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MASTER THESIS

TITLE: Multiple user connection strategies for optical OFDM networks

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Title: Multiple User Connection strategies for optical OFDM systems

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Overview

Orthogonal Frequency Division Multiplexing, OFDM, is an emerging modulation technique which is now used in most broadband wired and wireless communication systems. Its narrow multi-carrier nature provides a very effective solution to the undesirable effects caused by dispersive channels.

The OFDM applied to optical systems has been studied recently concluding that it is an appropriate solution to the chromatic dispersion, the most stringent impairment in single mode optical systems.

This Master Thesis presents a study of optical OFDM techniques applied to optical networks. From the many different strategies presently available for optical OFDM, here we focus in the most simple and cost-effective Intensity Modulation / Direct Detection with RF upconversion.

The Virtual Photonics software is used to simulate point-to-point OFDM links in the presence of signals coming from other users in order to see the effect of Optical Beat Interference (OBI), one of the more detrimental effects in optical OFDMA networks. Mathematical models are used to help to understand the results of simulations and based on that, strategies to overcome OBI are proposed.

A multiuser uplink simulation scenario has been built up, taking advantage of the VPI functionalities such as Cosimulation, definition of global variables that can automatically be updated, etc. The result has been a user-friendly and scalable simulation platform that allows for easy setup of simulations of the uplink of OFDMA networks, ready for the testing of the different OBI cancellation strategies also identified in this work.

INDEX

INTRODUCTION 1

CHAPTER 1.OFDM BASICS 4

- 1.1. Introduction 4
- 1.2. OFDM 4
- 1.3. Digital OFDM systems 6
  - 1.3.1. Transmitter 7
  - 1.3.2. Receiver 9

CHAPTER 2. OPTICAL SYSTEMS 11

- 2.1. Optical channel 11
  - 2.1.1. Chromatic dispersion 11
- 2.2. Optical modulation techniques 13
  - 2.2.1. Conventional Intensity Modulation / Direct Detection systems (IM/DD)..13
  - 2.2.2. Standard Mach-Zehnder Modulator 14
  - 2.2.3. Double sideband problem 16
- 2.3. Optical demodulation techniques 16
  - 2.3.1. Direct detection (DD) 16
- 2.4. IM/DD and the Chromatic dispersion effect 17
  - 2.4.1. Frequency selective fadings effect 17
  - 2.4.2. Intermodulation mixing products effect 18
  - 2.4.3. Carrier-sideband phase noise decorrelation 19

CHAPTER 3. OPTICAL OFDM SYSTEMS AND VPI SOFTWARE 20

- 3.1. Introduction 20
- 3.2. Optical IM/DD system with RF-upconversion 21
- 3.3. VPI software 22
  - 3.3.1. Hierarchical distribution and modular design 22
  - 3.3.2. Global parameters 23
  - 3.3.3. Cosimulation 24
- 3.4. Long-Haul Transmission demo 26
  - 3.4.1. Scenario and outputs 26
  - 3.4.2. ONU 28
  - 3.4.3. OLT 30
  - 3.4.4. Fiber links and filters 31

3.5. OFDM coding and decoding performed with Matlab code for point-to-point simulations ... 32
  3.5.1. FFT symmetry and Zero padding ... 32
  3.5.2. Cyclic Prefix ... 33
  3.5.3. Normalization ... 34
  3.5.4. Equalization ... 35
  3.5.5. Bit error rate calculation ... 36
CHAPTER 4.MULTIPLE USER CONNECTION STRATEGIES AND OBI MANAGEMENT ... 37
4.1. Same wavelength case ... 38
  4.1.1. Same wavelength strategy simulations ... 40
4.2. Different wavelengths at safety distance case ... 42
  4.2.1. Different wavelength at safety distance strategy simulations ... 43
CHAPTER 5.SIMULTANEOUS USERS DECODING ... 45
5.1. Introduction and goal ... 45
5.2. OFDMA uplink structure ... 45
5.3. Dynamic Bandwidth Allocation ... 47
5.4. RF frequencies of users ... 47
5.5. The FFT symmetry and the rearranging of subcarriers ... 49
5.6. Normalization at the ONUs output ... 51
5.7. Cyclic Prefix insertion and extraction in an optical OFDMA ... 51
5.8. PRBS for quality measurements and equalization ... 53
5.9. Equalization in optical OFDMA networks ... 54
5.10. ONUs matrix ... 54
5.11. Simulation scenario ... 55
  5.11.1. Universe ... 55
  5.11.2. Global parameters of the demo ... 55
  5.11.3. Electrical OFDM transmitter galaxy ... 58
  5.11.4. Electrical ODFM receiver ... 58
5.12. Results for different strategies ... 59
  5.12.1. Same wavelength ... 60
  5.12.2. Different wavelengths at a safety distance ... 61
5.13. Scalability and user friendliness ... 63
  5.13.1. The loop performance ... 64
  5.13.2. Sub-matrix finder at the output ... 65
  5.13.3. How to add an ONU? ... 66
CONCLUSIONS AND FUTURE LINES ... 68
6.1. Conclusions ... 68

6.2. Future lines 70
REFERENCES 71
Books 71
Papers and tutorials 71
UPC TelecommunicationDegreeThesis 72
Websites 72
ACRONYMS 73
APPENDIX A: PULSE SHAPING, OVERSAMPLING AND GAP GENERATION 74
A.1. Pulse shaping and oversampling 74
A.2. Zero padding strategy to create a gap between the optical carrier and the information subcarriers 75
APPENDIX B: OFDM CODING MATLAB CODE 76
APPENDIX C: OFDM DECODING MATLAB CODE 78

INDEX OF FIGURES

Figure I.1 Example of an optical access network in the uplink.......................... 1
Figure 1.1 FDM symbols coding general scheme.. 3
Figure 1.2 Orthogonality in frequency and time domain 5
Figure 1.3 IFFT block and the frequency domain OFDM symbol at its output... 5
Figure 1.4 Digital OFDM transmitter... 6
Figure 1.5 Zero padding at the edges to shift the aliases away........................ 7
Figure 1.6 Cyclic prefix extension in an OFDM information subcarrier 8
Figure 1.7 Synchronization in the cyclic prefix extraction 8
Figure 1.8 Digital OFDM receiver 9
Figure 2.1 Different symbol time arrivals due to chromatic dispersion............ 10
Figure 2.2 Diode laser schematic and characteristic curve 12
Figure 2.3 IM/DD scheme.. 13
Figure 2.4 Mach-Zehnder modulator scheme.. 13
Figure 2.5 IM modulation with Mach-Zehnder general schema and its quadrature point.. 14
Figure 2.6 MZM optical modulation curve.. 14
Figure 2.7 Double sideband effect produced by IM/DD modulation................ 15
Figure 2.8 Double sideband produced by the IM/DD system 17
Figure 2.9 Intermodulation mixing products cancelled in an ideal case.......... 17
Figure 2.10 Undesirable intermodulation mixing products at the output of the photodiode... 18
Figure 2.11 Phase noise descorrelation 18
Figure 3.1 IM/DD with RF upconversion optical OFDM system...................... 20
Figure 3.2 Electrical upconversion of the OFDM baseband signal 20
Figure 3.3 VPI universe 21
Figure 3.4 Hierarchical distribution 22
Figure 3.5 Cosimulation composition.. 24
Figure 3.6 Attached file and main parameters of the CosimInterface 24
Figure 3.7 Long-Haul demo universe 25
Figure 3.8 Universe parameters 26
Figure 3.9 ONU 27
Figure 3.10 Electrical OFDM transmitter galaxy 27
Figure 3.11 OLT 29
Figure 3.12 Electrical OFDM receiver galaxy 30
Figure 3.13 Optical channel.. 30
Figure 3.14 Matlab’s code snippet: Zero padding addition 32
Figure 3.15 Matlab’s code snippet: Zero padding extraction 32
Figure 3.16 Strategy for the cyclic prefix extraction 33
Figure 3.17 Matlab’s code snippet: Cyclic Prefix insertion.............................. 33
Figure 3.18 Matlab’s code snippet: Cyclic Prefix extraction............................ 33
Figure 3.19 Matlab’s code snippet: Normalization at the output of the coding (1/2) 33
Figure 3.19 Matlab’s code snippet: Normalization at the output of the coding (2/2) 34
Figure 3.20 Matlab’s code snippet: Normalization at the input of the decoding34
Figure 4.1 General schema of the same wavelength strategy........................ 37
Figure 4.2 Optical spectrum for three independent laser modulating at the same wavelength.. 38

Figure 4.3 Remodulation schema 38
Figure 4.4 General schema of the simulation 39
Figure 4.5 Optical spectrum.. 40
Figure 4.6 Constellation of the demodulated user 40
Figure 4.7 General schema of the different wavelengths at safety distance strategy 42
Figure 4.8 Optical spectrum for different optical carriers 43
Figure 4.9 Constellation diagram... 43
Figure 5.1 Multiuser universe scenario... 45
Figure 5.2 Optical spectrum of an optical OFDMA network 47
Figure 5.3 Zero padding strategy to guarantee the symmetry of the FFT operation... 48
Figure 5.4 Number of FFT and CP length in a TimeWindow depending on the chosen DBA factor.. 51
Figure 5.5 PRBS Joiner schema in the universe of the simulation 52
Figure 5.6 Universe of the OFDMA network in the uplink......................... 54
Figure 5.7 Universe parameters 55
Figure 5.8 Electrical OFDM transmitter galaxy 57
Figure 5.9 Electrical OFDM receiver galaxy 58
Figure 5.10 Optical spectrum for the same optical carrier 59
Figure 5.11 Constellation, EVM and BER for each user............................ 60
Figure 5.12 Optical spectrum for different optical carriers 60
Figure 5.13 Constellation, EVM and BER for each user............................ 61
Figure 5.14 Two ONUs scenario with 30 GHz space with 1 GHz resolution ... 61
Figure 5.15 BER evolution.. 62
Figure 5.16 SubMatrix finder module... 64
Figure 5.17 SubMatrix finder parameters 64
Figure A.1 Aliases shifted away by means of oversampling...................... 73
Figure A.2 Zero padding at the edges to create gap 74

INTRODUCTION

This Master thesis is focused onto optical orthogonal frequency division multiplexing (OFDM) systems for an optical access network. That implies the integration between OFDM modulation and optical communication systems.

The OFDM is one of the most used modulations in wireless communications. This technology is present in several standards like WLAN and WMAN as well as in the fourth generation of cellular communications.

Optical transmission systems such as Fiber to the Home (FTTH) and Fiber to the Building (FTTB) are growing in interest, mainly because fiber reaches higher bitrates than other physical mediums and tends to be constant in time. The demand of bit rate is increasing due to the fact that current applications are in real time and sophisticated, so they require a higher bandwidth.

OFDM has already demonstrated its capability to extend the reach and data transmission velocity in long-haul fiber applications [P4]. Due to the flexibility and reconfigurability inherent to OFDM formats, it is expected that they also offer advantages at the network access level.

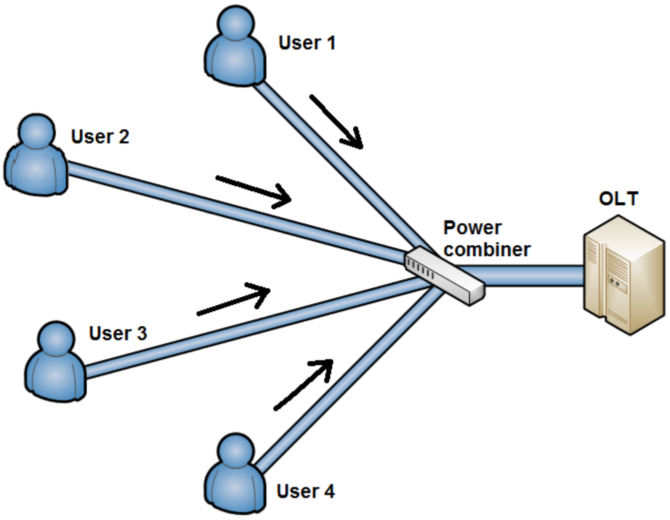


Figure I.1 Example of an optical access network in the uplink

A consortium aiming at unveiling the potential of OFDM modulation in optical access networks has been formed which gathers institutions from across Europe: Estonia, France, Germany, Greece, Spain and the United Kingdom. The consortium is called Accordance: A converged copper-optical-radio OFDMA-based access network with high capacity and flexibility [W2].

In this consortium UPC is in charge of investigating physical layer issues mainly through simulations and experiments.

This Master thesis is divided into five chapters apart from the introduction and conclusions chapters.

The first chapter is a revision of basic concepts about OFDM systems. So, both OFDM modulation and electrical OFDM transmitter/receiver will be explained.

The second chapter is about the optical systems. This chapter shows the optical modulation and demodulation techniques considered in this thesis: Intensity Modulation /Direct Detection (IM/DD).

The third chapter deals with the integration between OFDM modulation and the optical IM/DD systems. From the many options that can be considered for optical OFDM systems [T1, T3], this thesis work is focused on the IM/DD with RF upconversion optical system. The VirtualPhotonicsInc (VPI) software, which provides a built-in demo for this kind of optical OFDM system, is also presented here. The demo helps to understand the basics of the OFDM modulation over optical systems, and it can be used for simulating point-to-point systems. In chapter 4, the VPI demo is applied to see the effect of interferences among users multiplexed in OFDMA.

When considering the simultaneous detection of multiplexed users, however, as in chapter 5, the coding and decoding modules provided by VPI do not offer the required flexibility. That is why we have had to use the OFDM coding and decoding modules programmed in Matlab and operated within VPI through the cosimulation tool [T1, T3 and T5]. In chapter 3, it is included a description of those modules and the features which are more relevant to the work developed in chapter 5.

The fourth chapter is a description of the multiuser connection strategies for optical OFDM systems. In this chapter, the problems that arise when moving from a point to point network to an optical access network are treated. In an OFDMA format, different users are assigned to different electrical bands (subcarriers). In an optical OFDMA, the different users can also use the same optical carrier, or use different ones, or not use an optical carrier at all. Each alternative has advantages and drawbacks, as it will be seen by analyzing the point-to-point OFDM transmission in the presence of other OFDM signals coming from different users. The problem is often related to the Optical Beat Interference (OBI) at the receiver side and the VPI coding and decoding modules have been used for this purpose.

Finally, the fifth chapter explains the customized demos for simulation of multiple access uplink scenarios with simultaneous demodulation of all users in the OLT. This demo is based on Matlab OFDM coding and decoding modules. The strategies for the programming of a user-friendly and flexible simulation platform for the uplink of an optical OFDMA network are discussed, including Zero Padding at the edges to solve the symmetry problem, CP inclusion and extraction, RF carrier frequency locations and dynamic bandwidth allocation.

Special emphasis is placed on the scalability of the final structure, in the sense that new users can easily be added.

CHAPTER 1.OFDM BASICS

1.1. Introduction

This chapter is a review of basic concepts about optical OFDM.

