels are joined.

In addition, and inside an orange rectangle, the electric-optic step is found. As its name clearly indicates, it transforms the electric signal into optical. It is formed by 3 different modules, consisting on: On the top of the square, a laser, which generates a continuous wave optical signal, connected to a Mach-Zehnder modulator, which modulates in intensity signal light using a simple drive circuit. Finally, a laser driver is added in order to have the electrical signal in the amplitude range where it can be perfectly modulated by the Mach-Zender.

First, we have to set the width of the main lobe. As it can be seen in the schematic, we have four different channels. The main idea of Nyquist modulation is to be capable of fit the 4 channels in the time of bit. The time of bit, T_s , having a bit rate of 10GHz is 100ps. So, in order to fit the 4 channels in 100ps, we have to divide 100ps by 4, resulting $\frac{100ps}{4} = 25ps$. In order to achieve that in the schematic, we set the parameter SymbolRate to $4 * \text{BitRateDefault}$.

Now, it is time to set the delay between the different channels. In order to keep the orthogonality between the channels, the delay has to be equal to the width of the main lobe.

In the image below, we can first see the transmitted signal, with the different sincs overlapped.

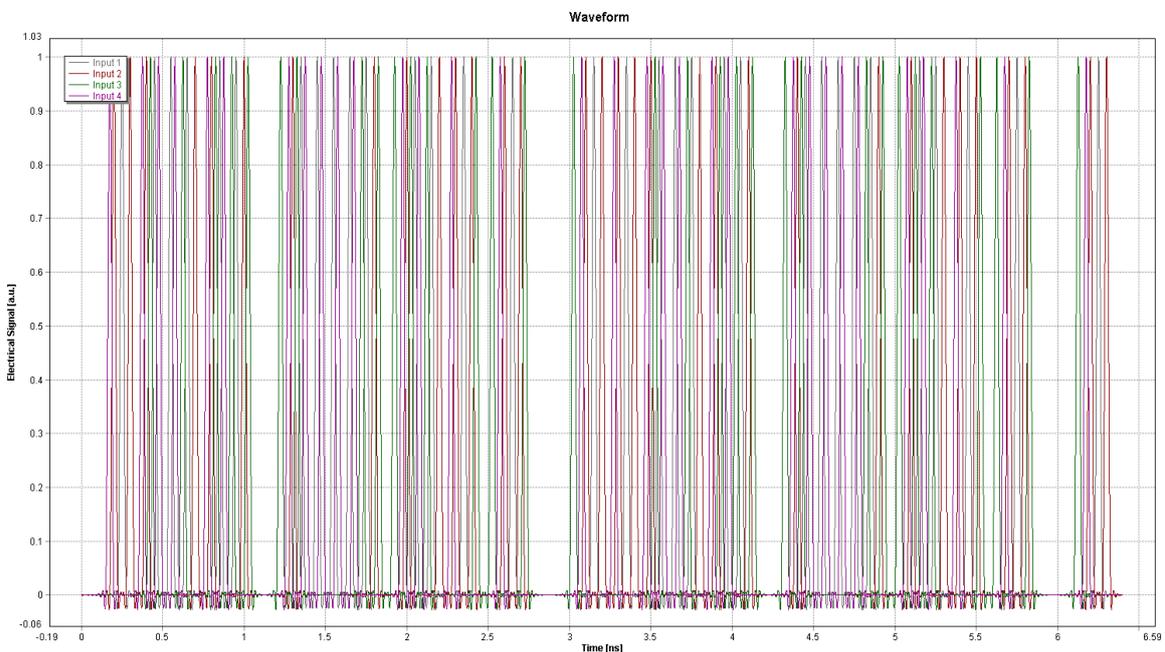


Figure 12: Electric Nyquist modulation. 4 channels overlapped

In the image below, the 4 sincs are perfectly fit in 100ps, between 400ps to 500ps.

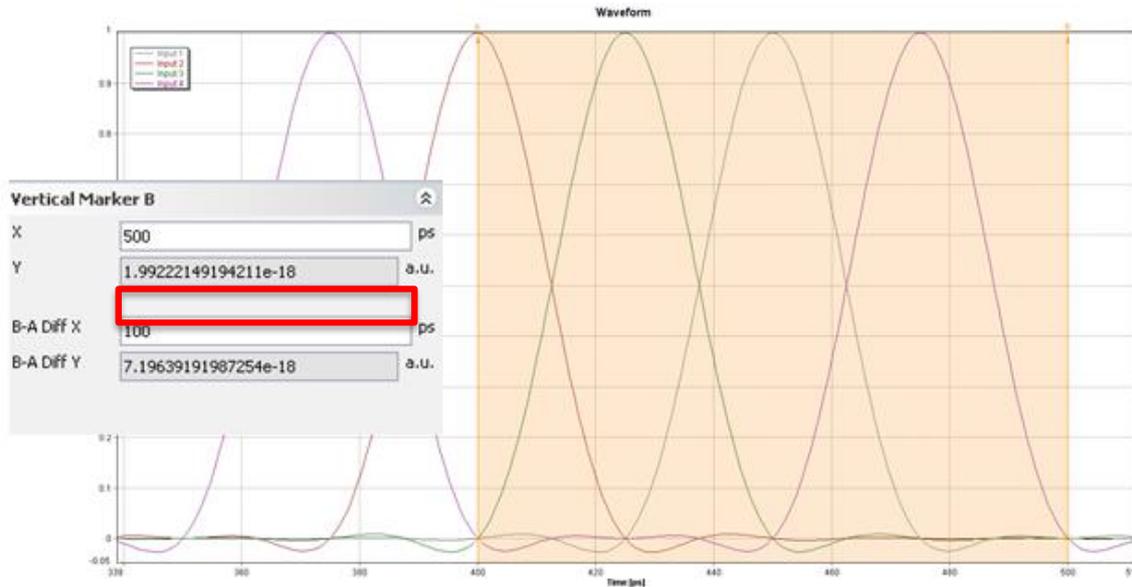


Figure 13: Electric Nyquist modulation. 4 channels overlapped zoom in

3.2.2. Receiver

The first module we find in the receiver's side, inside a purple box, is the optic-electric step. In this version it was the simplest possible, a photodiode, that transforms light into current where the photons are absorbed by the diode.

It is formed by 3 different modules, consisting on: On the top of the square, a laser, which generates a continuous wave optical signal, connected to a Mach-Zehnder modulator, which modulates in intensity signal light using a simple drive circuit. Finally, a laser driver is added in order to have the electrical signal in the amplitude range where it can be perfectly modulated by the Mach-Zender.

The receiver is formed by the red and yellow boxes. The red box conforms the recovery signal clock. The clock signal is a series of Nyquist pulses with a time interval between them of 100ps, the inverse of the bit rate as stated before. This pulses are separated 100 ps in order to recover every signal in every time of bit, as can be seen I the image below.

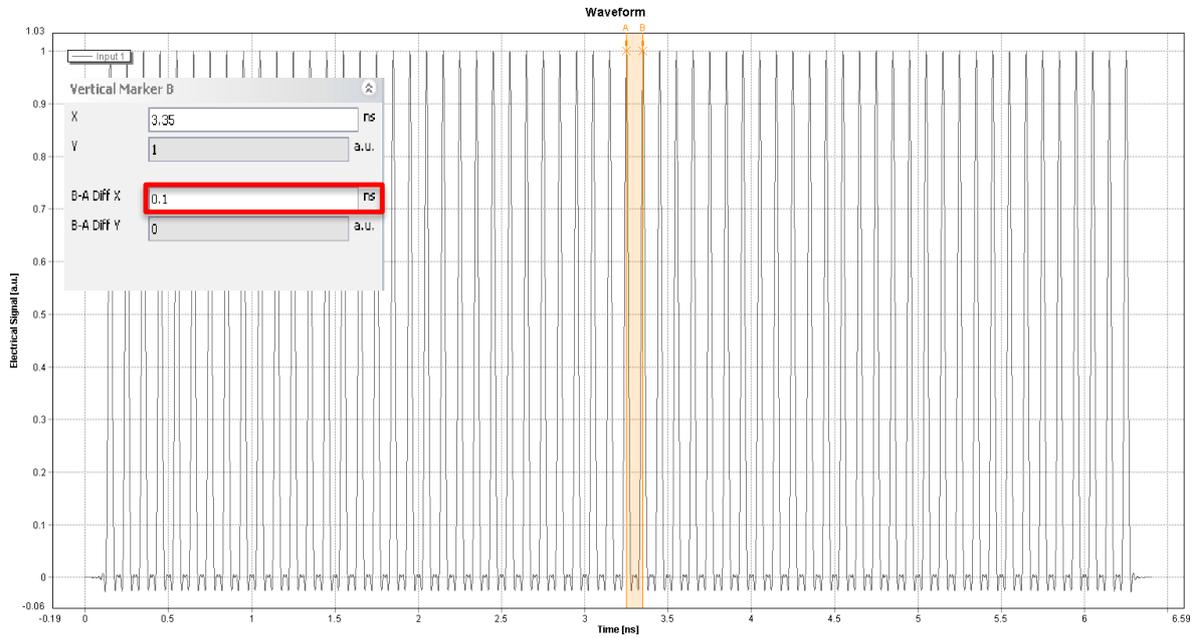


Figure 14: Electric Nyquist modulation receiver clock signal

In order to recover the transmitted signal, every branch of the receiver delays the received signal the same delay that was performed on the transmitter, but with the sign changed. Afterwards, the signal is multiplied by the clock signal and finally we obtain the recovered signal. In the image below it can be observed the transmitted and recovered signal eye diagram. Above, received, below, transmitted.

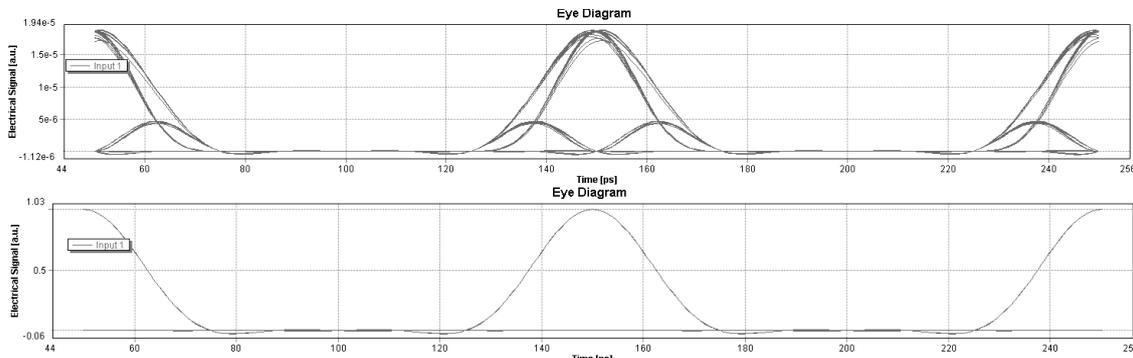


Figure 15: comparison between transmitted and received signal eye diagram

As it can be seen, the signal is almost perfectly recovered, with the appearance of some secondary lobes.