It will be explained in the following order: firstly, the basic concepts of Frequency Division Multiplexing; and, secondly, the blocks and concepts used for the digital generation of subcarriers and the analogue to digital conversion.

1.2. OFDM

The Orthogonal Frequency Division Multiplexing is a modulation technique where the information is sent modulated into different subcarriers or channels.

A basic scheme is shown in Figure 1.1. The input bits are mapped into complex symbols (usually following an M-QAM modulation) and after serial to parallel conversion, are sent in N different subcarriers. In the Figure 1.1, M=2 (4-QAM) and N=8.

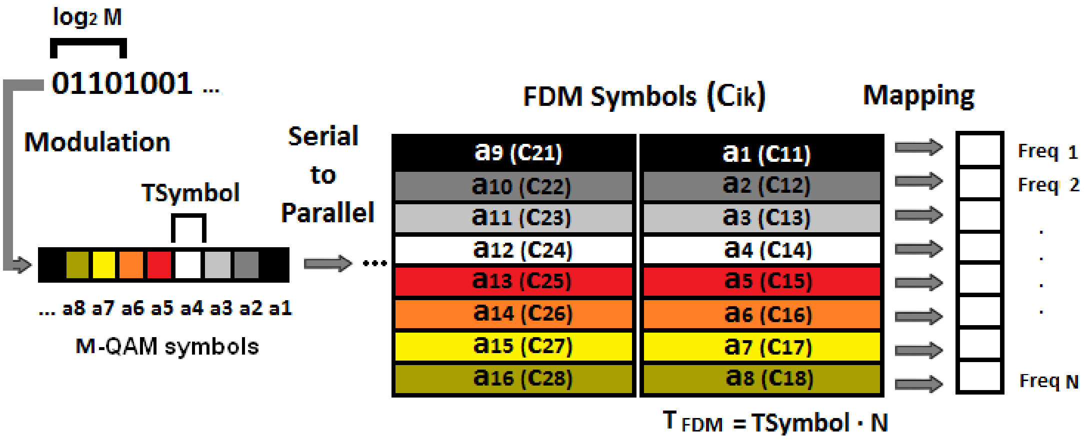


Figure 1.1 FDM symbols coding general scheme [T3]

The advantage mainly lies in the fact that in the presence of channel's selective frequency fadings only part of the symbols is lost whereas in a single-carrier system all the information is affected.

Furthermore, the channels can be made narrow enough to consider a flat channel spectral response, allowing single tap equalization; this is to say, using only one coefficient.

The above can also be understood by considering that a high speed signal is divided into many lower speed signals sent in parallel. When the symbol is made longer than the channel's impulse response, ISI affects one symbol at most and it can be easily equalized.

The spectral efficiency is maximized when the subcarrier spacing (*Δf*) is made equal to the inverse of the symbol length (T_{OFDM}), ($\Delta f = \frac{1}{T_{OFDM}}$). In this case, it can be seen that the different subcarriers are orthogonal to each other and thus, the spectra of the individual subchannels can be recovered in reception in spite of spectral overlap. This makes the OFDM modulation very spectrally efficient.

Following Figure 1.1, the mathematical expression of an OFDM signal x(t) in the time domain is as follows in Equation 1.1:

$$x(t) = \sum_{i=1}^{\infty} \sum_{k=1}^{N} C_{ik} e^{j2\pi\Delta f(t-iT_{OFDM})} \cdot p(t - iT_{OFDM})$$

(1.1)

The p(t) is known as the shaping pulse and in the ideal case is a perfectly squared pulse of length T_{OFDM}, a sinc function in the spectral domain.

In order to simulate a more realistic situation, the raised cosine function with a roll-off factor (α) will be used in the simulations. The ideal square pulse corresponds to the case α=0. See Annex A.

Using ($\Delta f = \frac{1}{T_{OFDM}}$), the above may be written:

$$x(t) = \sum_{i=1}^{\infty} \sum_{k=1}^{N} C_{ik} e^{j2\pi f_k t} \cdot p(t - iT_{OFDM})$$

(1.2)

The Equation 1.2 is valid if the condition ($\Delta f = \frac{1}{T_{OFDM}}$) is exactly fulfilled. As it will be shown in Chapter 4, due to multiple detection with decorrelated optical carriers in the upstream direction, the whole expression in Equation 1.1 will need to be used.

In the time domain, the orthogonality condition can be understood from the viewpoint that the subcarriers have an integer number of periods inside the shaping pulse and, therefore;

$$\int_{t}^{t+T} s_n(t) s_m(t) dt = 0 \rightarrow when\, m \neq n$$

$$\int_{t}^{t+T} s_n(t) s_m(t) dt = 1 \rightarrow when\ m = n$$

(1.3)

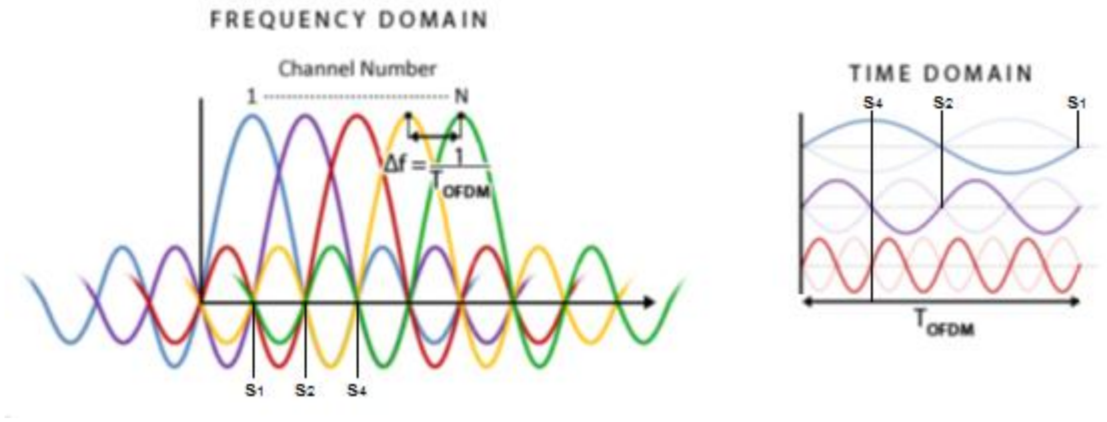


Figure 1.2 Orthogonality in frequency and time domain [P1]

1.3. Digital OFDM systems

If now we take Equation 1.2 and consider it is sampled every t=n·T_S, it is obtained:

$$X(nTs) = \sum_{i=0}^{N_{OFDM}} \sum_{k=0}^{N-1} C_{ik} . e^{j2\pi k \frac{1}{N.Ts} nTs} = \sum_{i=0}^{N_{OFDM}} \sum_{k=0}^{N-1} a_{ik} . e^{\frac{j2\pi kn}{N}}$$

(1.4)

The Equation 1.4 corresponds to the expression of the digital IFFT. This means that the OFDM signal can be obtained by applying the IFFT algorithm, after the serial to parallel conversion of the symbols, as can be seen in Figure 1.3.

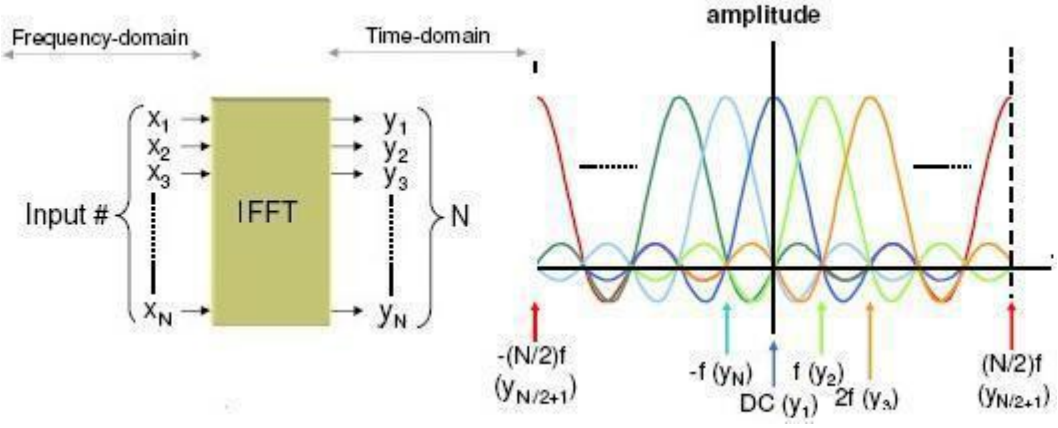


Figure 1.3 IFFT block and the frequency domain OFDM symbol at its output [P1]

The symbols at the IFFT input are arranged in the spectrum starting from the zero (DC) frequency. The second half of the input symbols would be located at frequencies which are higher than the Nyquist frequency. In practice, these frequencies are removed by the DAC and due to the periodicity of the discrete IFFT, they will be found at the left hand side (negative) part of the spectrum [B3].

It is worth noting at this point that, in the ideal OFDM spectrum, the subcarrier corresponding to the Nyquist frequency is found both at the positive and at the negative side of the spectrum. This will be very important when the individual OFDM spectrum of all the users has to be combined in a bigger spectrum to be simultaneously detected at the OLT, in chapter 5. The conclusion will be that, in order to multiplex all the users in an OFDMA fashion, the subcarrier allocated to the Nyquist frequency of each user has to be set to zero.

The orthogonality condition can be understood in the digital OFDM by considering that when the FFT operation is taken at the receiver, the discrete FFT is a sampled version of the spectrum of an OFDM frame. The samples are taken precisely at the points where one of the subchannels reaches its maximum value and the rest of subchannels go to zero, Figure 1.3.

1.3.1. Transmitter

In Figure 1.4, the following steps are necessary to obtain the OFDM signal.

From input to output, it can be seen, firstly, that the bit stream has to be arranged according to the used modulation. This thesis uses 4-QAM modulation, so two bits are mapped onto one symbol obtaining, thus, four different values for each symbol. Then, it has to be done a serial to parallel conversion in order to get a parallelized version of the obtained symbols.

Then, zero padding is inserted. The kind of zero padding considered in the figure has the purpose of shifting away the aliases produced by the DAC. In the next subsection it will be explained in detail.

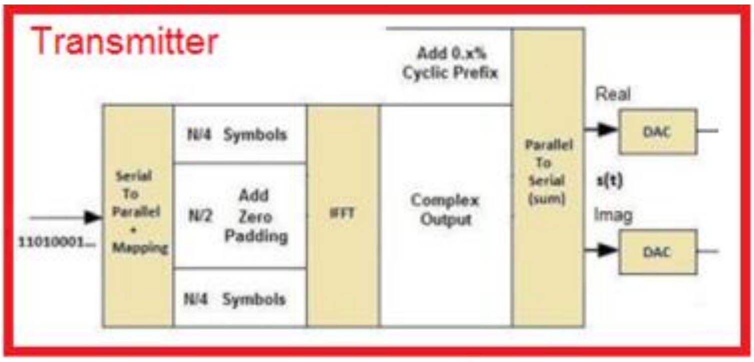


Figure 1.4 Digital OFDM transmitter [T1]

After that, IFFT is performed to obtain the digital OFDM signal. This can be seen, mathematically, in Equation 1.4.

After the IFFT stage, cyclic prefix is added in order to eliminate ISI and ICI. This will be explained in subsection 1.3.1.2.

Finally, the symbols are arranged and serialized. The real and imaginary parts are sent to two different DACs where they are converted from the digital to the analogue domain.

1.3.1.1. *Zero Padding*

When sampling with the DAC the symbols obtained, some aliases appear and it is difficult to filter them out from the sampled signal.

The solution is to shift the aliases away from the OFDM signal, by inserting zeros in the appropriate positions, as seen in Figure1.5. This insertion is done before the IFFT.

Due to the periodical nature of the FFT operation [B3], the zeros at the spectrum edges correspond to those located in the middle of the input sequence of the FFT. See figure 1.5.

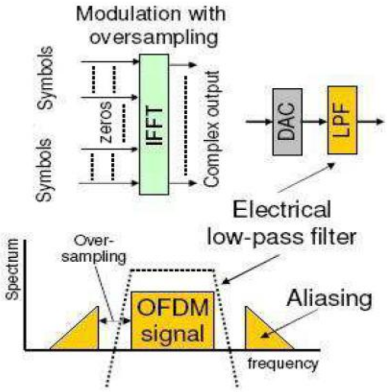


Figure 1.5 Zero padding at the edges to shift the aliases away [P1]

1.3.1.2. *Cyclic Prefix*

The channel dispersion extends the duration of the sent symbols giving rise to InterSymbolic Interference (ISI). In OFDM systems, this effect is avoided by inserting a guard time between OFDM symbols which needs to be larger than the channels delay spread, Figure 1.6.

This guard time is eliminated in reception to recover the symbols orthogonality. Due to the periodicity of the subcarriers, if the OFDM symbol is cyclically extended into the guard time (see Figure 1.6), there is some flexibility in selecting the point where the CP extraction must begin. The condition is that a complete interval of T_{OFDM} length is available for demodulation. Inside that interval, the subcarriers will retain their orthogonality regardless of the phases at the beginning of the interval. That helps to relax the requirements for synchronization. The proper phases for each subcarrier for a given synchronization instant are readily recovered through equalization. In Figure 1.7, it can be seen an example with the maximum and minimum choices of the synchronization point.

Figure 1.6 Cyclic prefix extension in an OFDM information subcarrier [T1]

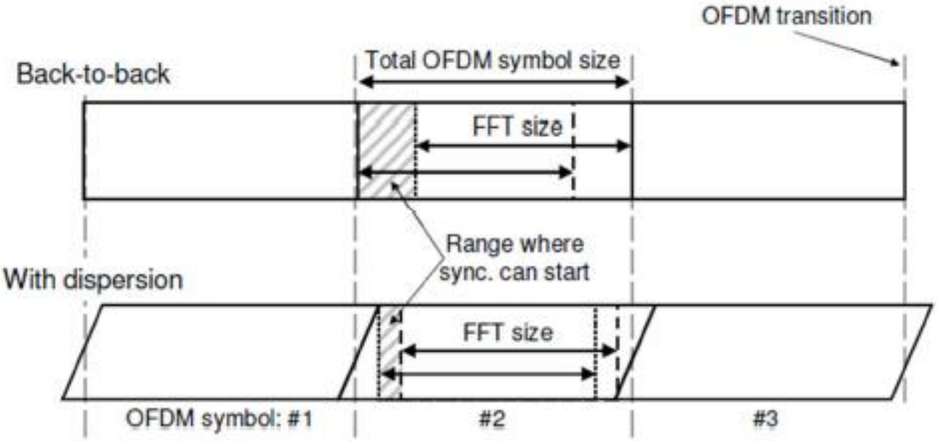


Figure 1.7 Synchronization in the cyclic prefix extraction [P2]

1.3.2. Receiver

In reception, the signal is recovered with the same operations as in transmission but in a reverse way.

Besides, an equalization of the optical signal can be done in order to recover precisely the signal amplitudes and phases.

The general schematic of the receiver can be seen in the Figure 1.8.

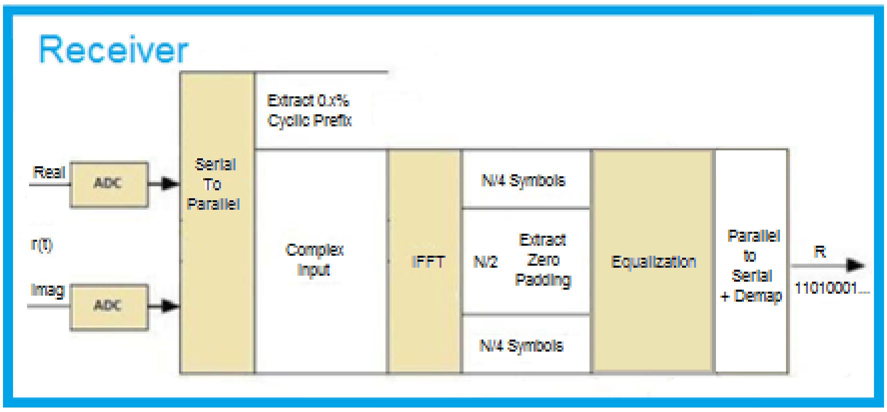


Figure 1.8 Digital OFDM receiver [T1]

1.3.2.1. Equalization

One of the best properties of OFDM systems is its ability to compensate for channel impairments. Equalization is carried out, in practice, by estimating the channel with some known training sequences. When the channel is estimated, it can be applied to the received signal to correct the phase and amplitude levels.

In this Thesis, equalization techniques have been applied at the receiver and they will be explained in Chapter 5. The simulations software allows equalization using the information sent by the transmitter.

CHAPTER 2. OPTICAL SYSTEMS

This chapter is a brief overview of the basic characteristics of optical transmission systems, with focus on the aspects which are more relevant to the application of OFDM modulation techniques.

2.1. Optical channel

Present fiber applications mainly use single mode fiber because it only suffers from chromatic dispersion while the multimode fiber also has intermodal dispersion, which highly limits the data bandwidth and reach. In this thesis, only single mode fiber will be considered.

2.1.1. Chromatic dispersion

Chromatic dispersion is the main limiting effect in a single mode optical fiber transmission. This effect produces a deterministic distortion. It causes a frequency dependence of the rate at which the phase of the wave propagates in the space and its effect on the transmitted optical signal basically scales quadratically with the data rate [B2]. This means that the phases of waves with different wavelengths do not travel at the same speed, so the subcarriers arrive at different times to the receiver. In the Figure 2.1, the effect of the chromatic dispersion in the time arrival of the different symbols can be seen.

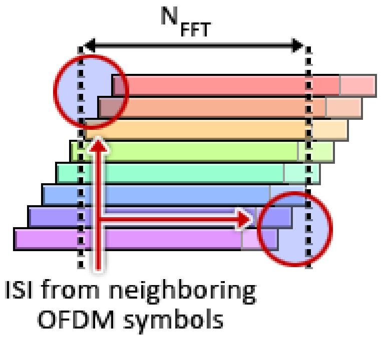


Figure 2.1 Different symbol time arrivals due to chromatic dispersion [T4]

This effect can be solved by adding a cyclic OFDM symbol extension which is bigger than the difference in arrival times among the subcarriers. This cyclic extension causes the loss of orthogonality and, therefore, it is removed before FFT demodulation in the receiver.

The frequency dependence of the phase can be seen in the frequency domain, Equation 2.1:

$$\mathrm{X_{out}}(\omega) = \mathrm{X_{in}}(\omega)\mathrm{e}^{-j\beta(w)z}$$

(2.1)

Where $\mathrm{X_{in}}$ is the transmitted signal Fourier transform, $\mathrm{X_{out}}$ is the received signal Fourier transform, $\beta(w)$ is the phase constant of the fundamental propagating mode and z is the fiber length.

In a dispersive channel, the phase constant β has a nonlinear dependency with the frequency so that the recovered signal at reception will differ from the transmitted one due to the different arrival times of the frequency components.

Since the operative bandwidth is very small when compared to the carrier frequency, $\Delta\omega=\omega-\omega_0<\omega_0,$ a slow variation of the phase constant inside the frequency bandwidth of the signal can usually be assumed. It is then possible to consider a Taylor expansion of the propagation constant about a central pulse frequency ω_0 up to second order terms. Thus, the Equation 2.2 is obtained:

$$\beta(w) \approx \beta_0 + \Delta\omega\beta_1 + \frac{\Delta\omega^2}{2}\beta_2$$

(2.2)

In the Equation 2.2, there are some coefficients that are considered important to be described:

- β_0 is related to the Phase Velocity ϑ_{ph}, which verifies Equation 2.3:

$$\beta_0 = \frac{\omega_0}{\vartheta_{ph}}$$

(2.3)

And it can be defined as the velocity at which the phase of a pure tone at frequency ω_0 would propagate.

- β_1 is related to the Group Velocity (ϑ_g) of the pulse by Equation 2.4:

$$\beta_1 = \frac{\partial\beta}{\partial\omega} = \frac{1}{\vartheta_g} = -\tau_g$$

(2.4)

The group velocity is defined as the varying rate of the wave envelope when it is propagated. The Group Delay τ_g, given in seconds/fiber length, gives the delay experienced by an envelope centered at frequency ω_0 , provided its bandwidth is not too large, the Taylor expansion would be no longer valid. It can also be thought that this delay is a kind of average delay of all the frequencies in a small bandwidth around the carrier.

- β_2 is related to the Group Delay Dispersion given by:

$$\beta_2 = -\frac{{\lambda_0}^2}{2\pi c} D = -\frac{c}{2\pi {f_0}^2} D \tag{2.5}$$

Being *c* the speed of light, λ_0 the corresponding wavelength and *D* the chromatic dispersion.

2.2. Optical modulation techniques

2.2.1. Conventional Intensity Modulation / Direct Detection systems (IM/DD)

The most straightforward way of modulating a signal over an optical carrier is the direct modulation of a laser feeding current. See figure 2.2, where the optical power versus current transfer function of a laser is shown. It can be seen that above a certain current threshold the optical power is proportional to the feeding current.

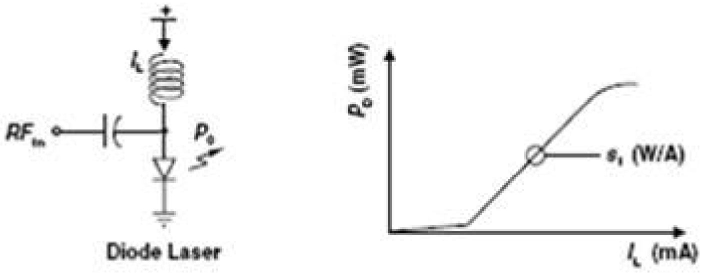


Figure 2.2 Diode laser schematic and characteristic curve [T1]

This is known as intensity modulation, since it is the intensity or optical power which is proportional to the information.

These proportional variations are detected at reception and the signal can be recovered because the photodiode performs the reverse operation.

The Figure 2.3 shows an electrical information signal s(t) modulated over an optical carrier. At the emission stage, the signal is converted from the electrical into the optical domain (E/O), and vice-versa at the reception stage (O/E). This scheme is called Intensity Modulation/ Direct Detection (IM/DD).

Figure 2.3 IM/DD scheme [T1]

2.2.2. Standard Mach-Zehnder Modulator

The direct modulation of a laser source has some advantages: it is cheap and also easy to adapt to low cost applications. Nevertheless, it is not very useful for advanced systems with high data rates and long distances, mainly due to the resonance frequency and chirp effects [B6]. For these reasons, resorting to external modulation is a good solution.

The Mach-Zehnder modulator (MZM) is a very popular external modulator. It has typically an RF input and another one for a DC bias, as seen in the Figure 2.4.

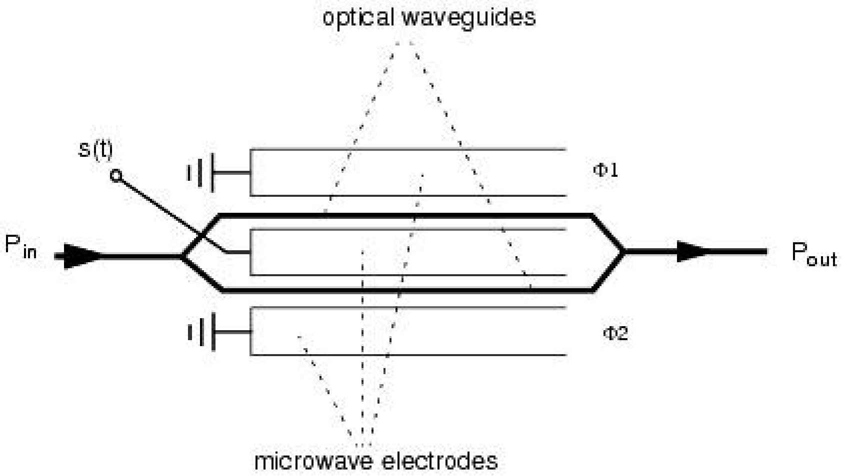


Figure 2.4 Mach-Zehnder modulator scheme [VPI help]

The material of the MZM has electro-optical properties, causing the phase of the optical wave propagating inside the MZM to acquire a phase shift proportional to the applied electrical field. The optical power P_{out} at the output of the MZM depends on the phase difference $\Delta\Phi$ between the two arms of the modulator, which can be changed by varying the bias of the MZM, Equation 2.6:

$$P_{out}(t) = P_{in}(t).\,d(t) = P_{in}(t)cos^2[\Delta\Phi(\mathrm{t})], and\ \Delta\Phi(\mathrm{t}) = \frac{\Delta\Phi_1(t) - \Delta\Phi_2(t)}{2} \tag{2.6}$$

Where d(t) is the MZM power transfer function and $\Delta\Phi_1$(t) and $\Delta\Phi_2$(t) are the phase changes in each arm caused by the applied modulation signal s(t).

As seen in the Figure 2.5, the bias point is situated in the linear zone of the transfer function to obtain a linear intensity-to-optical power relationship (IM). This point is known as the quadrature point and it is the most used in combination with DD. Furthermore, the general schematic of the IM modulation with Mach Zehnder can be seen in the mentioned figure.

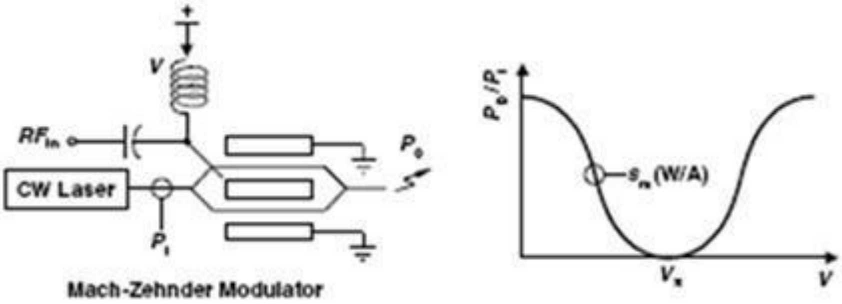


Figure 2.5 IM modulation with Mach-Zehnder general schema and its quadrature point [T1]

The relative phase of the two arms of a MZM is shifted by changing the bias. The Optical Field Modulation can be achieved by setting the bias of the MZM to the null point. This is shown in the Figure 2.6, where the transfer function of the optical intensity and the optical field are represented.

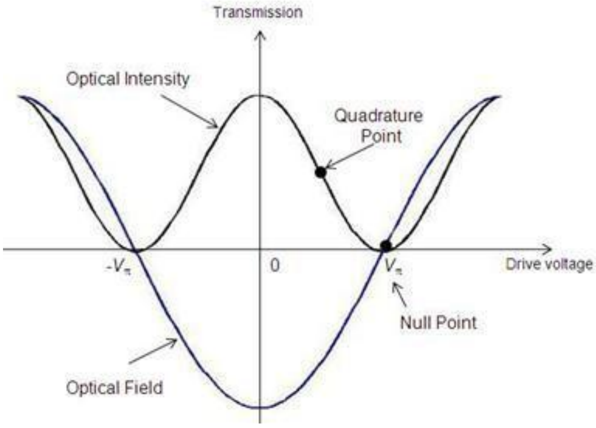


Figure 2.6 MZM optical modulation curve [VPI help]

2.2.3. Double sideband problem

The signal produced by a standard MZM and by any of the IM modulation systems is double sideband, as the OFDM signal is present symmetrically on both sides of the optical carrier. This is shown in the Figure 2.7, where A* is the complex conjugate of the main OFDM signal A.

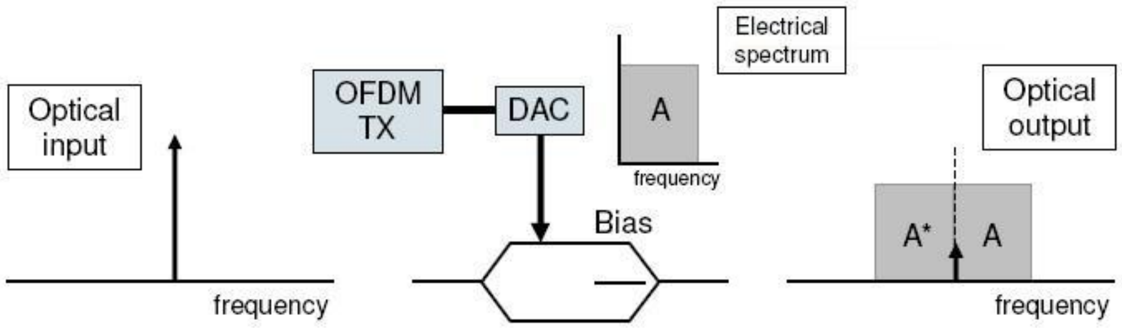


Figure 2.7 Double sideband effect produced by IM/DD modulation [P1]

The duplicated sideband generated by the MZM entails some considerable disadvantages for the optical OFDM systems. The main disadvantage is the chromatic dispersion fading. This undesirable effect will be explained later in subchapter 2.4.

2.3. Optical demodulation techniques

There are basically two detection techniques: direct detection (DD) and coherent detection (CO-D) [T1]. For this Master thesis, the direct detection has been chosen because it is simple and cost-effective. Although the coherent detection has positive contributions, it has higher design requirements because of the use of a local oscillator. It also requires a polarization control and needs phase noise compensation. For this reason, only the direct detection will be explained next.

2.3.1. Direct detection (DD)

For direct detection it is only required a photodiode. To describe its functioning mathematically, the Equation 2.7 has to be taken into account.

$$I(t) \propto |x(t)|^2 \tag{2.7}$$

The detected photocurrent is obtained by applying the square modulus operation over the low-pass equivalent of the incoming optical field.