3.2.3. Roll-Off effect

As mentioned in the part 2 of this paper, Nyquist pulses are characterized by the Roll-off factor, as lower it is, more rectangular in the frequency domain it is. However, more secondary lobes appear. In all the simulations until this point the Roll-off was set to 1, as it can be seen by the absence of almost any secondary lobe in the transmitted signal. A comparison both in the time and frequency domain is going to be done.

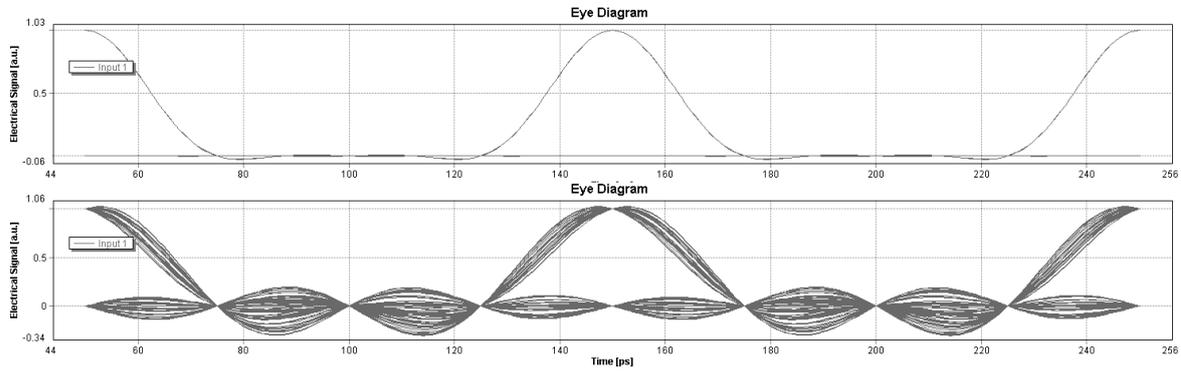


Figure 16: Exemplification of the Roll-off effect

In the image above, the same signal with different roll-off factor is depicted. In the first image, the roll off factor is 1, while in the second one is 0. As mentioned before, when the roll of is lower, more secondary lobes appear.

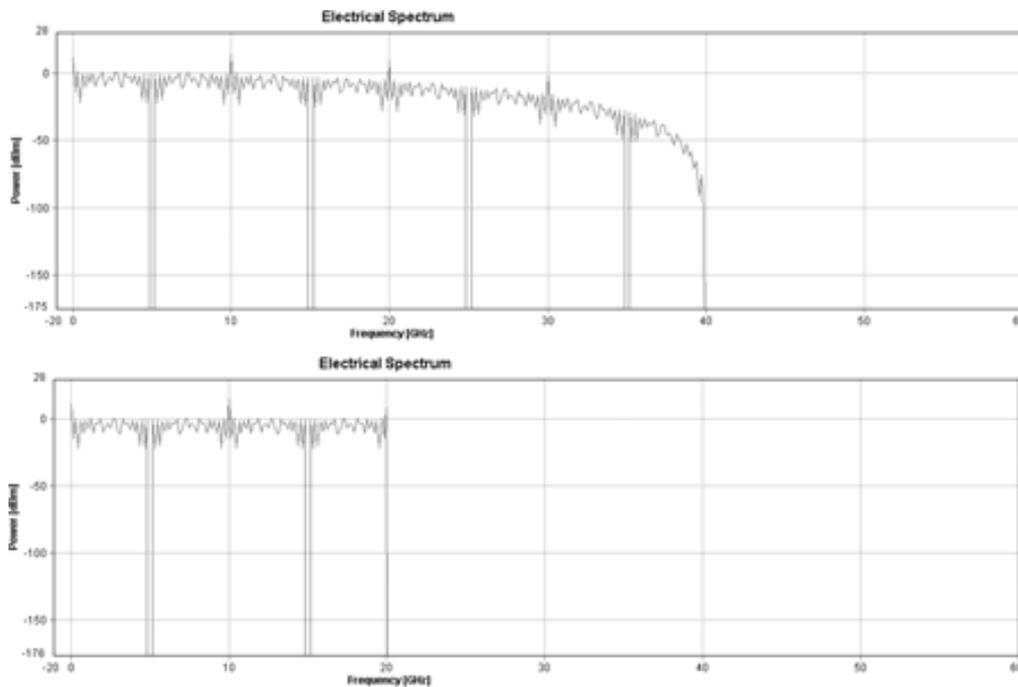


Figure 17: Exemplification of the Roll-off effect when affecting bandwidth

Like in the previous image, the first graphic shows the signal with a roll-off factor of 1, while in the second one, the roll-off factor is 0. With a roll-off factor of 1, it can be seen that the bandwidth is way more spread, arriving almost to 40GHz, while when the roll off is 0, the bandwidth abruptly falls at 20GHz. For this reason, it is said that the roll-off factor measures the excess of bandwidth beyond the Nyquist bandwidth.

3.3. QAM using Nyquist modulation

In this schematic, we mix the QAM concept with the Nyquist modulation. We gather all the elements explained in previous sections and conform a schematic that uses both concepts as it can be seen in the image below.

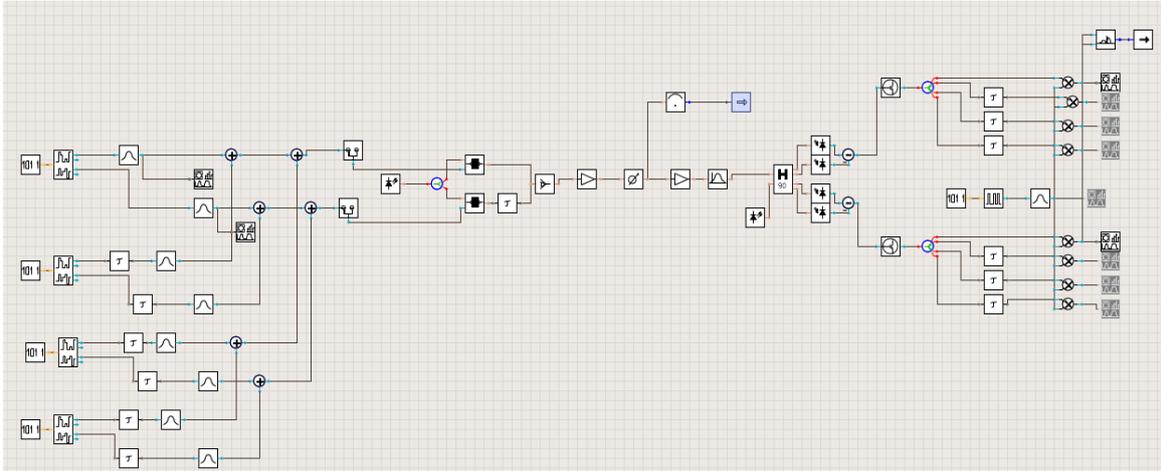


Figure 18: QAM using Nyquist modulation schematic

On the left side, 4 QAM signals generators, each one generating a 16QAM signal. Then, each one of the QAM signals is modulated like explained before using Nyquist modulation. Then the electric-optic step explained in the QAM section can be seen. Afterwards, the modules used to simulate the noise of the receiver and used in the simulation scripts are found. Finally, the QAM receiver with the opto-electric step and the Nyquist receiver are found, doing the same process in both the inphase and quadrature branches.

First, we are going to talk about the main parameters we set in order to have this schematic working properly. First off all, and in order to have the same number of symbols than in the previous studied schematics, and due to the fact that we are using a modulation that uses more bits per symbol, in the studied case, 4, because we are using a 16 QAM modulation. For this reason, the time window and the SampleRateDefault has been multiplied by four, resulting:

- TimeWindow: $128 \cdot \text{BitsperSimbol} / \text{BitRateDefault}$
- SampleRateDefault: $\text{BitsperSimbol} \cdot 16 \cdot \text{BitRateDefault}$
- BitRate: 10GHz

Where BitperSimbol is a changeable parameter depending on the QAM used, in this case, 4.

Firstly, we are going to observe the 4 QAM signals overlapped after going through the Nyquist modulation elements.

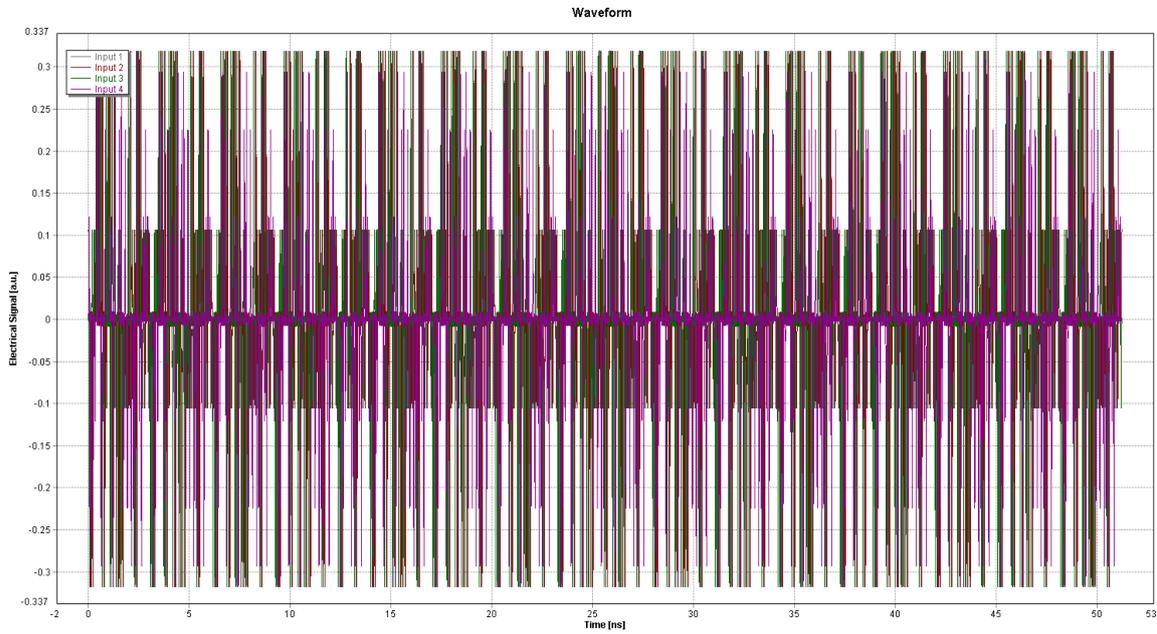


Figure 19: QAM using Nyquist modulation 4 overlapped channels

When doing a zoom in:

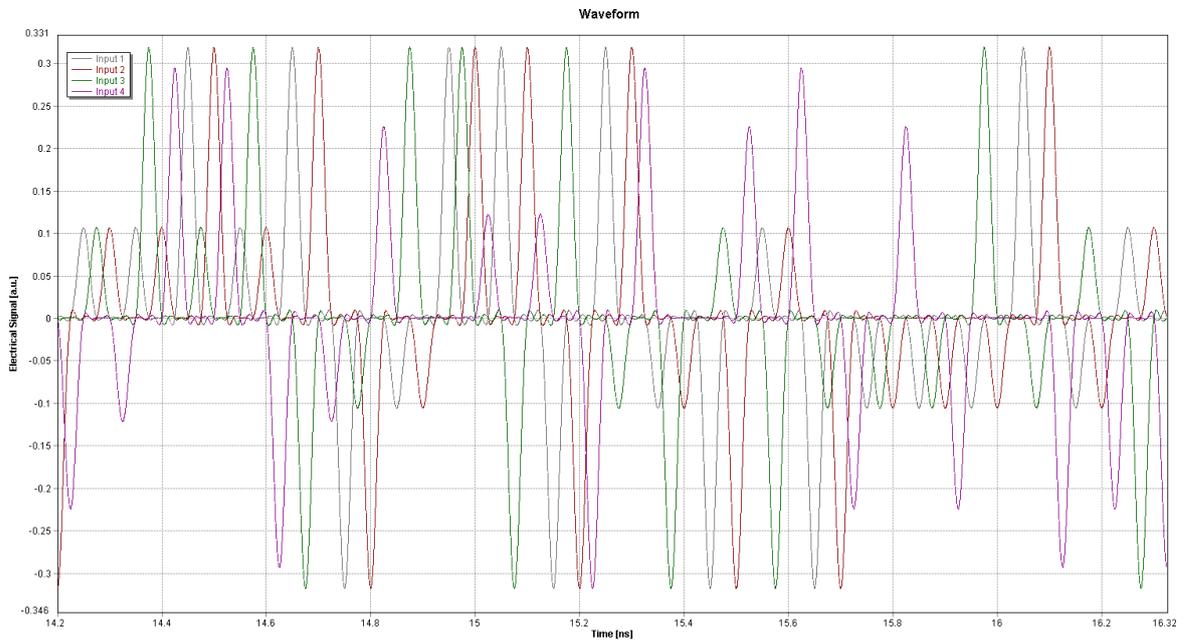


Figure 20: QAM using Nyquist modulation 4 overlapped channels zoom in

As it can be seen in the image, the sincs pulses are correctly synchronized. In addition, the 4 levels of the 16 QAM modulation can be observed. To better observe this situation, we are going to analyse the eye diagram.

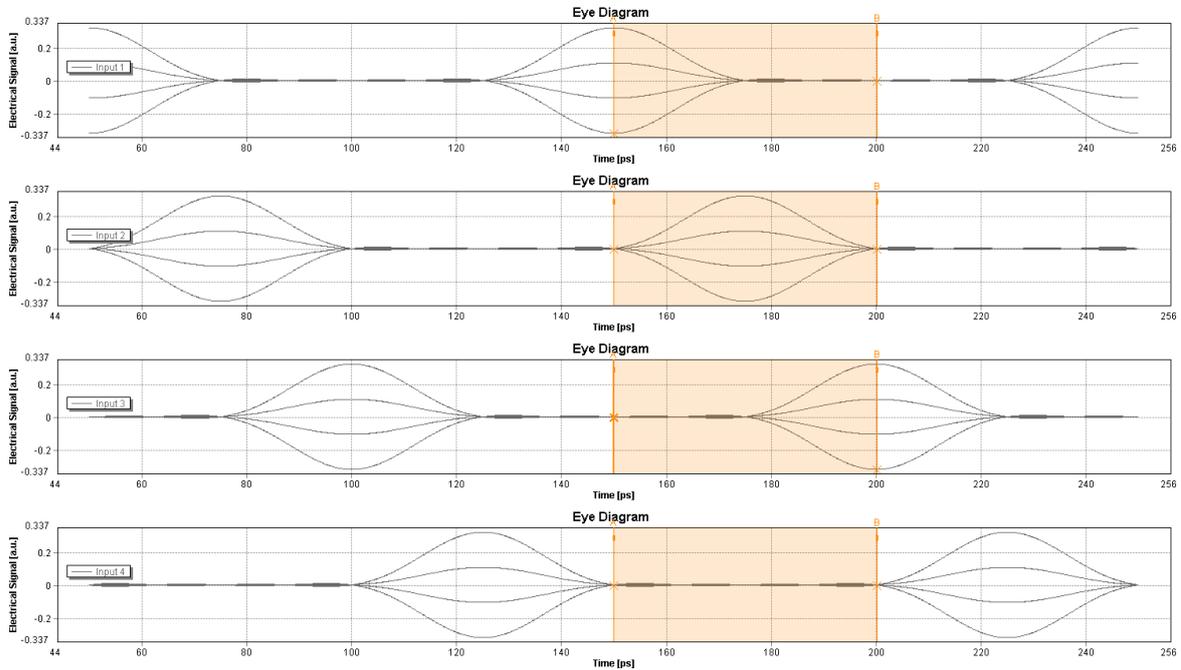


Figure 21: QAM using Nyquist modulation. Eye diagram of the 4 channels

As it can be seen, the four levels are easy distinguishable. In addition, it can be seen that the maximums of the signals are aligned with the 0 and beginning of the following one.

Finally, we are going to compare the inphase and the quadrature of one of our QAM modulations in the transmitter side and in the receiver side.

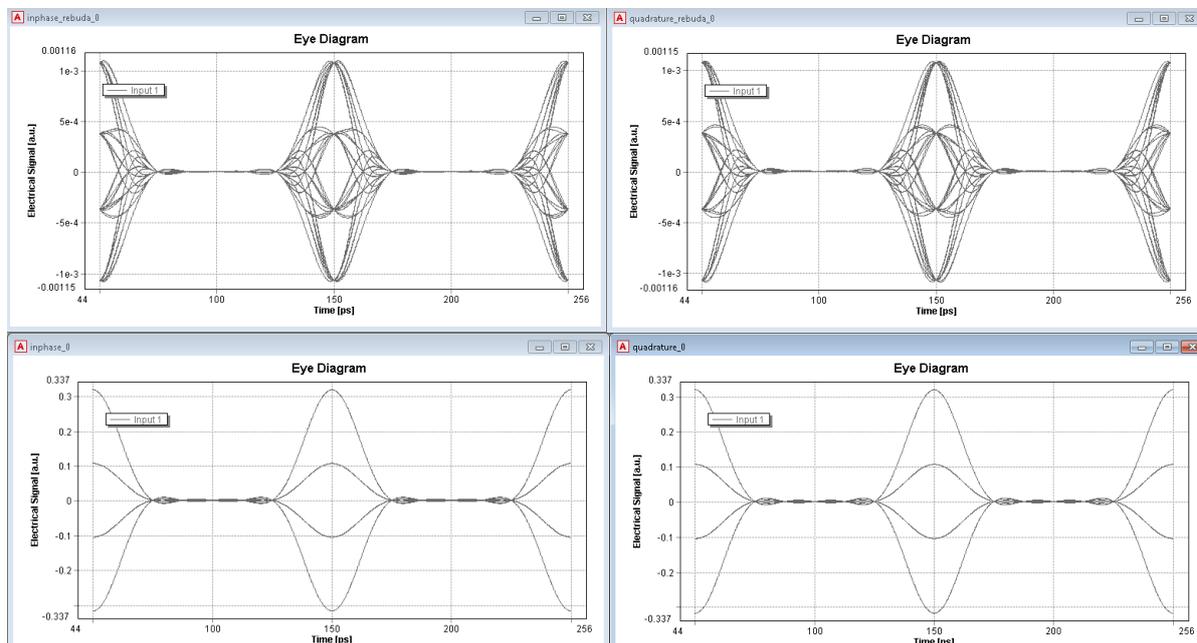


Figure 22: QAM using Nyquist modulation. Transmitted and received inphase and quadrature eye diagram

Down we have the transmitted inphase and quadrature respectively. On the top, the received ones. As it can be seen, the received signals are not as perfect as on the

transmission side, However, in the important points, the ones in the middle, the 4 levels are perfectly distinguished.

3.4. Interfering Schematics

All the previous presented schematics were leading into this point where the crosstalk is going to be calculated. To do that, a complete module is included in the schematics working as an interfering signal as it can be seen in the image, inside a blue box.

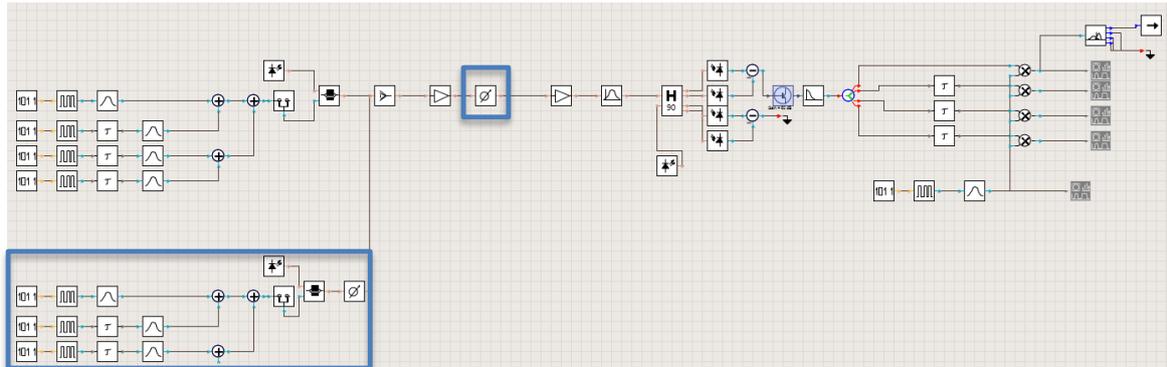


Figure 23: Optical Nyquist modulation interfering schematic

In addition, inside the blue box, an attenuator can be seen. This is used to simulate the crosstalk. The power in both branches is the same due to the fact that they are basically equal, meaning that the seeds in the PRBS are different. So, we will be capable of attenuating the interfering signal and with a script calculate the power necessary to have a BER of 10^{-3} for different attenuations.