The square modulus operation generates second-order harmonics and intermodulation products which, in and ideal IM/DD transmission, will be mutually cancelled. In this way, the received signal is an exact replica of the modulation signal.

Conversely, under the effect of chromatic dispersion, the necessary phase relationships between the modulated signal spectral components are altered and it is found that the received signal is affected by nonlinear distortion. This is explained in detail in the following subchapter.

2.4. IM/DD and the Chromatic dispersion effect

As explained in subchapter 2.1.1, fiber propagation has mainly the effect of adding a phase shift which is different for every frequency component in the signal. The difference in phase shift among frequency components is proportional to the propagated fiber length and to the square of the spectral distance between them.

For IM/DD systems three are basically the effects of chromatic dispersion in the quality of the detected signal: frequency selective fading, intermodulation mixing products and carrier-sideband phase noise decorrelation. These effects are explained in the following subsections.

2.4.1. Frequency selective fadings effect

The chromatic dispersion fading effect is a direct result of the double sideband nature of the IM modulation signal. When recovering the signal by using DD, both bands mix with the carrier and add together in the same electrical frequency. Due to chromatic dispersion, they have different phase shifts, and, as a result, there could be destructive interferences between them that cancel or, at least, attenuate the signal in reception. The effect is analogous to the image frequency effect in heterodyne transmission systems. As an illustration, Figure 2.8 shows the optical spectrum of a double sideband signal obtained with a MZM in quadrature point in the VPI software. The double sideband can be removed by means of an optical filter. However, that eliminates the possibility of changes in the operative wavelength (no colorless operation), and depends on the performance of the optical filters being used. In the context of optical networks, efforts should be directed towards finding solutions that do not include optical filtering in the ONUs.

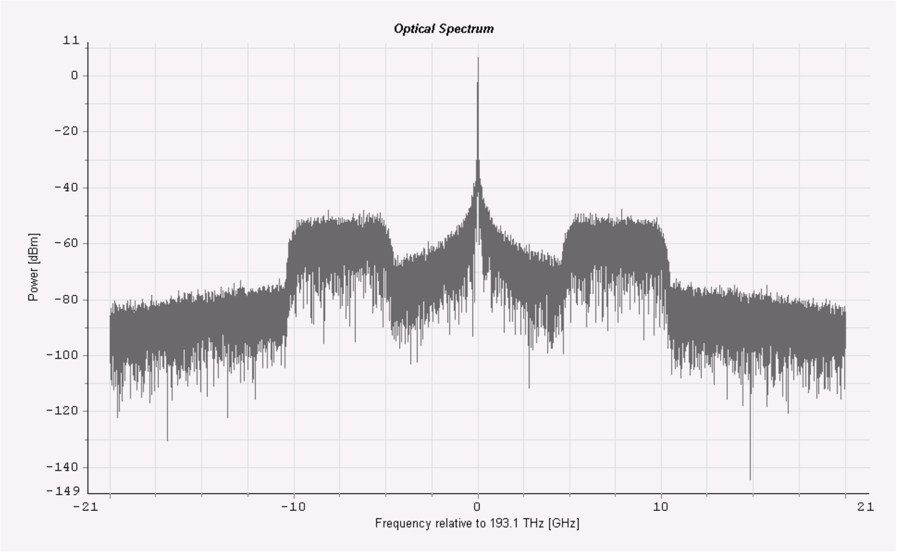


Figure 2.8 Double sideband produced by the IM/DD system [VPI]

2.4.2. Intermodulation mixing products effect

Due to the square-law transfer function of the photodiode (Equation 2.7), the electrical detected signal is the result of the mixing of the different optical spectral components. The information signal is obtained as the mixing of the OFDM sideband and the carrier whereas the mixing between subcarriers gives rise to intermodulation products. In a back-to-back (B2B) IM/DD system, the generated intermodulation products have the precise amplitudes and phase, so that they mutually cancel. In the Figure 2.9, an ideal case is represented.

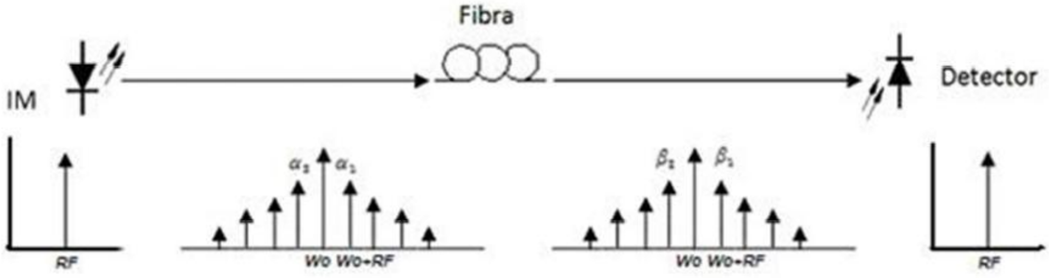


Figure 2.9 Intermodulation mixing products cancelled in an ideal case [T1]

When there is fiber, the effect of chromatic dispersion alters the necessary phase relationships among the spectral components with the result that some intermodulation products appear at the photodiode output, as seen in the Figure 2.10.

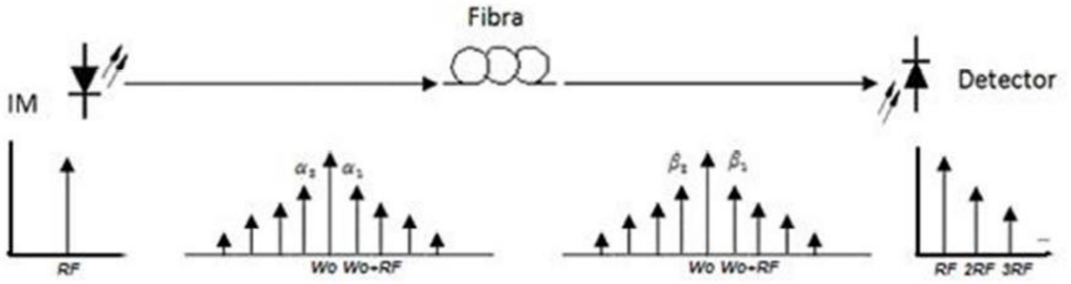


Figure 2.10 Undesirable intermodulation mixing products at the output of the photodiode [T1]

If a spectral guard band is left between the optical carrier and the information sideband whose width equals the information sideband, the intermodulation products will not interfere with the signal.

2.4.3. Carrier-sideband phase noise decorrelation

One of the main advantages of IM/DD is their robustness against phase noise fluctuation of the light source. Since the optical carrier and sideband are phase noise correlated, the detected signal coming from their mutual mixing is free from phase-noise. This is only true to the extent that the signal does not travel a too long fiber distance. The Figure 2.11 shows the effect graphically.

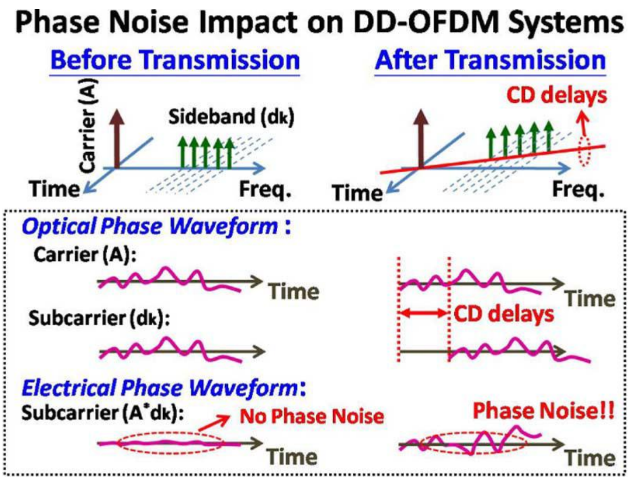


Figure 2.11 Phase noise decorrelation [P3]

Unfortunately, when the fiber distance is long, there appears a phase noise decorrelation between the optical carrier and the information. To solve this effect, pilot tone equalization techniques can be used [P3].

CHAPTER 3. OPTICAL OFDM SYSTEMS AND VPI SOFTWARE

3.1. Introduction

In Chapter 1, it was explained that the OFDM signal is naturally a complex signal with in-phase and in-quadrature components and that performance heavily relies on the equalization of the channel, which is assumed to be well described by a linear input-output transfer function. On the other hand, in Chapter 2, it was shown that an optical transmission system is naturally an intensity modulation and direct detection system, which modulates only the intensity of the signal and it is intrinsically non-linear due to the effect of chromatic dispersion.

Then, it is obtained that, on the one hand, it is necessary to modulate phase and quadrature components and to have a linear channel and, on the other hand, one has an intensity modulation (only one component) and an intrinsically nonlinear channel.

At present, there are many different alternatives to optical OFDM systems. An extensive review can be found in [T1, T3 and T5]. For its simplicity, we have chosen here the IM/DD with electrical RF IQ upconversion format. This format is explained in subsection 3.2.

Also, the software used to simulate the optical OFDM system, VirtualPhotonicsInc (VPI) will be described. The software includes an example demo for an optical OFDM system optimized for Long-Haul applications, which is based on an IM/DD with RF upconversion optical OFDM format. Even when our focus is optical networks, this demo helps us to understand how to apply the OFDM systems theory to optical transmission systems and to simulate some impairments related to the simultaneous propagation of optical OFDM signals coming from different users, such as for example the Optical Beat Interference (OBI).

Therefore, a detailed explanation will be provided along with interesting capabilities offered by the software, from which a lot of benefits have been taken, when designing the simulations in this Master thesis.

The VPI modules, and specifically the OFDM coding and decoding, that are used in the OFDM for Long-Haul Transmission demo, will be the basis of the simulations and work presented in chapter 4, whereas, for the work related to the simultaneous detection of multiplexed users, provided in chapter 5, the OFDM coding and decoding modules in Matlab have been required [T1 and T3] to program the new features that are not implemented in the demo.

So that, both OFDM coding and decoding would be explained through this chapter.

3.2. Optical IM/DD system with RF-upconversion

Figure 3.1 shows the basic scheme of an IM/DD with RF upconversion optical OFDM system.

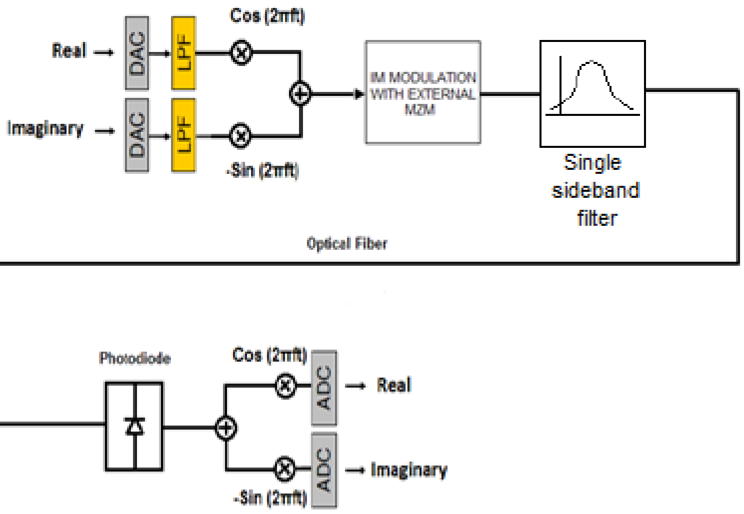


Figure 3.1 IM/DD with RF upconversion optical OFDM system [T5]

As seen, the two outputs of the DACs carrying the real and imaginary parts of the electrical OFDM signal are in-phase and in-quadrature respectively upconverted to an RF frequency. Then, they are added up and fed to the optical IM modulating device, an MZM biased in the quadrature point in the simulations in this Master Thesis.

The necessary channel linearity for equalization is achieved in this o-OFDM format by choosing an electrical frequency f_{RF} such as f_{RF}=1.5 BW, with BW the total bandwidth of the OFDM signal. That ensures both that the optical higher order sidebands generated by the IM modulation will not spectrally overlap, and that the electrical second-order products, generated by the photodiode in detection, will fall outside the signals bandwidth and can be filtered out in reception. See Figure 3.2.

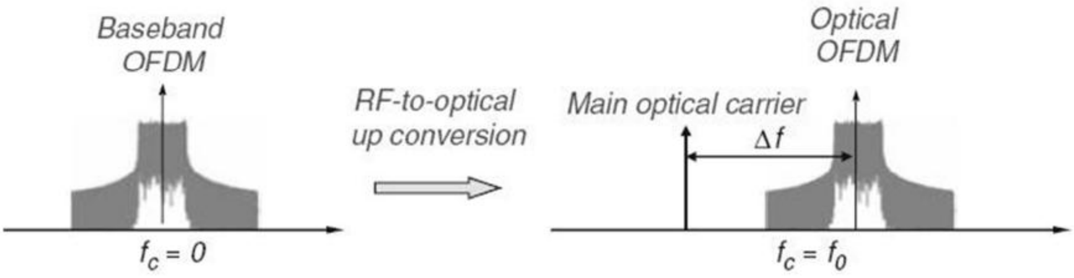


Figure 3.2 Electrical upconversion of the OFDM baseband signal [B1]

An optical SSB filter can also be in place to prevent CD amplitude fadings, but depending on the bandwidths and reach of the application, we will try to avoid it for colorless operation.

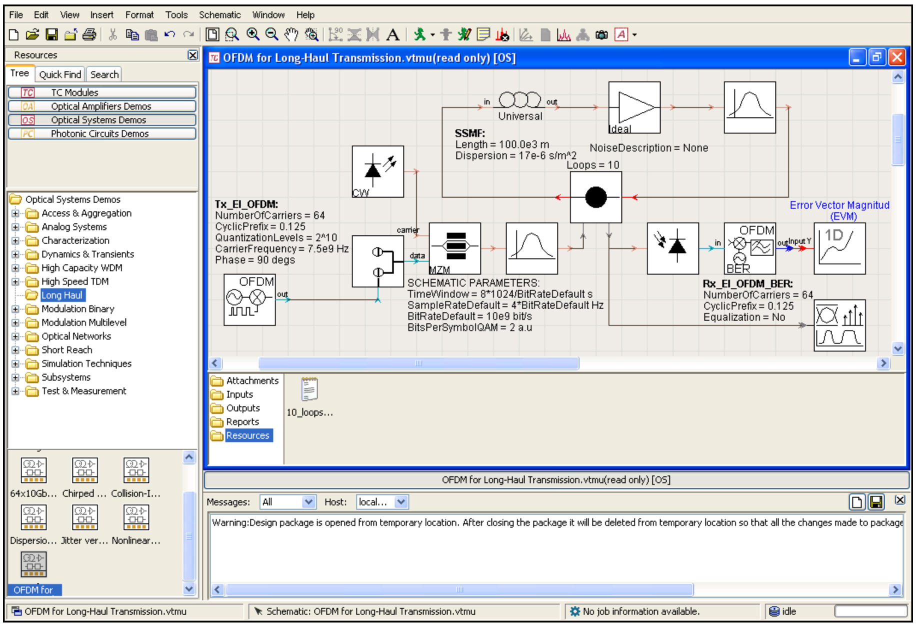
3.3. VPI software

The VPI suite gathers a set of software applications designed for running photonic simulations. From this suite, VPI TransmissionMaker Optical Systems is the used application for the research of Multiple user connection strategies for optical OFDM networks in the context of this Master thesis.

However, the OFDM coding and decoding modules offered by VPI are not transparent and do not offer the flexibility required by all the tests that we want to perform. For this reason, the UPC research group decides to create its own blocks making use of the VPI capability to interconnect with other modeling softwares such as Matlab [T1, T3 and T5]. This can be done by means of the cosimulation blocks, explained in subchapter 3.3.4.

3.3.1. Hierarchical distribution and modular design

The VPI software is based on a hierarchical distribution and uses interconnectable blocks. Those blocks simulate devices such as coders, fibers, spectrum analyzers..., as seen in the Figure 3.3. Each of these blocks has tunable parameters to adjust different behaviors. The blocks have documentation sheets in order to explain their utility and the different settings for their parameters.



SSMF:
Length = 100.0e3 m
Dispersion = 17e-6 s/m^2

NoiseDescription = None

Loops = 10

Tx_El_OFDM:
NumberOfCarriers = 64
CyclicPrefix = 0.125
QuantizationLevels = 2^10
CarrierFrequency = 7.5e9 Hz
Phase = 90 degs

SCHEMATIC PARAMETERS:
TimeWindow = 8*1024/BitRateDefault s
SampleRateDefault = 4*BitRateDefault Hz
BitRateDefault = 10e9 bit/s
BitsPerSymbolQAM = 2 a.u

Rx_El_OFDM_BER:
NumberOfCarriers = 64
CyclicPrefix = 0.125
Equalization = No

Warning:Design package is opened from temporary location. After closing the package it will be deleted from temporary location so that all the changes made to package

Figure 3.3 VPI universe

In addition, VPI software includes some structured designs called “demos” such as the Long Haul. This demo shows a point to point optical OFDM system that uses IM Mach-Zehnder modulation and direct detection with RF upconversion. See Figure 3.3.

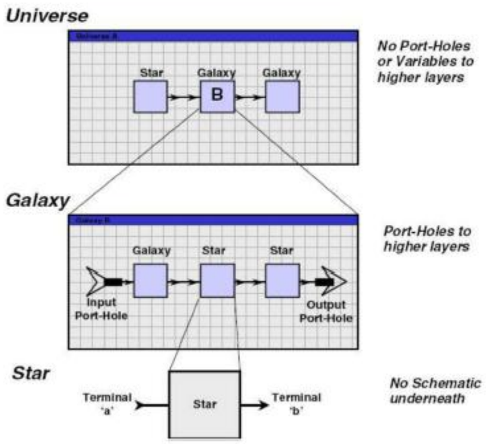


Figure 3.4 Hierarchical distribution [T3]

In Figure 3.4, it can be seen the hierarchical distribution graphically.
Without more ado, the hierarchical distribution in levels will be explained as follows:

Stars: Third level. It contains an indivisible element with a specific functionality. It has either inputs or outputs, or both.

Galaxies: Second level. It is composed of stars and galaxies interconnected. The galaxies can show its internal design if a “Look inside” is allowed in the settings menu. It has either inputs or outputs, or both, that are then used in a higher level galaxy or in the universe.

Universe: First and top-most level. It is composed of several stars and galaxies interconnected. It is the only module where the simulation can be run by the user.

The universe is the level where the user can run the program. For this reason, the simulation parameters are located at this stage. This means that these parameters are global, this is to say, they can be used inside the galaxies and stars if it is necessary.

3.3.2. Global parameters

VPI provides a set of defined global parameters that are used for the simulator. The most relevant are listed below:

- TimeWindow: This parameter sets the length in time in which a block of data is represented. This time will inevitably define the spectral resolution of the simulated signals. It is linked to the bit rate since an integer number of bits needs to be simulated.

$$TimeWindow = \frac{N}{BitRateDefault} \text{ [s]} \tag{3.1}$$

  Where N is the total number of bits in the simulation.

  Thus, it can be seen in Equation 3.1 that the TimeWindow should comprise an integer number of bits; otherwise, the program will fire an error.

- SampleRateDefault: It determines the number of samples taken by second. This value determines the maximum simulation frequency limited by the Nyquist rate. In addition, the value of this parameter is directly related with the resolution in the time domain.

  When working with periodic signals, the following condition has to be accomplished due to the fact that VPI works with the FFT algorithm, Equation 3.2.

$$\begin{gathered} \#samples = TW.SR = 2^m \\ with\ m\ an\ integer\ number \end{gathered} \tag{3.2}$$

  Finally, the SampleRate is defined as follows, Equation 3.3.

$$SR = \frac{2^m}{N \cdot BR} \text{ [Hz]} \tag{3.3}$$

- BitRateDefault: It defines the rate at which bits are transmitted through the system. Thus, the transmitting bandwidths depend on this value. Due to the fact that this thesis is working with multilevel modulation schemes, the symbol rate has to be also considered in Equation 3.4.

$$SymbolRate = \frac{BitRate}{BitsPerSymbol}\left[\frac{symbols}{second}\right] \tag{3.4}$$

3.3.3. Cosimulation

The cosimulation block allows some part of the simulation be handled by a programming engine external to VPI. For this reason, some processing data may be run by Matlab or Phyton.

The cosimulation feature is composed by three modules. It can be seen in Figure 3.5.

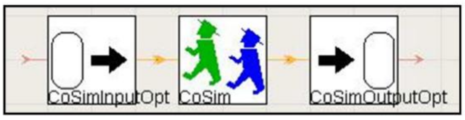


Figure 3.5 Cosimulation composition

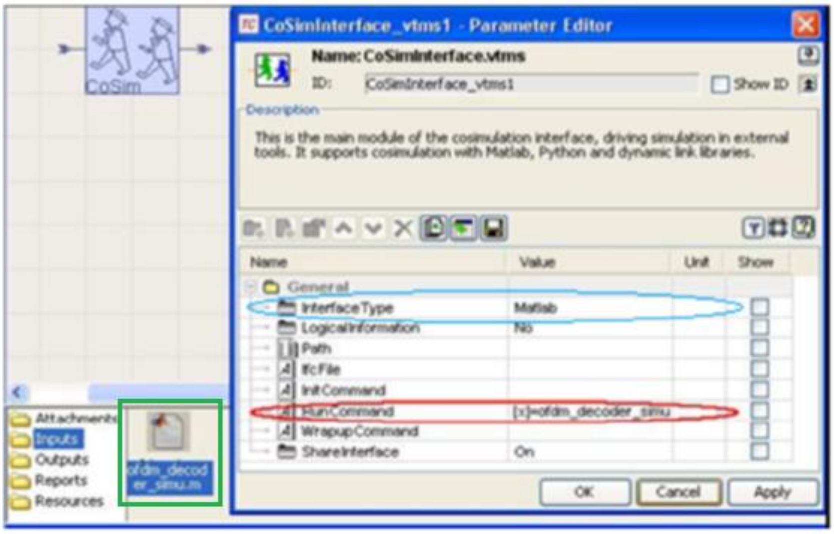
It can be seen that there is an input and an output. The block in the middle is called CosimInterface and it is the block where the code is executed.

The CosimInterface has an internal parameter called RunCommand. This parameter is where the function is called. As the programming engine is Matlab, the function calling looks like:

$$OutputName = FunctionName(opticalOrElectricalInput, global\ parameters, single\ variables)$$

- The OutputName is the output of the function. This is the output which the CosimInterface sends to the CoSimOutput. The CoSimOutput block is dedicated to decide the name of the output and its type of data.

- The FunctionName is the name of a Matlab attached file, shown in Figure 3.6.



Name: CoSimInterface.vtms
ID: CoSimInterface_vtms1 ☐ Show ID

Description

This is the main module of the cosimulation interface, driving simulation in external tools. It supports cosimulation with Matlab, Python and dynamic link libraries.

Name	Value	Unit	Show
General			
InterfaceType	Matlab		☐
LogicalInformation	No		☐
Path			☐
tfcFile			☐
InitCommand			☐
RunCommand	[x]=ofdm_decoder_simu		☐
WrapupCommand			☐
ShareInterface	On		☐

Figure 3.6 Attached file and main parameters of the CosimInterface

The InterfaceType can be seen highlighted in blue, the RunCommand in red, and finally, the location of the attached Matlab file in the VPI project tree is indicated by a green square.

- The opticalOrElectricalInput is the input provided by VPI simulation. This is relative to the CoSimInput. This block is dedicated to decide the name of the input and its type of data.

- The global parameters or single variables are relative to the parameters in each galaxy.

In chapter 5, the cosimulation blocks will be explored in detail because the coding and decoding and the multiple user connection strategies are performed by means of Matlab programming.

3.4. Long-Haul Transmission demo

The Long-Haul Transmission demo is an optical OFDM system demo provided by VPI. This demo consists in a transmission over 1000 km optical fiber link with IM/DD with RF upconversion optical OFDM system, explained in section 3.2.

3.4.1. Scenario and outputs

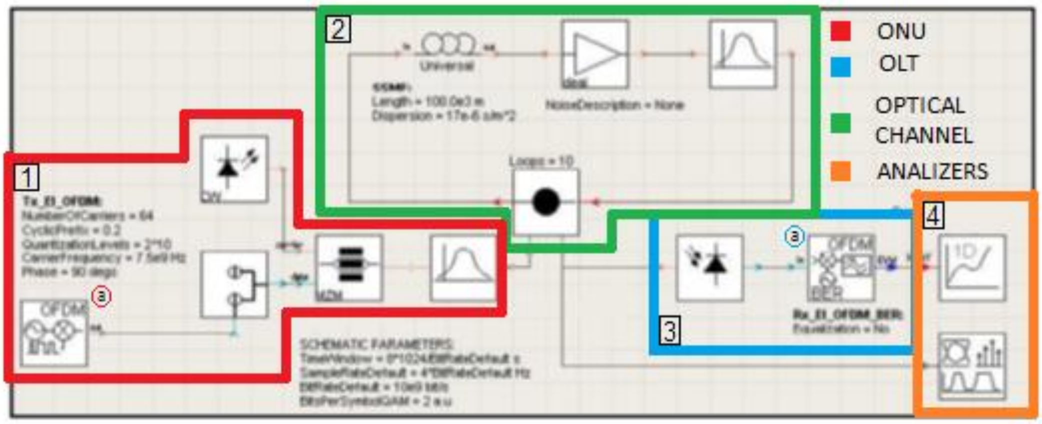


Figure 3.7 Long-Haul demo universe

The Figure 3.7 shows the Universe of the Long-Haul Transmission Demo. In the figure, the different parts of the system have been highlighted: the ONU can be seen in red, the optical channel is distinguished in green, the OLT is highlighted inside the blue box and, finally, the analyzers can be seen in orange. The stages are numerated and some components have letters. The numbers correspond to the elements in the system and the letters refer to those stages that can be looked inside. With these instructions, the elements are explained as follows:

1) ONU: The Optical Network Unit is the user equipment. It is composed by the electrical OFDM transmitter and the optical modulation stage comprising: the

laser, the drive amplitude, the Mach-Zehnder modulator and the single sideband filter.

   a) The electrical OFDM transmitter galaxy is composed by the OFDM coding, the pulse shaping and the RF upconversion. The internal structure of this galaxy is discussed in section 3.3.4.2.

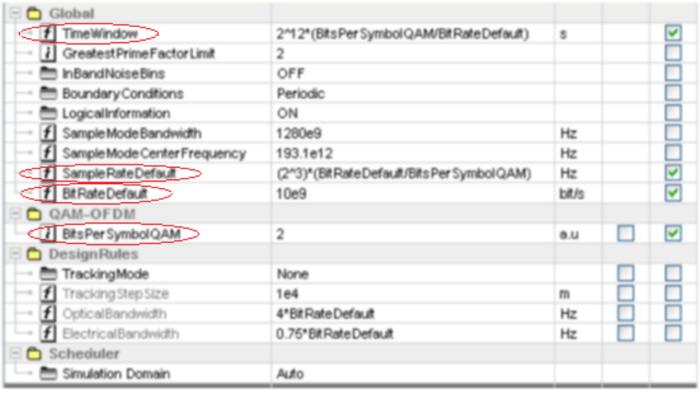
2) Optical Channel: The optical channel is the physical medium which the information is sent through. The fiber is described as a number of loops in order to put amplifiers and filters at a certain number of kilometers. The elements involved are the fiber, the amplifiers and the filters for each loop.

3) OLT: The Optical Line Terminal is where the information of a group of users is processed. Since we focus in the uplink direction, this is the receiver in this simulation. As the demo is operating with a direct detection modulation, the OLT is composed by the photodiode for detection and an electrical OFDM receiver.

   a) The electrical OFDM receiver galaxy is composed by the OFDM decoding, the RF downconversion and the equalization. The internal structure of this galaxy is discussed in section 3.3.4.4.

4) Analyzers: The VPI software has some analyzers to show the signal behavior. In this demo, there are three kinds of output results: the received constellation, the Error Vector Magnitude (EVM) at the receiver output and the spectrum at the receiver input.

The universe parameters can be seen in the Figure 3.8.



Global				
TimeWindow	2^12*(BitsPerSymbolQAM/BitRateDefault)	s		☑
GreatestPrimeFactorLimit	2			☐
InBandNoiseBins	OFF			☐
BoundaryConditions	Periodic			☐
LogicalInformation	ON			☐
SampleModeBandwidth	1280e9	Hz		☐
SampleModeCenterFrequency	193.1e12	Hz		☐
SampleRateDefault	(2^3)*(BitRateDefault/BitsPerSymbolQAM)	Hz		☑
BitRateDefault	10e9	bit/s		☑
QAM-OFDM				
BitsPerSymbolQAM	2	a.u	☐	☑
DesignRules				
TrackingMode	None		☐	☐
TrackingStepSize	1e4	m	☐	☐
OpticalBandwidth	4*BitRateDefault	Hz	☐	☐
ElectricalBandwidth	0.75*BitRateDefault	Hz	☐	☐
Scheduler				
Simulation Domain	Auto			

Figure 3.8 Universe parameters

The most important parameters are those that are highlighted. For the desired 10 Gbps bitrate simulation with 4-QAM modulation, it is required a 5 GHz bandwidth. Therefore, the RF carrier is set at 7.5 GHz in order to generate a 5 GHz guard band to avoid the intermodulation mixing products.

Since the SampleRateDefault is 4 times larger than the required optical bandwidth (10 GHz), the Nyquist theorem is accomplished. Finally, the TimeWindow is 8,192 µs. This means that according to the BitRate, the number of bits in this simulation is 8192.

The universes and galaxies, in addition, allow the user the option of showing the internal parameters.