Furthermore, in case of not having the same power on both branches, for example, having different QAM modulations, and to properly calculate the crosstalk, an amplifier can be added limiting the power at his output in order to have the same power in both branches and precisely calculate the crosstalk.

4. Results

In this section, the results obtained after using some simulation scripts in order to obtain crosstalk results between different type of modulations are going to be presented.

The simulation script used to calculate the crosstalk level can be found in the appendices. However, a brief explanation of its functionality is going to be made. The simulation reduces or increases the attenuation of the attenuator in the middle of the optical signal (inside a blue square in image 34) depending if the BER is over 10^{-3} . Each step, this change on the attenuation gets smaller until reaching a pre-set point. This process is developed for every crosstalk level.

4.1. Intensity Modulation

To begin with, the previous presented schematic of the optic Nyquist modulation is going to be interfered by the same type of schematic, as it can be seen in figure 23. In the graphic below, it can be seen for every crosstalk level, the sensitivity. In other words, which power level do we need in order to have a BER under 10^{-3} for every crosstalk level. In addition, for different roll-off factors a trace in the graphic is presented. In this simulation, the number of subcarriers is 4. The power for both, the main and interfering signal was set by and amplifier to 0dB. The crosstalk measures the difference between the main signal, always set to 0dB, and the signal interfering which is attenuated.

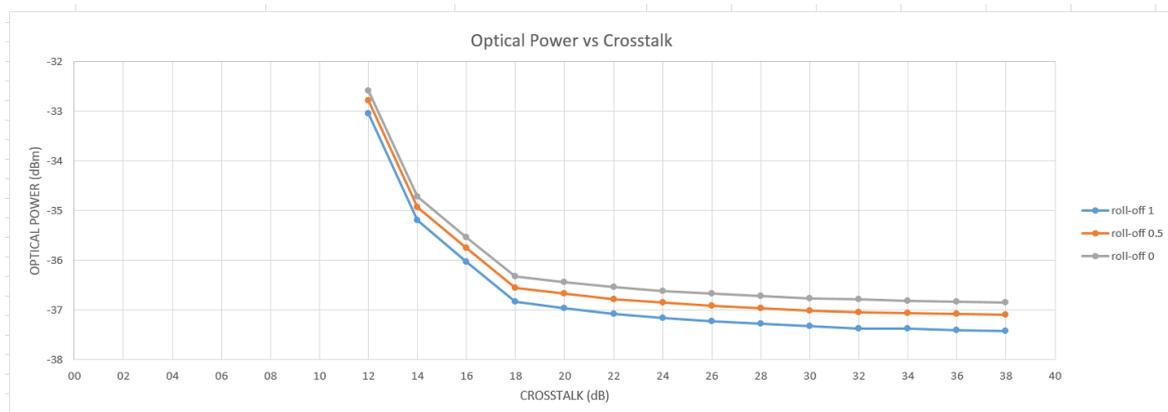


Figure 24: Optical power vs crosstalk using Intensity modulation with different roll-off effects

As it can be seen, for high crosstalk levels, the optical power needed is pretty stable, around -37.4dBm. if we set a penalty of 2dB, we can see that approximately -35dBm of power are achieved when we have a crosstalk of 14dBm. For this reason, it can be said that the system has a crosstalk toleration of 14dB. Under that point, the power needed to achieve a BER under 10^{-3} increases really fast until a point where no matter no matter how much the power is increased, the BER will not go under 10^{-3} .

In addition, it can be seen that for the different Roll-off factors, the behaviour of the system is really similar. When the roll-off increases, the absolute sensitivity increases and the Roll-off tolerance remains the same.

Finally, it is going to be observed how the number of subcarriers affect the Crosstalk in the intensity modulation scenario. In the image below, the same scenario is depicted for 4, 8 and 16 subcarriers.

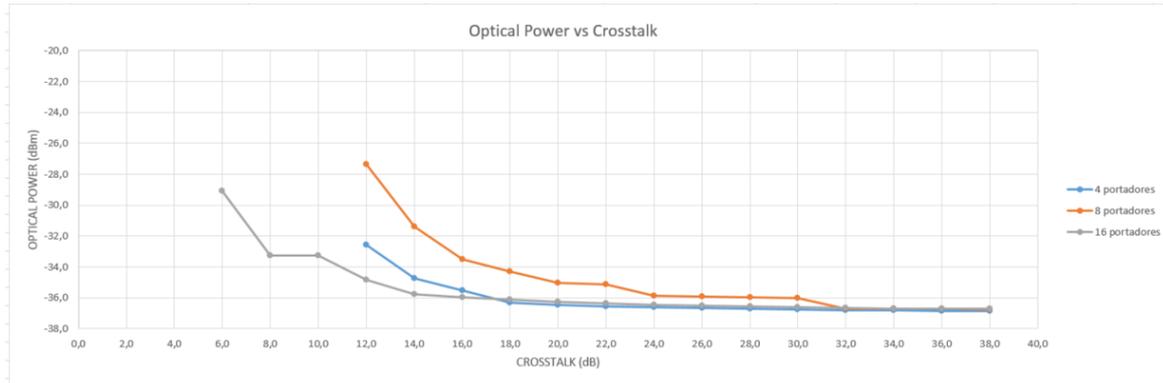


Figure 25: Optical power vs crosstalk using Intensity modulation different subcarriers

The system works in a very similar way for both the 16 and 4 subcarriers scenarios. Having both a crosstalk tolerance of 14dB. However, or the 8 subcarrier one, the crosstalk tolerance is worse as can be seen in the image, around 18dB.

4.2. QAM Nyquist modulation

In this section, we are going to compare the 16QAM Nyquist modulation with the 4 QAM Nyquist modulation. In addition, we are going to compare the results of the Nyquist modulation with the results of the QAM modulation.

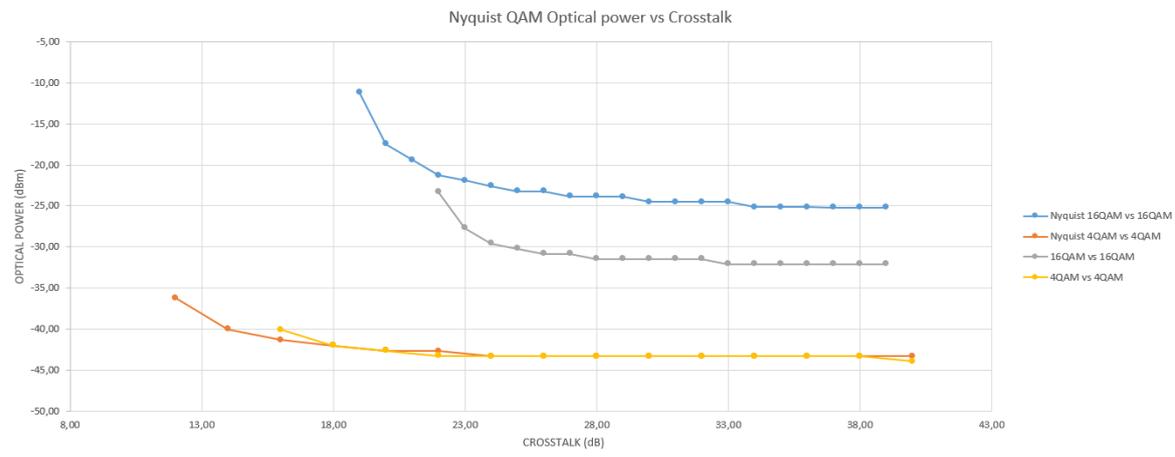


Figure 26: QAM vs Nyquist QAM comparison

As with the intensity modulation, we can observe the sensitivity for different levels of crosstalk. The blue one, representing the 16QAM Nyquist modulation with 16QAM Nyquist modulation interfering. The power needed is around -25dBm. As did before, setting a 2dB penalty, we have a power of -23dBm around 25dB. We can state that the crosstalk tolerance is 25dB. On the other hand, the grey one represents the simple 16QAM with a simple 16QAM interfering. As it can be seen, the level of sensitivity needed is around 8dB lower. However, in terms of crosstalk, both schematics behave in a similar way, Having for the simple 16QAM also a Crosstalk tolerance of 25dB.

For the 4QAM Nyquist modulation case, it can be seen that the power needed is really inferior compared to the 16QAM case, around -43dBm. As we have been doing, setting A 2dB penalty, we find that the crosstalk tolerance is 16dB. In addition, the simple 4QAM case behaves both in sensitivity and crosstalk terms in a very similar way as the Nyquist modulation case. In this case, we have a crosstalk tolerance of 15dB.

Furthermore, another comparison is going to be made. Until this point, we were comparing two signals with the same type of modulation. Now, we are going to compare how different modulations affect crosstalk.

In this first graphic, we are going to compare how the 16QAM Nyquist modulation is affected by a 16QAM Nyquist modulation, a 4QAM Nyquist modulation and an intensity modulation.

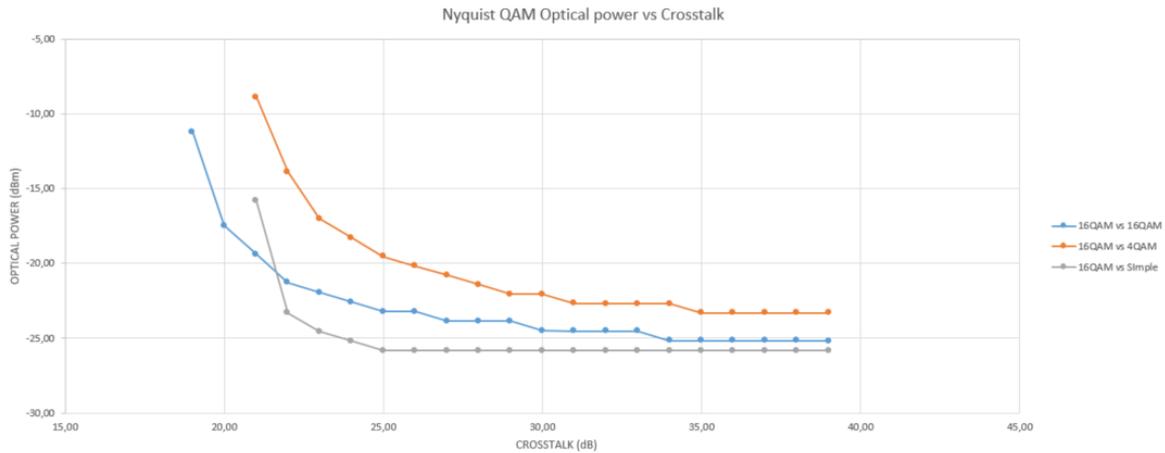


Figure 27: Nyquist 16QAM with different QAM order interfering

As it can be seen, the one having a better crosstalk tolerance is when the 16QAM is interfering, of 26dBm, and the worst one, the 4QAM, with 28dBm. For the 4QAM Nyquist modulation, which graphic can be seen below, the one with the best crosstalk tolerance is when the 4QAM is interfering.

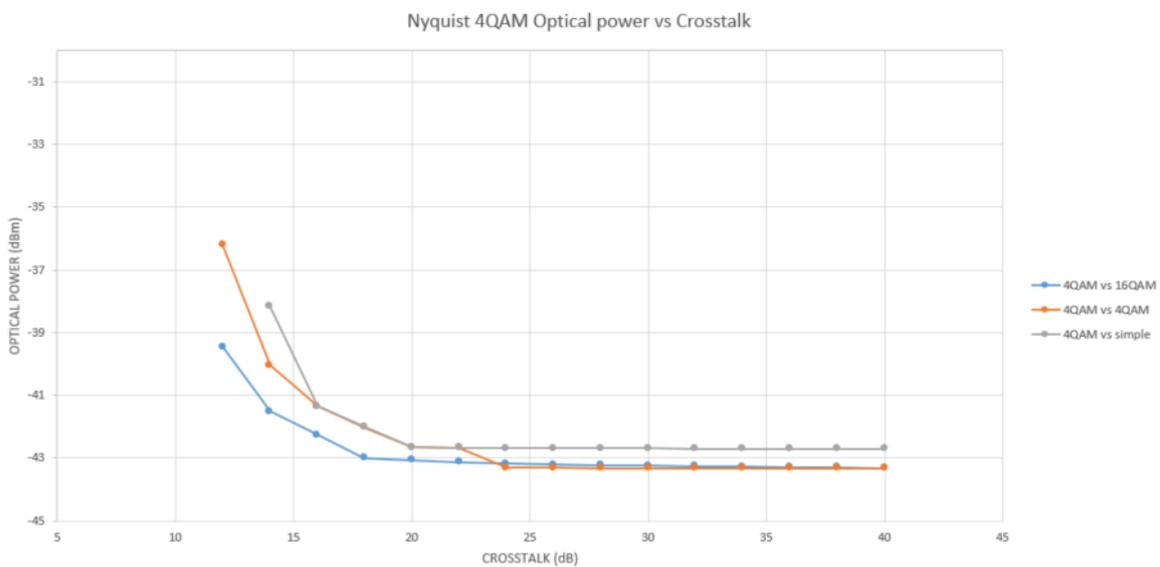


Figure 28: Nyquist 4QAM with different QAM order interfering

5. Budget

PROJECT COSTS				
CONCEPT	DETAIL	NUMBER OF HOURS	COST/HOUR	FINAL COST
Documentation (redaction and review)	Project Proposal	10	8 €	80 €
	Critical Design Review	20	8 €	160 €
	Group results	10	8 €	80 €
	Final Report	40	8 €	320 €
	Final presentation	15	8 €	120 €
Nyquist Modulation Investigation	Documentation about the topic	20	8 €	160 €
	State of the art	15	8 €	120 €
	Nyquist modulation performance	10	8 €	80 €
	Learning about software	20	8 €	160 €
Simulation Programming	First simulation test	15	8 €	120 €
	Transmitter/receiver assemble	40	8 €	320 €
	pass to optical domain	20	8 €	160 €
	writing simulation scripts	20	8 €	160 €
Software	Software license			150 €
Study of simulations	Analyze results	30	8 €	240 €
	Draw conclusions	15	8 €	120 €
	Further research	15	8 €	120 €
TOTAL		315		2.670 €

Table 2: Budget

6. Conclusions and future development:

As a conclusion for this project, we are able to say that we were capable of having a model for the Nyquist modulation working properly in the electric and optical domain, and we were able to take results about its BER also when having another module of the same characteristics interfering. In this case, we were able to observe that the Crosstalk really is a factor to have into consideration.

For different roll-off levels, the crosstalk tolerance of the system was constant, of 14dB although the absolute sensitivity varied as the roll-off decreases. Also, the number of subcarriers was changed in order to see how it affected the crosstalk. However, no conclusive results were obtained.

In addition, we were capable of having a model for a QAM modulation, and capable of guaranteeing its correct functionality by observing the transmitted and received signals. Furthermore, A Nyquist modulation using QAM was properly developed, and its transmitted and received signals correctly observed.

Comparing the simple QAM and the Nyquist QAM, for the 4QAM case the sensitivity was identical. However, when comparing for the 16QAM, for the Nyquist version the sensitivity was of -25dBm and in the simple version -32dBm.

In addition, we arrive into the conclusion that as we lower the QAM order, the less power needed in order to have a BER under 10^{-3} for both the simple QAM and the Nyquist QAM. Furthermore, measures of different signals interfering where taken. In the table below, those crosstalk results can be seen.

<u>MAIN MODULATION</u>	<u>INTERFERING MODULATION</u>	<u>CROSSTALK TOLERANCE</u>
16QAM Nyquist	16QAM Nyquist	25dB
16QAM Nyquist	4QAM Nyquist	28dB
16QAM Nyquist	Intensity modulation	22dB
4QAM Nyquist	16QAM Nyquist	14dB
4QAM Nyquist	4QAM Nyquist	14dB
4QAM Nyquist	Intensity modulation	16dB

Table 3: Crosstalk results with different QAM interfering

It can be observed that when using the same QAM modulation both in the transmitted and interfering signals, the crosstalk tolerance is better than when using another QAM order modulation.

Comparing Nyquist modulation with OFDM transmission systems we find the advantage that there is no need of doing FFT (Fast Fourier Transform), that allow us to multiplex dis-multiplex the signal in middle steps of the transmission.

After seeing these results, we can guess what the following steps could be. We could, for example, adding optical fiber between the transmitter and the receiver. It would be interesting to observe the tolerance to dispersion and non-lineal effects and how it affects crosstalk. In addition, it can be studied how affects changing the relative phase between the main and interfering signal.



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. It could be interesting to see how a desynchronization between the clock and the transmitter would affect. In addition, in a realistic system, the length of the Nyquist pulses should be limited, not like in an ideal environment, where the longer those pulses are, the better.

Bibliography:

- [1] Alba Pagès, ICOM. Chapter III.2: IQ modulation and coherent demodulation.
- [2] Gregori Vazquez, CDA. Chapter 3: Frequency selective channels.
- [3] Joan M. Gené, TC. Chapter 5: Optical Receivers.
- [4] Joan M. Gené, TC. Chapter 4: Optical Transmitters.
- [5] Alba Pagès, ICOM. Chapter III.2: IQ modulation and coherent demodulation.
- [6] Joan M. Gené, Optical Fiber Communications. Coherent detection.
- [7] Evaluation of optical OFDM signals crosstalk Tolerance. Adrià Escolano Beltran
- [8] Investigation on Nyquist Modulation for Fiber-Optic Communications, Jonathan Casal Rodríguez
- [9] Investigation on Nyquist Modulation and Multiplexing for Fiber Optic Communications, Marc Jubany Ticó
- [10] Real-time Nyquist pulse generation beyond 100 Gbit/s and its relation to OFDMR. Schmogrow, M. Winter, M. Meyer, D. Hillerkuss, S. Wolf, B. Baeuerle, A. Ludwig, B. Nebendahl, S. Ben-Ezra, J. Meyer, M. Dreschmann, M. Huebner, J. Becker, C. Koos, W. Freude, and J. Leuthold
- [11] Performance Comparison of single-sideband Direct Detection Nyquist-subcarrier Modulation and OFDM. M. Sezer Erkilinc, Stephan Pachnicke, Helmut Griesser, Benn C. Thomsen, Polina Bayvel, and Robert I. Killey
- [12] Spectrally efficient WDM Nyquist pulse-shaped Subcarrier Modulation Using a Dual-Drive ma
- [13] Signal-signal beat interference cancellation in spectrally-efficient WDM direct-detection Nyquist-pulse-shaped 16-QAM subcarrier modulation. Zhe Li, M. Sezer. Erkilinc, Stephan Pachnicke, Helmut Griesser, Rachid Bouziane, Benn C. Thomsen, Polina Bayvel, and Robert I. Killey

7. Appendices

7.1. Rest of Simulations performed during the project development

7.1.1. QAM crosstalk comparison

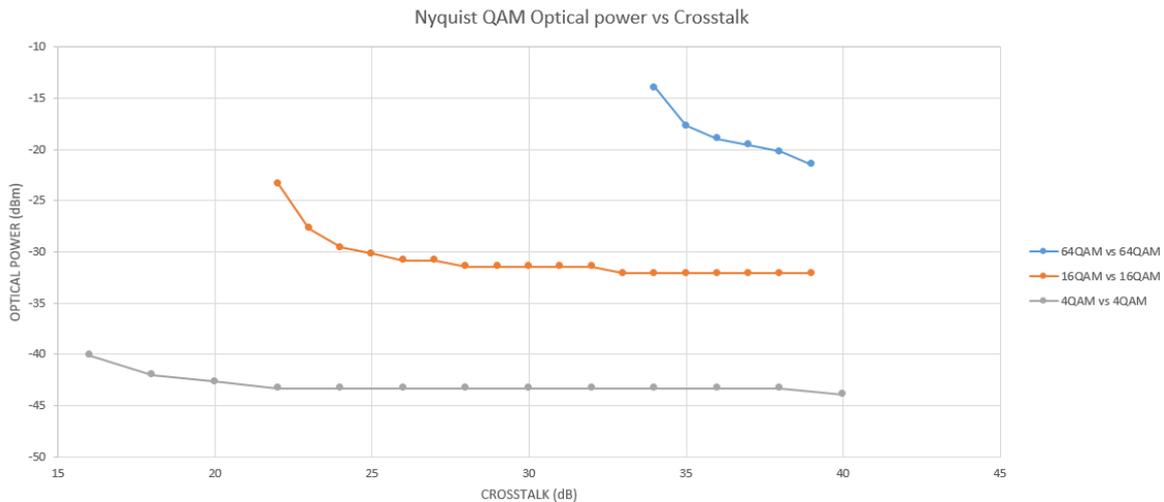


Figure 29: simple QAM crosstalk comparison

In this graphic, we can see the comparison between the 64QAM, the 16QAM and the 4QAM. The power needed for a BER of 10^{-3} decreases with the order of the modulation. For the 4QAM we need a power around -43dBm, for the 16QAM a power around -32dBm and for 64QAM a power around -21dBm