From now on, the three main stages in the universe will be explained in detail: ONU, OLT and optical channel. Furthermore, since the software is hierarchical, the explanation is done from outside to inside.

3.4.2. ONU

The ONU, which comprises both the electrical OFDM transmitter and the modulator, can be seen in Figure 3.9.

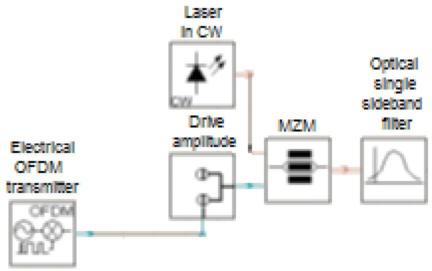


Figure 3.9 ONU

3.4.2.1. *Electrical OFDM transmitter galaxy*

By ‘Look-inside’ clicking on the electrical OFDM transmitter galaxy in the universe (the block at the left in Figure 3.9), the Figure 3.10 is obtained. It can be seen that the galaxy is composed by 5 elements: a pseudo-random bit generator, the OFDM coding, pulse shaping and RF upconversion stages and, finally, the LogicAddChannel.

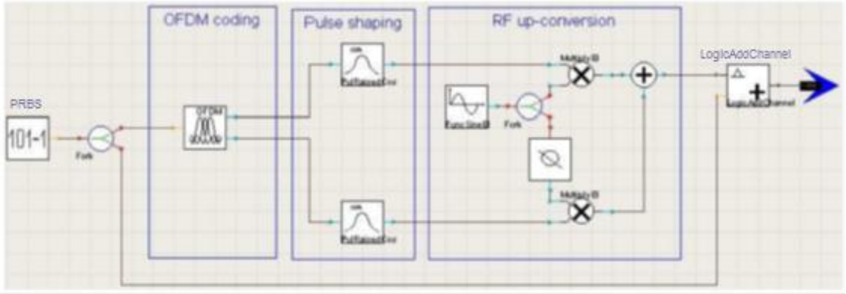


Figure 3.10 Electrical OFDM transmitter galaxy

- ***Pseudo-Random bit generator:*** Its name is PRBS (Pseudo Random Bit Sequence). This block is in charge of generating the bit sequence that will travel through the system. The sequence length is the number of bits in the transmission: *TimeWindow*BitRate*.

- ***OFDM coding stage:*** It is the block where the codification of the bits for the transmission is done, as well as the insertion of some overheads. The "look inside" operation is not allowed and therefore we cannot know exactly which are the operations performed over the input sequence in order to get the OFDM modulation, and we also cannot add or change any of the features. Two significant operations are explained as follows:

    - ***Cyclic prefix:*** There is a Cyclic Prefix insertion to avoid ISI. By default, a 20 % of the number of FFT samples is used for this overhead. This value is tunable but it has to be always a percentage of the total FFT size.

    - **Upsampling operation:** The OFDM output symbols are oversampled in order to obtain the simulation sequence. That is how the DAC operation is simulated in the software. In order to select the number of samples for a simulation, it has to be considered that, the larger it is, the more realistic the simulation, but also the slower.

$$factor = \frac{SampleRateDefault}{\frac{BitRateDefault}{BitsPerSymbolQAM}} \tag{3.5}$$

- ***Pulse shaping stage:*** It is a raised cosine with a roll-off factor of 0.2.

- ***RF upconversion stage:*** A complex RF upconversion is done with an RF=7.5 GHz.

- ***LogicAddChannel:*** This block is useful for the modules to share the sent information. For example, it contains the original PRBS signal and this will be useful for the BER calculations and the trainings, where the real bit sequence and the received sequence will be compared.

The study of the OFDM systems basis, provided in Chapter 1, allows to figure out the structure of the OFDM coding and decoding modules in order to replicate them by using Matlab programming and, even in some cases, to provide more advanced functions. In addition, since the internal structure of the module is completely transparent to the person carrying out the simulations, exact knowledge of the functions performed over the signal and the effect of every parameter on the final outcome is provided. Customization of the tests is possible by making changes directly over the Matlab code.

3.4.2.2. Optical modulation in the ONU

It is composed by a MZM whose electrical and optical inputs are, respectively, the electrical OFDM transmitted signal connected to the MZM driver and a laser in continuous wave (CW).

The laser driver sets the optical modulation index relative to the half-wave voltage of the MZM. The electrical OFDM transmitter output is multiplied by the value set in the driver before inserting the output in the MZM.

The bias parameter in the MZM is fixed to 0.5 because it is working in the quadrature point (QP) for IM. The laser is in charge of providing the optical carrier to be modulated in the MZM. The most important parameters are as follows:

- Emission frequency: 193.12 THz
- Average power: 5 mW
- Linewidth: 1 MHz

The single sideband filter is connected at the output of the MZM. As explained previously (section 2.4.4), the filter suppresses the lower sideband.

3.4.3. OLT

The OLT, which comprises both the demodulator and the electrical OFDM receiver, can be seen in Figure 3.11.

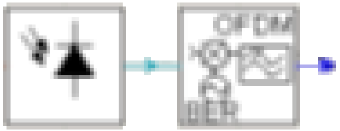


Figure 3.11 OLT

3.4.3.1. Optical demodulation in the OLT

It is composed by a photodiode working in direct detection configuration. Its parameters are:

- Photodiode model: PIN
- Responsivity: 1A/W

Furthermore, chromatic dispersion is compensated by correcting the phase shifts perceived in the photodiode by means of the equalization.

3.4.3.2. *Electrical OFDM receiver galaxy*

By ‘Look-inside’ clicking on the electrical OFDM receiver galaxy in the universe (the block placed at the right in Figure 3.11), the demodulation galaxy can be seen. It is depicted in Figure 3.12 and performs the reverse operation done in the transmitter.

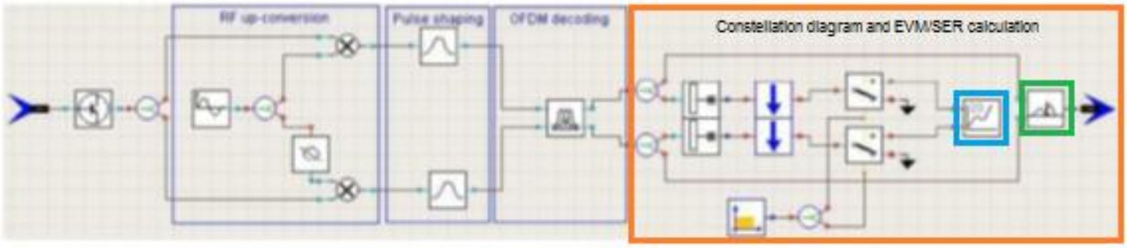


Figure 3.12 Electrical OFDM receiver galaxy

There are the same stages than in the electrical OFDM transmitter galaxy but in the reverse order. However, there is a new stage inside the orange box to calculate the constellation diagram (inside the blue square) and the EVM or SER (highlighted inside the green square). This is the constellation constructor.

In addition, the OFDM decoding performs equalization by inserting some given coefficients that are only useful for the parameters of this specific demonstration. This equalization is optional and the user can choose if it is applied or not.

3.4.4. Fiber links and filters

The channel and its elements can be seen in Figure 3.13.

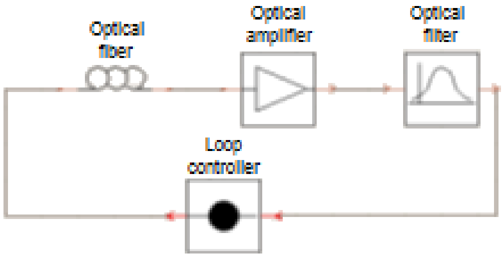


Figure 3.13 Optical channel

To work with the same conditions than in a practical scenario, the fiber link is done with a loop. In each loop, the losses are compensated by means of an optical amplifier. In addition, since the ASE noise (Amplified Spontaneous Emission) appears due to the amplification, an optical filter is inserted to restrict it at the detection spectral band. The demo is constructed, thus, with 10 loops of 100 Km each loop.

3.5. OFDM coding and decoding performed with Matlab code for point-to-point simulations

This late in the Master thesis, as it is explained in the Introduction, there are two available options for the coding and decoding modules. Those offered by VPI are not so much flexible and scalable, so that, in [T3], the coding and decoding with Matlab embedded through the cosimulation feature was decided to be designed.

In chapter 5, it will be considered that, due to the different techniques that appear in the coding and decoding of a multiuser schema, it is necessary to use the optimized Matlab code provided in [T3].

So that, the Matlab coding and decoding advanced techniques incorporated in this module are explained as follows. With the intention of not overloading this subchapter, only the key techniques will be taken into account.

3.5.1. FFT symmetry and Zero padding

The FFT symmetry, explained in subchapter 1.3, is the fact that the last half of the IFFT samples at the coding becomes shifted to the beginning of the stream, thus, disordering the samples. In a point-to-point scenario this phenomenon is solved by itself because at the decoding stage the FFT is performed, and, another time, the shift is done in the same manner and the disorder is cancelled.

The shift is produced due to the fact that the spectrum has to be symmetrical. So, as explained in the subchapter 1.3, the sample that is left at the edges is exactly the same. Thus, the sample is repeated in both positive and negative frequencies.

When a Zero padding strategy is done to shift the alias generated by the roll-off factor of the DAC, it has to be taken into account that the zeros must be introduced in the middle of the IFFT input to find the zeros at the edges at the output of the IFFT. In [B3], there is a detailed explanation of this technique.

The coding and the coding modules in Matlab provide a technique that consists of a vector that contains the zero positions. This vector is allocated in the global parameters and provides flexibility because there are other zero padding techniques that can be applied without any change in the code.

This vector, called *ZP_mask*, will be very useful for the multiuser scenario in the chapter 5. It can be seen the code in the Figures 3.14 and 3.15.

```
%% Zero padding is inserted to obtain a matrix of size (N_FFT x
NTS_OFDM)
A_ones = ones(1,N_FFT); % Vector of ones with length N_FFT
A_ones(ZP_Mask) = 0; % Insert in the ones vector the zeros
introduced by the user in ZP_Mask
Nc_Mask = find(A_ones); % Generate a new vector Nc_Mask with the
positions where it has to be information
xx1_OFDM_ZP = zeros(N_FFT, NTS_OFDM); % Generate a zeros matrix of
N_FTT x NTS_OFDM
xx1_OFDM_ZP(Nc_Mask,:) = xx1_OFDM_INFO; % Fill in the zeros matrix
with information in the positions indicated by Nc_Mask
```

Figure 3.14 Matlab's code snippet: Zero padding addition

```
%% Zero Padding extraction
A_ones=ones(1,N_FFT); % Vector of ones with length N_FFT
A_ones(ZP_Mask) = 0; % Insert in the ones vector the zeros
introduced by the user in ZP_Mask
[Nc_Mask] = find(A_ones);% Generate a new vector Nc_Mask with the
positions where it has to be information
yy1_QAM=yy1_FFT(Nc_Mask,:)% Generates a matrix with only information
provided by the Nc_Mask
```

Figure 3.15 Matlab's code snippet: Zero padding extraction

3.5.2. Cyclic Prefix

The CP insertion is always done as explained in 5.3, but we have considered in this Master Thesis two possibilities for the CP extraction.

The first possibility is equal to the extraction in the Long-Haul Transmission Demo. The CP is inserted taking the last part of the sequence with CP extension and placing it at the beginning of the sequence. Then, the CP is extracted by removing the first part of the sequence with CP extension.

The second possibility is related to the software choice of reference frequency in the fiber, which is actually simulating the synchronization in the receiver [T3]. Due to the software choice of the reference frequency is just at the middle of the signal, the TimeWindow begins at this point and the information before the reference frequency is moved to the end of the sequence (See Figure 3.16). According to the analysis in [T3], this is the correct extraction for the settings in the VPI simulator.

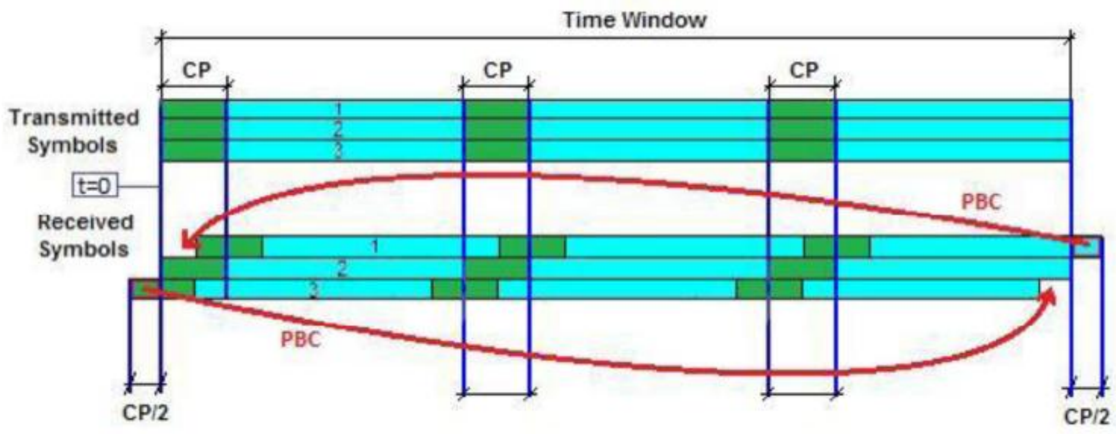


Figure 3.16 Strategy for the cyclic prefix extraction [T3]

```
%% Cyclic prefix is added to each OFDM symbol
     xx1_CP=[xx1_IFFT(1+N_FFT-CP:N_FFT,:);xx1_IFFT];
```

Figure 3.17 Matlab’s code snippet: Cyclic Prefix insertion

```
%% Remove CP
% move the last half CP at the start of string (before or after
removing
yy1_CP_OUT = yy1_SP(CP_length/2+1:FrameLength-CP_length/2,:);
```

Figure 3.18 Matlab’s code snippet: Cyclic Prefix extraction

3.5.3. Normalization

The coder output of the Long-Haul Transmission demo has a normalization performed with the purpose of obtaining a maximum unity modulus in its largest temporal sample.

At the decoder the same operation is done to the input sequence so that its largest sample has unity modulus.

```
% Normalization at the output of the OFDM coder
h = modem.qammod('M',BpS);
const = h.modulate(0:BpS-1); % “const” are all the values that can
take the constellation and depends on the chosen modulation choose
by means of the BpS parameter
```

Figure 3.19 Matlab’s code snippet: Normalization at the output of the coding (1/2)

```
y = y./max(abs(const));
y = y./sqrt(2);
modul = sqrt(real(y).^2+imag(y).^2);
maxmod = max(modul);
y_real_mod = real(y)./maxmod;
y_imag_mod = imag(y)./maxmod;

% Electrical data packet send to the MZM
y = y_real_mod + y_imag_mod*1i;
```

Figure 3.19 Matlab's code snippet: Normalization at the output of the coding (2/2)

```
% Normalization at the input of the OFDM decoder
modul = sqrt(real(y).^2+imag(y).^2);
maxmod = max(modul);
y_real_mod = real(y)./maxmod;
y_imag_mod = imag(y)./maxmod;
% Electrical data packet to decode
y = y_real_mod + y_imag_mod*1i;
```

Figure 3.20 Matlab's code snippet: Normalization at the input of the decoding

3.5.4. Equalization

The equalization performed in the Long-Haul Transmission demo and the programmed in Matlab are following different techniques. One is based in user provided equalizer coefficients while and the other calculates them by using training sequences that is, comparing the sequence at the input with the sequence recovered in reception. When the channel is estimated, it can be applied to the received signal to correct the phase and amplitude levels.