7.1.2. 64QAM crosstalk

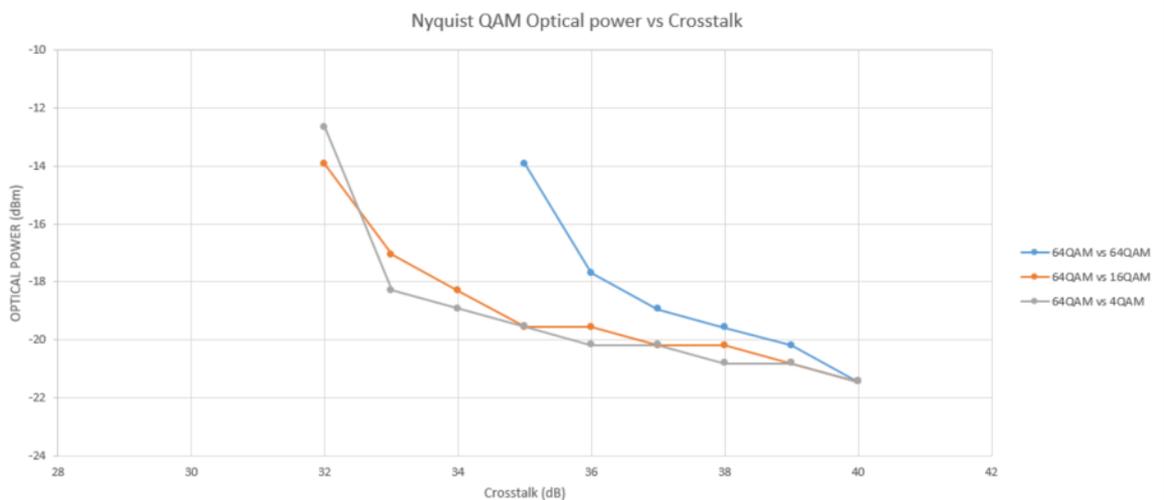


Figure 30: simple 64QAM with different order QAM interfering

In this case, we are transmitting a 64QAM signal, with different signals interfering, 64QAM, 16QAM and 4QAM. As it can be seen, the power needed is around -21dBm with a crosstalk of 40dB. After that point, it quickly increases the power needed to have a BER under 10^{-3} until reaching the point around -32dB crosstalk where it is impossible to have a BER under that limit.

7.1.3. 16QAM crosstalk

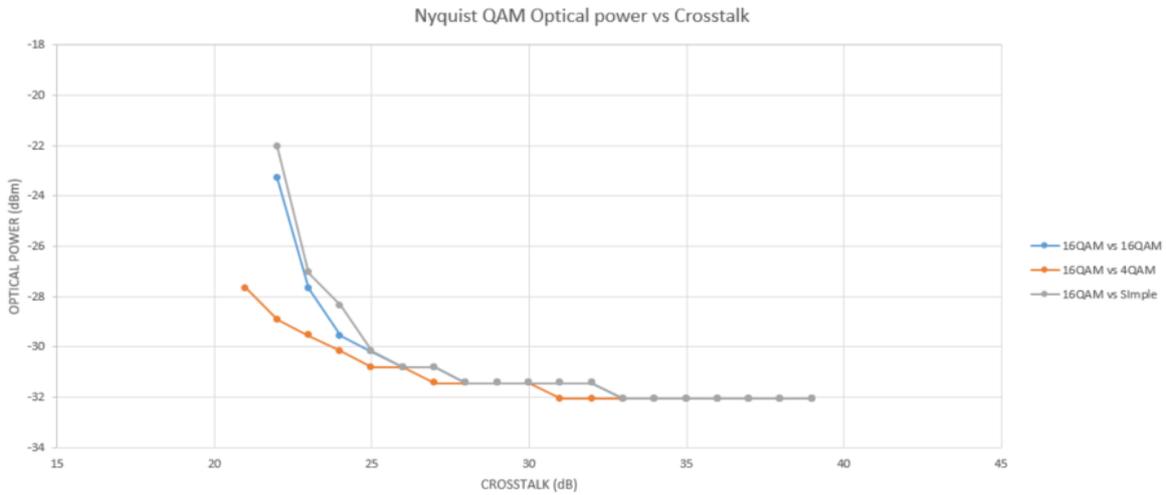


Figure 31: simple 16QAM with different order QAM interfering

Similar to the Nyquist case, the power needed for the different interfering signals is similar as well as its behaviour. For the 3 cases, we have a crosstalk tolerance of 25dB.

7.1.4. 4QAM crosstalk

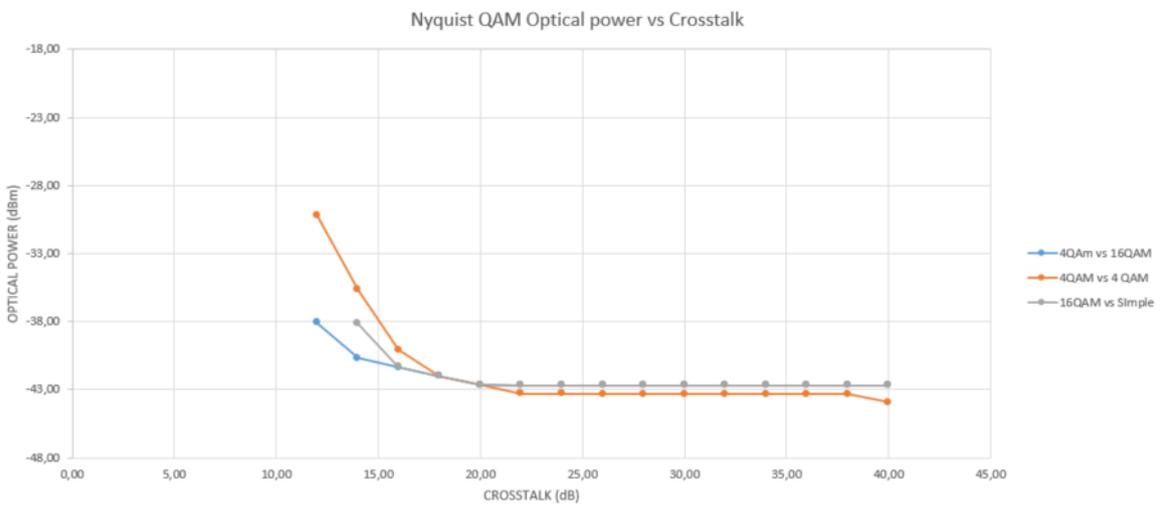


Figure 32: simple 4QAM with different order QAM interfering

As before, similar to the Nyquist case, we need for the 3 cases a power around -43dBm. In all 3 cases, we have a crosstalk tolerance of 15dB.

7.2. Simulation scripts

7.2.1. Crosstalk simulation script

```
set all "C:/Users/pfc_jgene1/Desktop/SIMULACIONES/"
append all "all.txt"
set BER_found "C:/Users/pfc_jgene1/Desktop/SIMULACIONES/"
append BER_found "BER_found.txt"
set ATT1 40.0
set ATT2 8.0
set inc 2.0
set BER 0
set BER_Trobada 0
set power 0
set ATTMax 80.0
set ATTMin 0.0
while {$ATT2 >= 0} {
    while {$BER_Trobada != 1} {
        setstate Attenuator_vtms1 Attenuation $ATT1;
        run 1
        wrapup
        set BER [statevalue PostValue_vtms2 InputValue];
        set power [statevalue PostValue_vtms1 InputValue];
        if {[expr $BER > 1.0e-3]} {
            set ATTMax $ATT1;
            if {[expr ($ATTMax - $ATTMin) < 0.5]} {
                set BER_Trobada 1;
            } else {
                set ATT1 [expr ($ATTMax + $ATTMin)/2]
            }
        }
        if {[expr $BER < 1.0e-3]} {
            set ATTMin $ATT1;
            if {[expr ($ATTMax - $ATTMin) < 0.5]} {
                set BER_Trobada 1;
            } else {
```

```

set ATT1 [expr ($ATTMax + $ATTMin)/2]
    }
}

set result [open $all a]
puts $result "Atenuacio (dB):"
puts $result $ATT1
puts $result "Potència Optica (dBm):"
puts $result $power
puts $result "BER:"
puts $result $BER
close $result
}

set result2 [open $BER_found a]
puts $result2 "Atenuació Interferent"
puts $result2 $ATT2
puts $result2 "Atenuacio (dB):"
puts $result2 $ATT1
puts $result2 "Potència Optica (dBm):"
puts $result2 $power
puts $result2 "SER:"
puts $result2 $BER
close $result2

set BER_Trobada 0;
set ATT2 [expr $ATT2 - $inc];
set ATT1 40.0;
set BER 0.0;
set power 0.0;
set ATTMax 80.0;
set ATTMin 0.0;
setstate Attenuator_vtms2 Attenuation $ATT2;

}

```

7.3. Raised cosine Filter

The raised cosine filter is a filter frequently used in digital modulation due to the ability to minimise intersymbol interference (ISI). It is a low pass implementation of a Nyquist filter, which gives name to this modulation.

The raised cosine has odd symmetry about $1/2T$, where T is the period of the communication system. The frequency-domain description is:

$$H(f) = \begin{cases} T, & |f| \leq \frac{1-\beta}{2T} \\ \frac{T}{2} \left[1 + \cos \left(\frac{\pi T}{\beta} \left[|f| - \frac{1-\beta}{2T} \right] \right) \right], & \frac{1-\beta}{2T} < |f| \leq \frac{1+\beta}{2T} \\ 0, & \text{otherwise} \end{cases}$$

In the image below a representation of a raised-cosine filter can be seen.

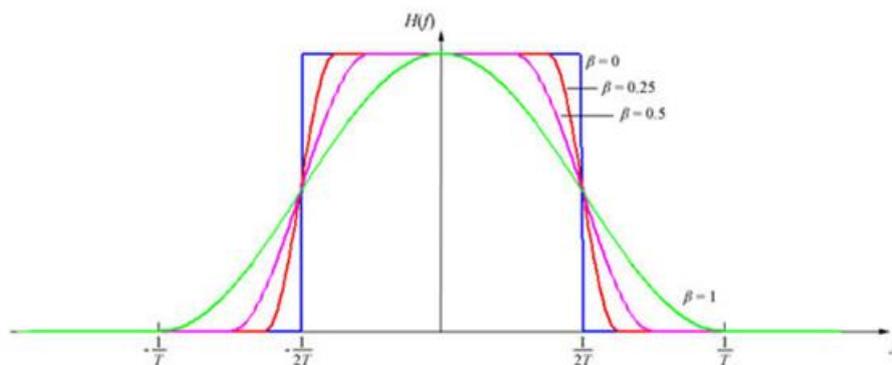


Figure 33: raised-cosine filter

As it can be observed, the form of the filter depends on the parameter β , called Roll-off factor. The roll-off factor is a measure of the excess bandwidth of the filter, the bandwidth occupied beyond the Nyquist bandwidth.

The description of the impulse response of a raised cosine filter is:

$$h(t) = \begin{cases} \frac{\pi}{4} \operatorname{sinc} \left(\frac{t}{2\beta} \right), & t = \pm \frac{T}{2\beta} \\ \operatorname{sinc} \left(\frac{t}{T} \right) \frac{\cos \left(\frac{\pi \beta t}{T} \right)}{1 - \left(\frac{2\beta t}{T} \right)^2}, & \text{otherwise} \end{cases}$$

Below, we have an image of the impulse response. This figure is quite important because it will be observed during most simulations along this paper.

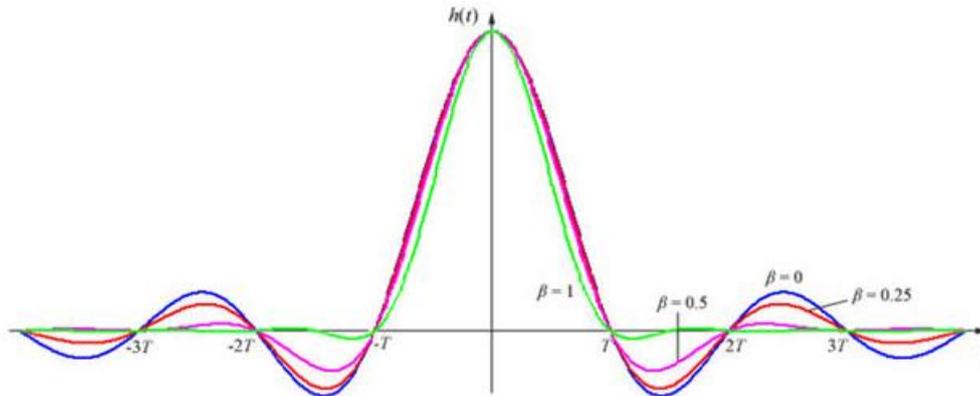


Figure 34: raised cosine impulse response

7.4. QAM modulation

QAM is a modulation scheme. It can be applied to both analogical signals and bit streams. In the scenarios we are going to study, we will focus on the digital case. The QAM modulation works as following:

Two signals, or in our particular case, two bit streams are modulated in amplitude using ASK (Amplitude Shift Keying). Later, it is made that this two carrier waves are out of phase with each other by 90° . After this process, both signals are summed, obtaining a resulting waveform that is a combination of a PSK (Phase Shift Keying) and ASK.

To better understand this modulation, First, we are going to explain how the transmitter and receiver for a general QAM modulation work. Later on this section, we are going to briefly explain how we actually implemented on the schematics that will be fully studied in following sections of this paper.

7.4.1. QAM Transmitter

In the image below, we can see how a QAM transmitter is structured. First, the original bit stream is split into two independent signals. This signals are modulated in Amplitude independently the first channel, called inphase, is usually multiplied by a cosine while the other channel, called quadrature, is multiplied by a sine. Doing that, we achieve a 90° degree phase between them. Finally, both signals are added and sent.

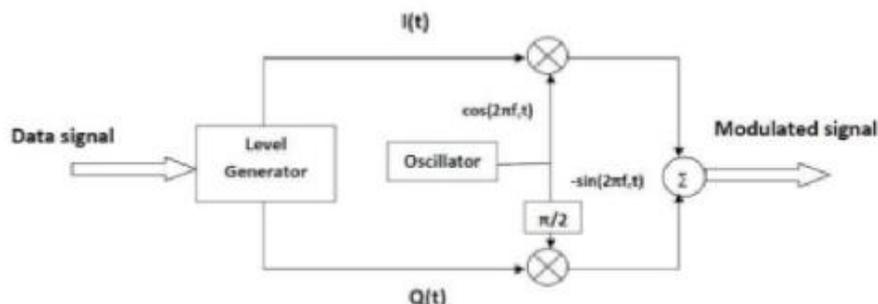


Figure 35: QAM transmitter

When putting this transmitter into practice, we used two Mach-Zender Modulators with a 90° degree phase between them. In every case, the amplitude modulation was different

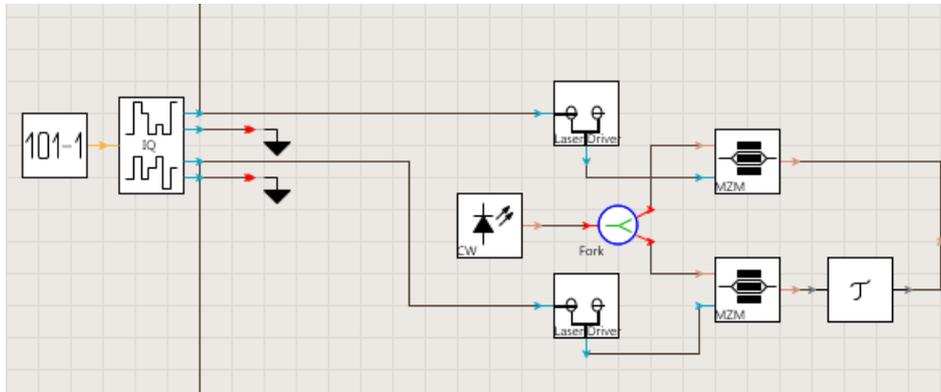


Figure 36: M transmitter in the Schematic

7.4.2. QAM Receiver

The receiver performs the inverse operation than the transmitter. After receiving the signal, in one channel it multiplies it by a cosine and filters it to recover the inphase signal. In the other channel, the signal is multiplied by a sine and filtered to recover the quadrature signal.

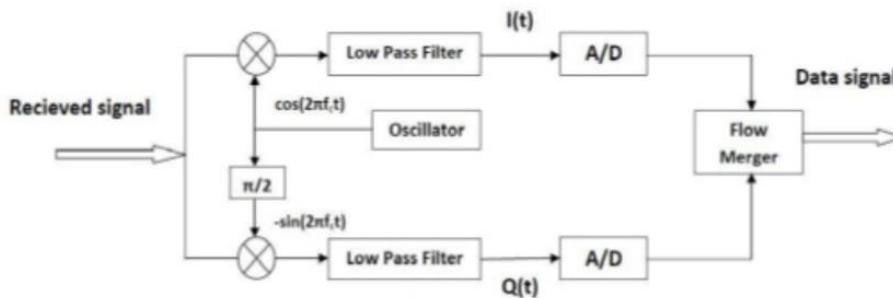


Figure 37: QAM Receiver

In the schematic, the Receiver is formed by a filter and a Quadrature Optical Hybrid. The Quadrature Optical Hybrid generates from 2 input signals (the received one and a local oscillator) 4 signals with 90 degree phase difference. Combining them as seen in the figure, we recover the inphase and the quadrature signals.

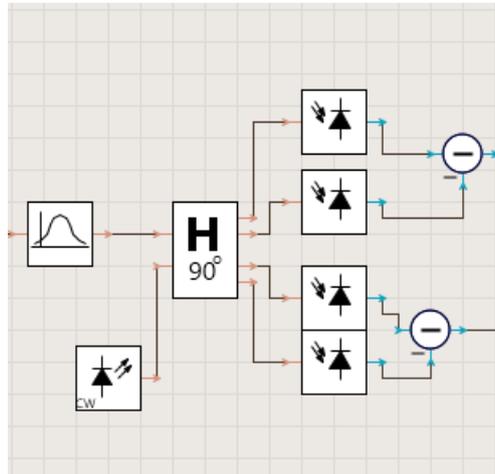


Figure 38: QAM Receiver in Schematic

7.4.3. Formal Presentation

We have the following transmitted signal:

$$s(t) = i_s(t) \cdot \cos(2\pi f_c t + \varphi_c) - q_s(t) \cdot \sin(2\pi f_c t + \varphi_c)$$

Being:

$$i_s(t) = \sum a_i[n] \cdot p(t - nT)$$

$$q_s(t) = \sum a_q[n] \cdot p(t - nT)$$

That means that we can rewrite the $s(t)$ expression like:

$$s(t) = \text{Re} \left\{ \sum_n (a_i[n] + ja_q[n]) \cdot p(t - nT) \cdot e^{j(2\pi f_c t + \varphi_c)} \right\}$$

Where:

$$a_i[n] + ja_q[n] = |a[n]| e^{j\varphi_a[n]}$$

Making $s(t)$:

$$s(t) = \sum_n |a[n]| \cdot p(t - nT) \cdot \cos(2\pi f_c t + \varphi_c + \varphi_a[n])$$

So in function of the codified symbol both phase and amplitude vary.

we need to see how the receiver structure is:

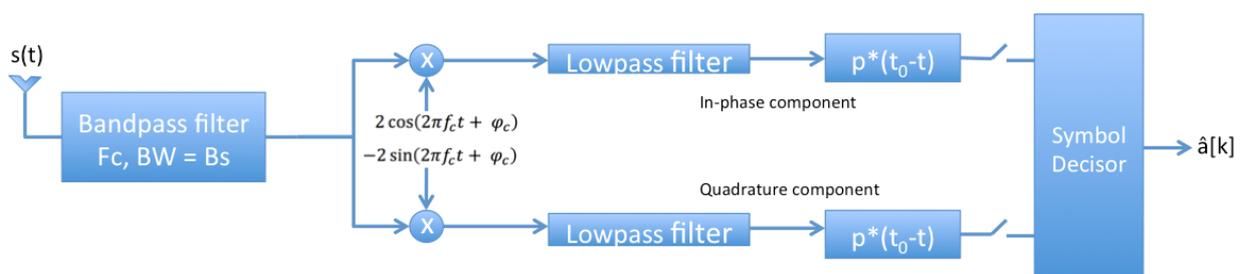


Figure 39: QAM transmitter scheme

As perfectly seen in the above figure, the Coherent receiver allows us to recover both the In-phase and Quadrature components so the symbol decision block can tell which was the sent symbol every time $\rightarrow \hat{a}[k]$.