So that, the demo equalization is provided of higher accuracy if both the Matlab decoding and the demo are compared [T3].

The Matlab decoding module allows the equalization to be done with the real PRBS sent through the system by means of the Logical Channels. The PRBS can be added to the function and, thus, the channel estimation can be done accurately.

The channel spectral response can be approximated by using a determined number of symbols. The Matlab decoding allows the user to decide this number of symbols by means of a variable called *N_training*. Thus, both transmitted and received symbols are compared using a matrix with the number of useful subcarriers in the rows and the *N_training* number of symbols in the columns.

3.5.5. Bit error rate calculation

This calculation is not available in the Long-Haul transmission demo. However, in optical systems is a very useful measure because the feasibility of the system is determined by a given BER threshold. The standard quality requirement for optical networks is a BER threshold at 10^{-3} in the worst case.

The code of the BER calculation is programmed using XOR operations to each bit to compare the input and output bits. Finally, the rate is obtained by counting errors and dividing the total number of errors by the total number of bits in the system.

CHAPTER 4.MULTIPLE USER CONNECTION STRATEGIES AND OBI MANAGEMENT

In the previous chapters, the OFDM modulation, the optical systems and the integration between OFDM modulation and IM/DD optical systems have been explained. From the many different options for optical OFDM systems [T1, T3 and T5], because it leads to more cost-effective solutions, the IM/DD with RF upconversion type of o-OFDM has been studied.

However, the systems presented are designed for point to point settings. For this reason, it has to be done a study of the strategies that can be used for an optical access network.

Some concepts about optical access networks are given as a basis in [T5].

As outlined in the introduction, the aim is to study the OFDM access strategies for the uplink. In those strategies, each user is assigned a different set of subcarriers. In an optical OFDM system, those subcarriers are modulated over an optical carrier. Different alternatives can be considered for the spectral location of the optical carrier of every user.

Because the optical carrier suppression using MZMs at the null point is a costly alternative, often requiring additional filtering for enough suppression [T1,T3 and T5], basically two are the options regarding the optical carrier at the ONUs: same wavelength or different wavelengths at a safety distance which ensures the interference falls below a quality threshold. Both strategies face in practice technical problems and also have advantages. It will be seen in the following paragraphs.

Firstly, we begin by analyzing the same wavelength case in section 4.1. It will be seen through simulations that, due to the decorrelation among optical carriers, a multiple detection effect is obtained that destroys the signal. The solution is to use an auxiliary carrier in detection.

In section 4.2, the different wavelength scheme is studied. In this case, the optical wavelengths of each user are located at a safety distance from each other, so that mixing products among signals coming from different users do not interact. Therefore, the multiple detection phenomenon is not found. Nevertheless, the number of users that can be multiplexed is limited by the available optical bandwidth.

In this chapter, the goal is to analyze the fundamental effects that appear when it is considered the simultaneous transmission of OFDM signals. This means that, it is focused on the possible interferences among the signals coming from different users. In other words, the effect of transmitting multiple optical carriers is studied by recovering only one user and neglecting the rest. Therefore, it is used both the OFDM coding and decoding of point-to-point systems, and specifically the modules provided by VPI.

4.1. Same wavelength case

In order to optimize the available spectrum, it is interesting and desirable ONUs using the same optical carriers. At the OLT, the information signals from the different ONUs can be detected in different electrical bands. See figure 4.1.

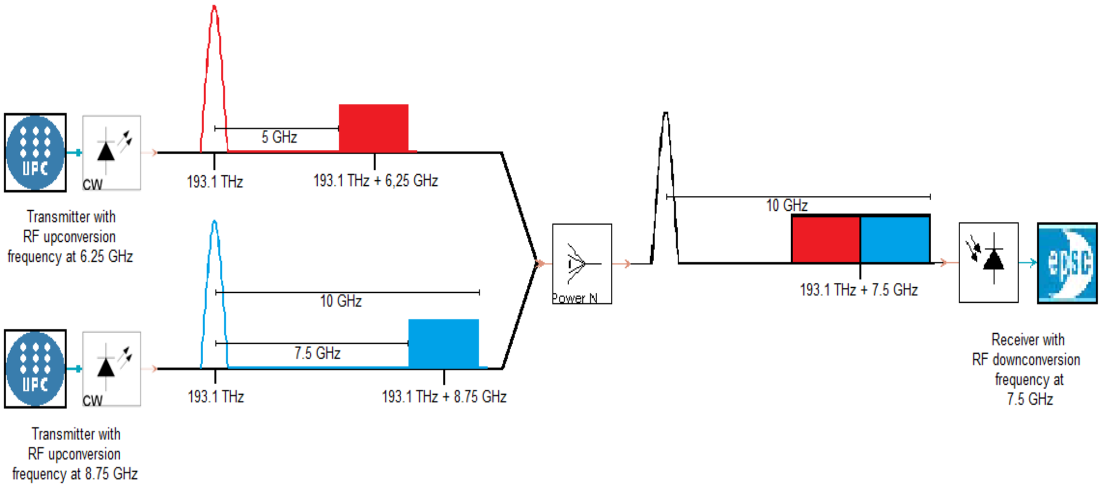


Figure 4.1 General schema of the same wavelength strategy

In the above example, it is considered that the two ONUs have the same bandwidth (same number of subcarriers) assigned. Since in this thesis work it is considered that all ONUs have the same QAM level, they also will have the same bit rate. In the OLT, the two ONUs sequences will be demodulated in an FFT block with twice the size.

It is worth noting that the spectral guard band for every ONU has to be equal to the total bandwidth of all ONUs together, if the original carrier wants to be used. In a practical case, two options can be chosen to generate the optical carriers: independent laser and remodulation.

- Independent laser: This option needs stringent requirements on the laser frequency to ensure exactly same wavelengths. It can be seen in the Figure 4.2, three independent lasers with the same optical carrier modulating three different users at different electrical frequencies.

- Remodulation: The optical carrier is generated and sent from the OLT and remodulated in the ONUs using Electro-Absortion Modulators. This schema suffers from Rayleigh backscattering issues and also amplifiers have to be added at the ONU side to recover loss due to the long distance travelled [B5]. The remodulation schema can be seen in Figure 4.3.

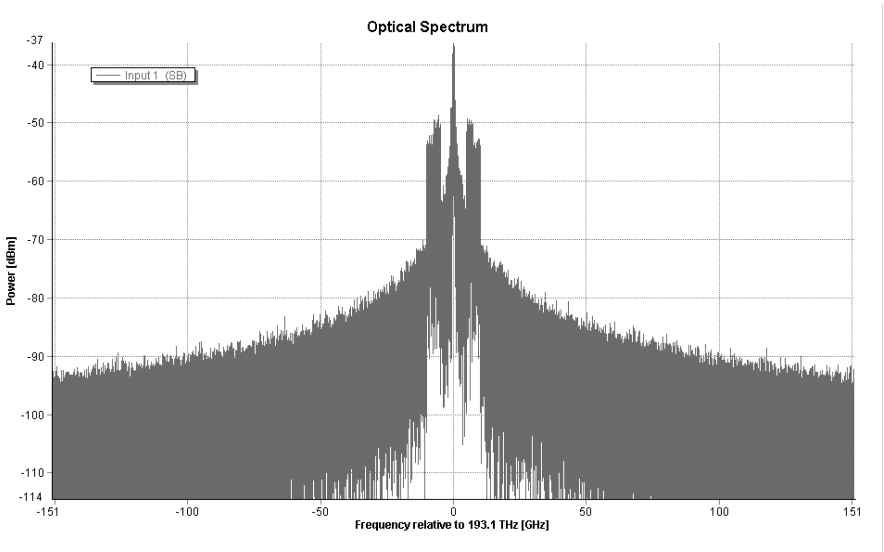


Figure 4.2 Optical spectrum for three independent laser modulating at the same wavelength

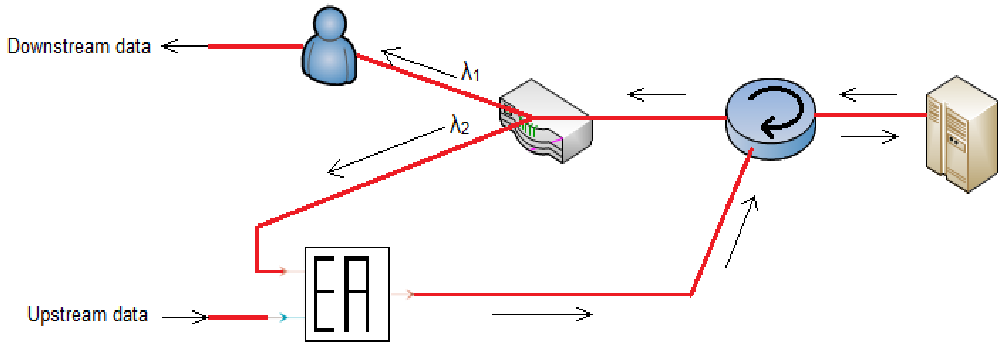


Figure 4.3 Remodulation schema

In either of the two options, even if the optical carriers are exactly at the same frequency, when directly detected at the OLT, the phase noise of the carriers coming from different ONUs will be decorrelated and multiple detection phenomena, such as those shown in section 2.4.2, will be obtained.

This means that, in practice, in order to properly recover the signal, an auxiliary carrier will be necessary in detection at a different spectral location. This auxiliary optical carrier will be decorrelated with respect to all the users' signals but, then, phase noise compensation can be performed for accurate decoding.

The decorrelation among lasers can be simulated in VPI by making use of the RandomNumberSeed. When this parameter is established at the same number (different from zero) for all the lasers, they will be correlated. When this value is different in each laser, or set to zero, they are decorrelated.

4.1.1. Same wavelength strategy simulations

At this moment, it can be done a simulation to check the effect of independent lasers transmitting information with the same wavelength but decorrelated.

The aim of this simulation is to know the reach of the effects of decorrelated lasers in the constellations. Unfortunately, the better calculation that can be done is the BER but it is not provided by VPI electrical OFDM receiver module. So the effect of decorrelated lasers has to be checked in the constellation diagram.

Figure 4.4 shows the general schema and some of the parameters taking part in the simulations. It can be identified in the scenario two ONUs transmitting information to an OLT. Both ONU lasers are transmitting an optical carrier with 193.1 THz frequency.

The red ONU is transmitting 16 carriers information at an upconverted frequency of 7.5 GHz.

The blue ONU is transmitting 16 carriers information at an upconverted frequency of 17.5 GHz.

Both ONUs sequences are modulated over a 4-QAM modulation, so that 2 bits per symbol is set in the parameters.

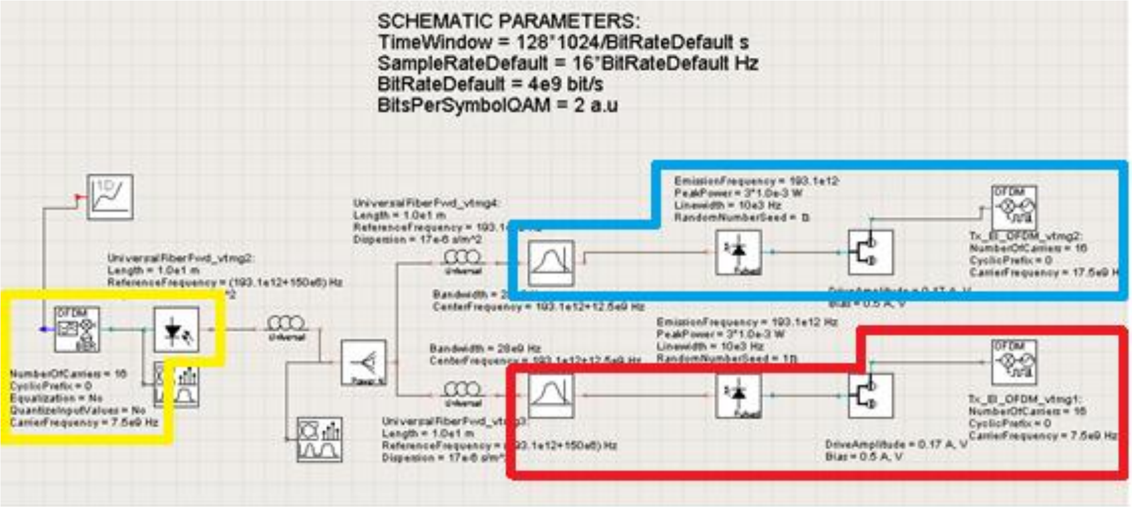


Figure 4.4 General schema of the simulation

The OLT is in charge of receiving the information of both ONUs. Its downconversion frequency is set to 7.5 GHz, so the information transmitted by the blue ONU is discarded because its electrical band is far away from the downconversion frequency. Although the blue one is discarded, the effects of its optical carrier are present in the optical spectrum and, thus, in the demodulation process. It can be seen in Figure 4.5 the optical spectrum.

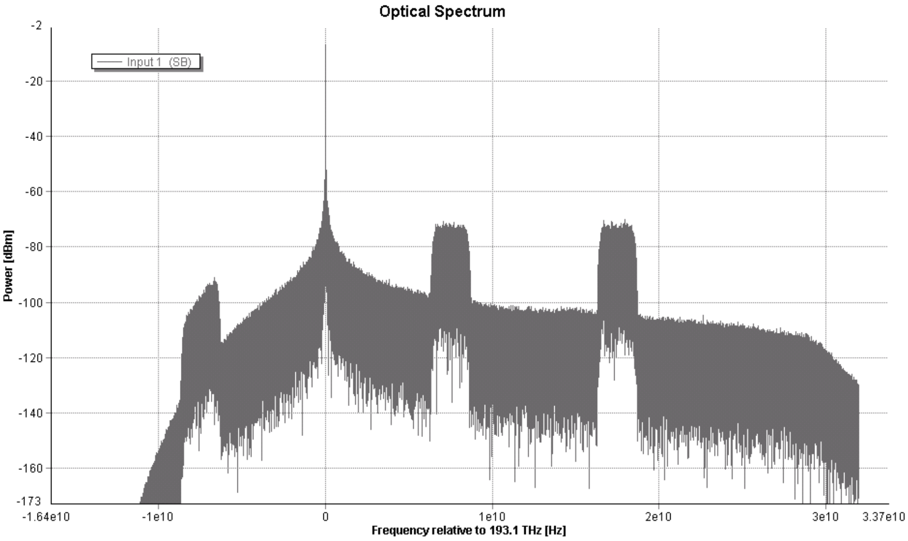


Figure 4.5 Optical spectrum

The optical carriers at a relative frequency of 193.1 THz can be seen. The two information carriers can be pointed at 7.5 GHz and 17.5 GHz respectively. The left sideband is not present because there is a single sideband (SSB) filter to avoid effect of frequency selective fadings.