Next we need to know is how this receiver is generated optically, which can be seen in the following figure:

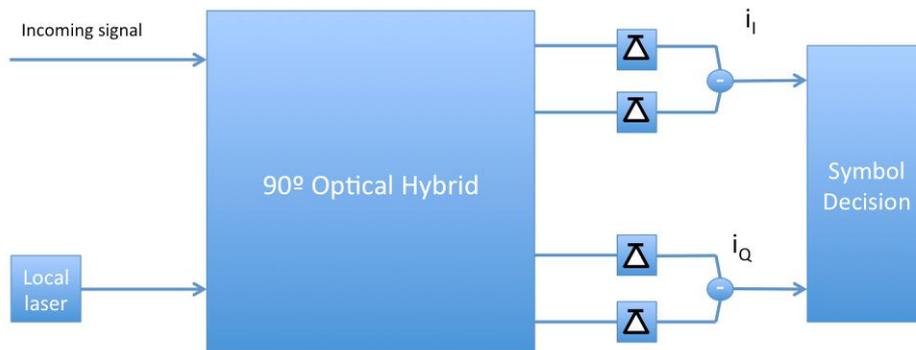


Figure 40: QAM receiver scheme

Notice how the 0° and 180° outputs of the Hybrid are subtracted to obtain the In-phase component at the exit of the photodiodes and the 90° and 270° outputs of the Hybrid are subtracted to obtain the Quadrature component at the exit of the photodiodes.

7.4.4. Simple QAM schematic

This schematic was used as a first approach to the QAM modulation. It is capable of generating different types of QAM modulation. The block on the left side, inside a blue box, is a module that is a universal electrical IQ coder-driver that generates driving signals for various types of optical transmitters for mQAM.

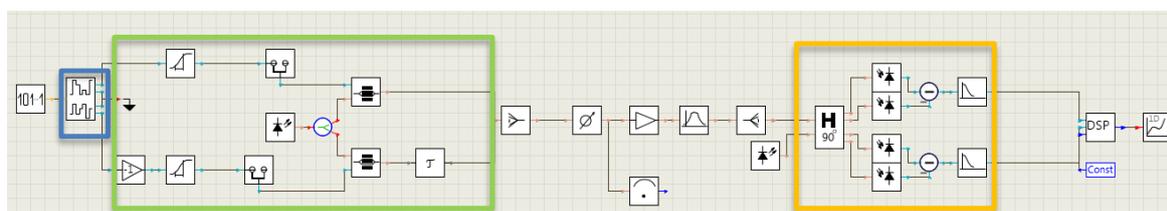


Figure 41: QAM schematic

After that, inside the green box, The QAM transmitter is found. It is formed by 2 MZ modulators, driven by the same laser signal, and two laser drivers. Finally, as explained before, one of the branches, the quadrature one, is delayed 90 degrees from the inphase branch. In addition, there is a signal inverter just after the QAM coder. This module is there because after many testing, it was discovered to be needed to be capable of calculating proper SER

Finally, in the yellow box, the QAM receiver is found. It is formed by a filter and a Quadrature Optical Hybrid. The Quadrature Optical Hybrid generates from 2 input signals

(the received one and a local oscillator) 4 signals with 90 degree phase difference. Combining them as seen in the figure, we recover the inphase and the quadrature signals.

In the next image, the Transmitted and received signals are compared. It can be seen that we are using a 16QAM modulation, due to the fact that there are 4 levels both in the inphase and the quadrature signals. The two images on the left part are the quadrature ones, with the transmitted one on the top. In the same way, on the right side the inphase signal is located, with the transmitted inphase on the top.

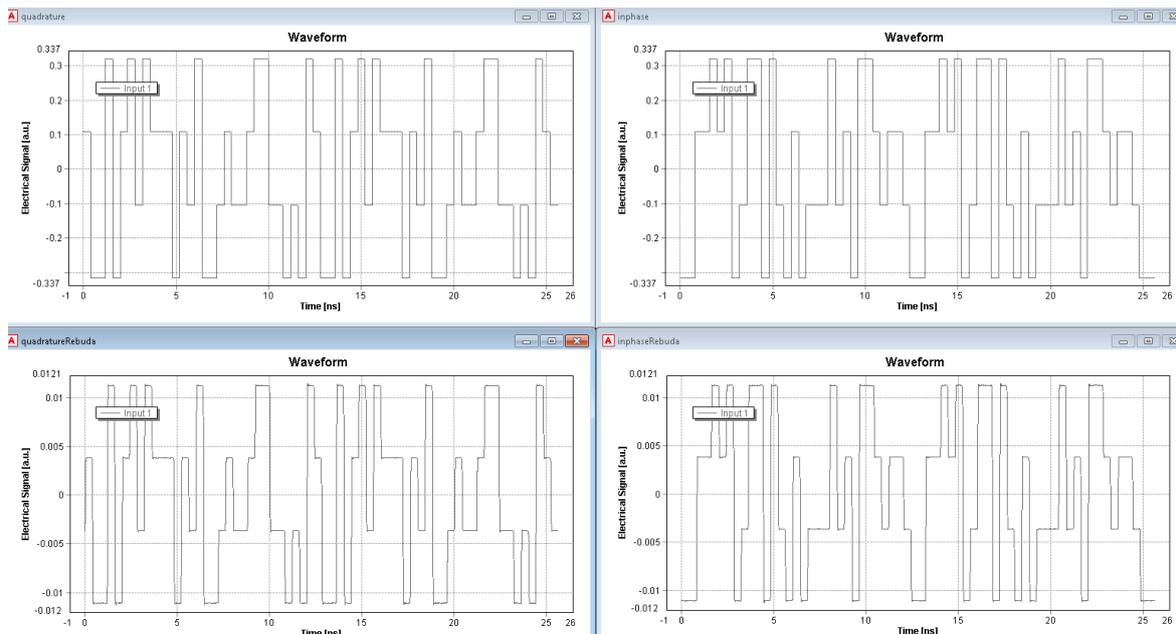


Figure 42: QAM transmitted and received inphase and quadrature signals

In the next image, and in the same way as before, the eye diagram for the inphase and quadrature signals is depicted.

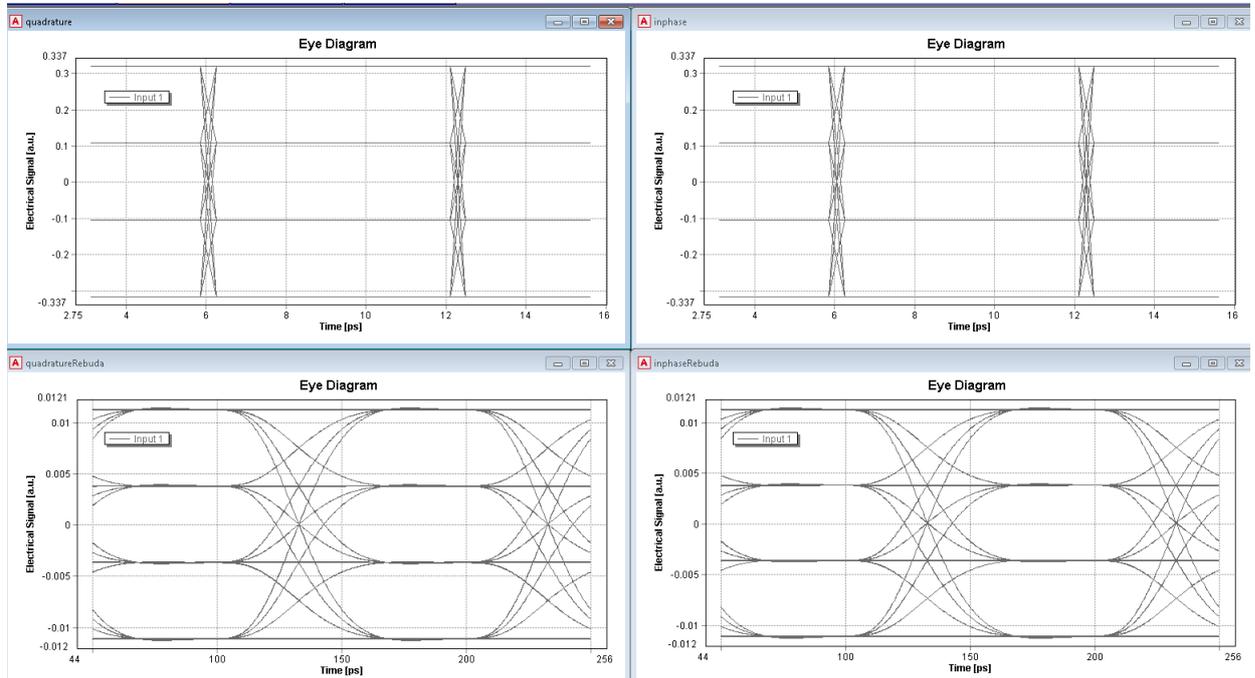


Figure 43: QAM transmitted and received inphase and quadrature eye diagram

Glossary

OTDM: Orthogonal Time Division Multiplexing

OFDM: Orthogonal Frequency Division Multiplexing

QAM: Quadrature Amplitude Modulation

ASK: Amplitude Shift Keying

PSK: Phase Shift Keying

ISI: Intersymbol Interference

BER: Bit Error Rate

SER: Symbol Error Rate