The image depicted below in Figure 4.6 shows the effect of multiple detection with decorrelated optical carriers in the constellation of the demodulated ONU.

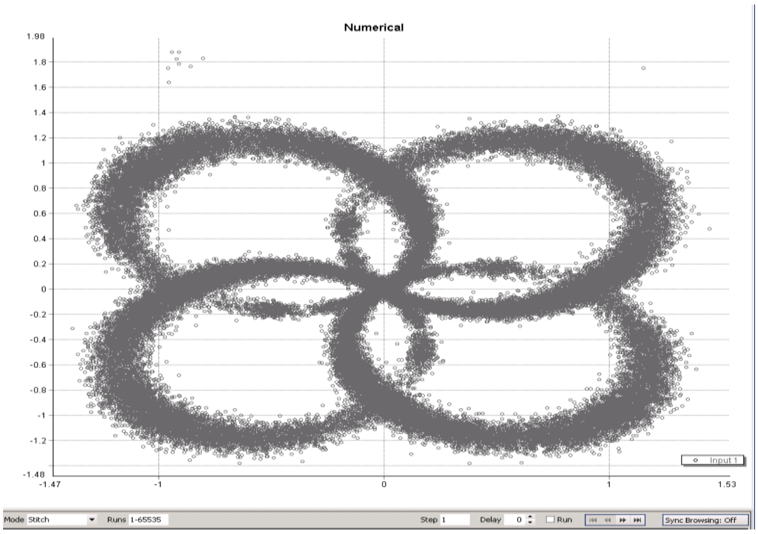


Figure 4.6 Constellation of the demodulated user

It can be seen that the obtained constellation is far from the ideal.

To gain some insight, and try to understand the obtained constellations, it can be considered that two carriers at the same wavelength but with different phase noise can be understood as fluctuating around the nominal carrier, in such a way that, at any given time, they have slightly different wavelengths. That allows us to use the mathematical model of two optical carriers with slightly different optical wavelengths to try to understand the simulation results.

Following the discussion in Chapter 1, it is taken Equation 1.1, the original OFDM signal.

$$x(t) = \sum_{i=1}^{\infty}\sum_{k=1}^{N} C_{ik} e^{j2\pi\Delta f(t-iT_{OFDM})} \cdot p(t - iT_{OFDM})$$

(1.1)

It is worth remembering that to recover the orthogonality, the T_{OFDM} period of the signal has to be perfectly accomplished ($\Delta f = \frac{1}{T_{OFDM}}$).

However, the decorrelation can be seen as an offset added to the frequency spacing (*Δf*) in such a way that $\Delta f \neq \frac{1}{T_{OFDM}}$ and the approach in Chapter 1 cannot be longer valid. Now, an offset to the frequency spacing can be added ($\Delta f = \frac{1}{T_{OFDM}} + \mathrm{d}f$). Therefore, Equation 4.1 is obtained.

$$x(t) \approx \sum_{i=1}^{N} e^{-j2\pi i \frac{\mathrm{d}f}{T_{OFDM}}} \sum_{k=1}^{K} C_{ik} e^{j2\pi\Delta f t} . p(t - iT_{OFDM})$$

(4.1)

For *df<<Δf*,a new phase component in each symbol can be seen at the beginning of the expression. The mentioned component, in addition, depends on each symbol, so that, for each symbol, a new phase shift would appear. The fact that it appears in each symbol makes the depicted constellation in Figure 4.8 have a ring shape, since the phase shifts are originated around each symbol.

4.2. Different wavelengths at safety distance case

In this case, free-running lasers can be considered in each ONU with a wide enough spectral gap between their optical carrier wavelengths. Schemes that constantly ensure the required spectral gap among optical carriers through OLT laser temperature control have been proposed [P5]. This configuration requires some freedom to choose the optical wavelength of every user and, therefore, single side band filters are not allowed.

The spectral gap among optical carriers allows interfering mixing products among spectral components to be kept below a quality threshold. See figure 4.7.

One of the advantages of this configuration is that the spectral guard band for each ONU is only the bandwidth of that ONU, since each user can be thought of as independently detected. The idea is that it is guaranteed enough spectral separation, so that they can effectively be taken as several point-to-point detections

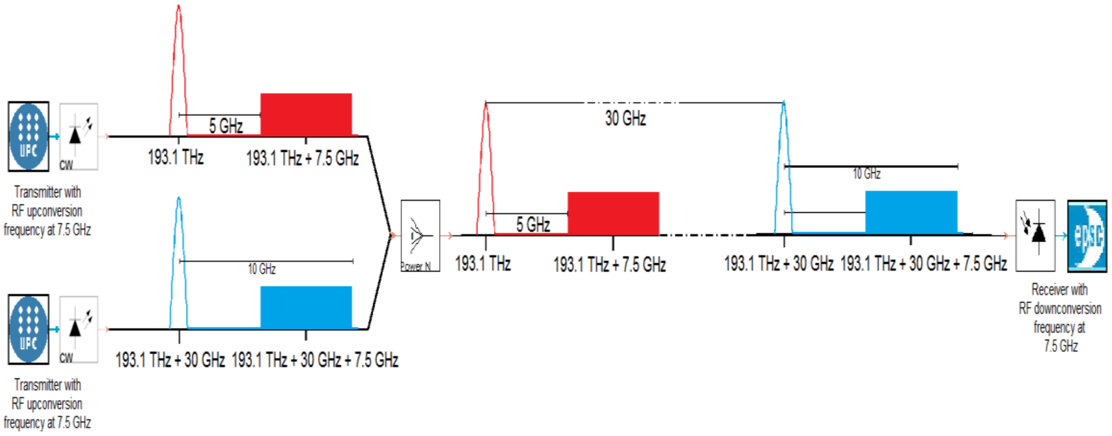


Figure 4.7 General schema of the different wavelengths at safety distance strategy

4.2.1. Different wavelength at safety distance strategy simulations

Now, the different wavelength at safety distance strategy can be tested using the scenario in the previous simulation. The optical carrier of the ONU, that will be not processed, is 30 GHz separated from the useful optical carrier of the other ONU.

The optical spectra of the simulation can be seen in Figure 4.8. Two optical carriers separated 30 GHz among them are distinguished with both double sidebands.

The obtained constellation can be seen in Figure 4.9. It shows its four perfectly located points for each symbol.

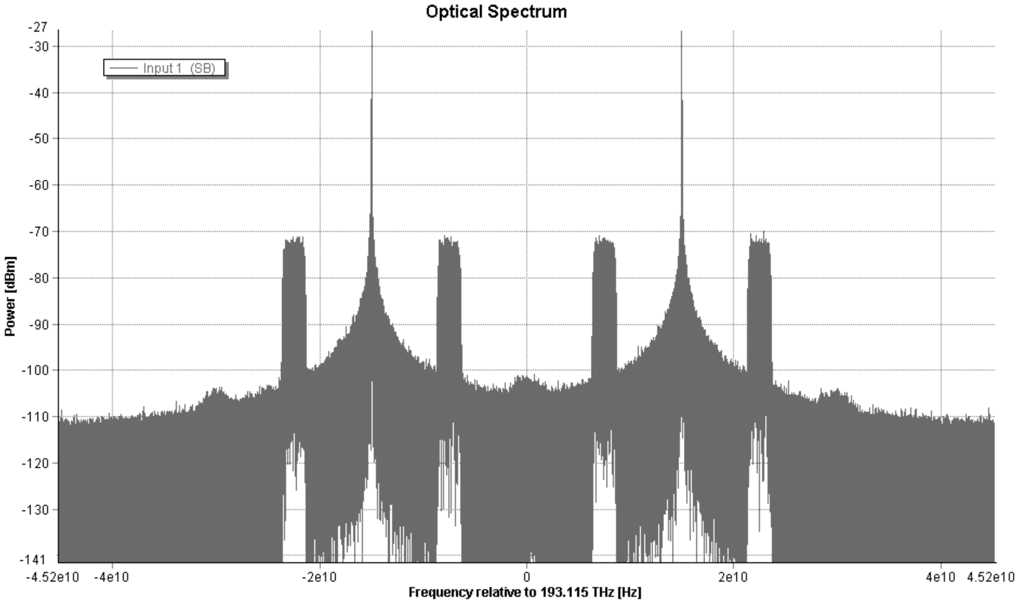


Figure 4.8 Optical spectrum for different optical carriers

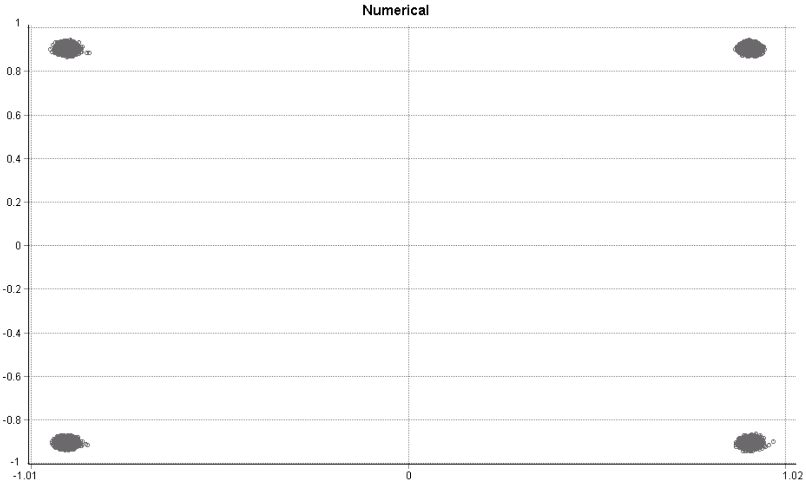


Figure 4.9 Constellation diagram

CHAPTER 5.SIMULTANEOUS USERS DECODING

5.1. Introduction and goal

In chapter 4, some multiple user connection strategies have been studied. The deleterious effect of OBI due to the presence of other users multiplexed over the same fiber in a point-to-point OFDM system has been analyzed. Also proposals to mitigate the OBI effect on optical networks have been made.

In this chapter, we will focus on the design of a simulation platform that allows simultaneous detection of OFDMA users. The goal is to develop a customized demo for the user-friendly and easy setup of uplink multiuser simulations.
This platform should:

- Be easily scalable to any number of users
- Allow zero insertion to achieve the required multiuser FFT symmetry nature
- Allow the inclusion of CP and equalization for each user
- Allow for Dynamic Bandwidth Assignment among the users

The useful simulation outputs for each user are the following:

- Constellation diagram
- Error Vector Magnitude (EVM)
- Bit Error Rate (BER)

5.2. OFDMA uplink structure

The Figure 5.1 shows the ideal schema of an optical OFDMA network based in IM/DD with RF upconversion. It can be seen that the ONUs are located at the left of the universe and there is an OLT to govern those ONUs. This OLT is in charge of demodulating together the combined OFDM stream coming from all the ONUs and to decompose it into the bit sequence corresponding to each ONU.

For the purposes of simulation we have considered that the 3 optical carriers have the same wavelength and are perfectly correlated. In practice, this will not be the case and probably an auxiliary carrier will be required in detection (see subsection 4.1). The details of this kind of detection scheme are left for future works.

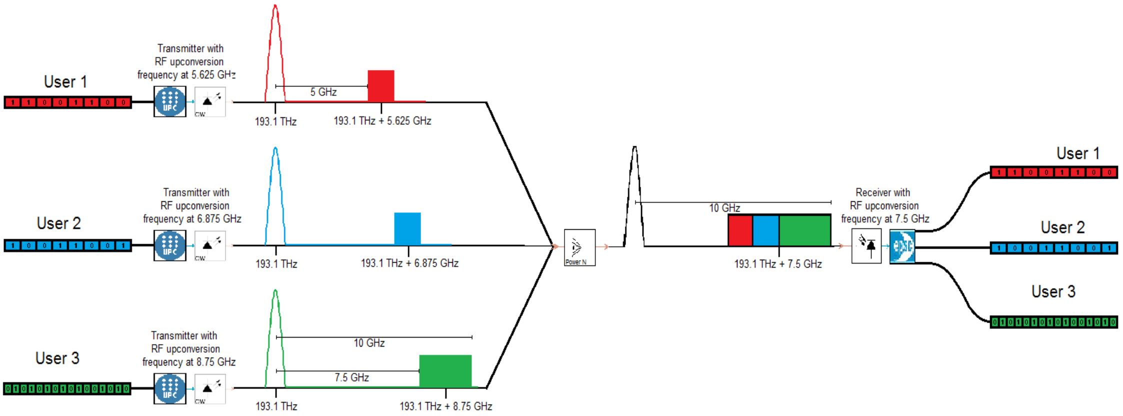


Figure 5.1 Optical OFDMA network based in IM/DD with RF upconversion schema

The PRBS generators on its side will be configured as decorrelated by setting their RamdomNumberSeed to different values, so that we can confirm that bit error rate calculations are done correctly. Also, they have to be set to the specific bit rate assigned to each user. For user friendliness, this, as also many other parameters, is actually automatically configured by making use of the global variables of the universe as explained in subchapter 5.11.2.

The coding and decoding provided by VPI do not offer the flexibility required in the multiple user connection system. Therefore, Matlab coding and decoding are necessary.

The ONUs used for the OFDMA system are canonical. This implies that were designed thinking in the possibility of providing scalability because it can be added as many ONUs as desired repeating the same block.

The OLT is a new product designed and it is also custom-made. The code of the OFDM decoding and the VPI modules are connected in such a way that it can be used both as a point-to-point and as a multiuser schema with dynamic number of ONUs, meaning by dynamic that the number of ONUs can change without causing any problem.

Furthermore, in order to calculate precise measurements, there is a new Matlab cosimulation feature (PRBS Joiner) that is very useful to collect the PRBS bit sequences of each ONU, concatenate it and, finally, send to the OLT through a Logical Channel.

With reference to the decoding modules: how to process the signal and, after performing the FFT, how to separate each ONU.

It is worth noting that the system scalability is a requirement. For this reason, after the IFFT, the OLT decoding is done ONU by ONU inside a loop. This provides the capability of decoding as many ONUs as desired without introducing any change in the decoding stage.

Although the modules developed are ready for tests that include some length of fiber, in this chapter, to focus on the proper performance of the basic features, all tests conducted have considered back-to-back configurations.

5.3. Dynamic Bandwidth Allocation

The total bit rate of the scenario is 10 Gbps; this is to say; the maximum bit rate that the OLT can handle. This is the bit rate that ONUs should share and there are many strategies to distribute it: depending on the traffic, depending on the QoS…Regarding to this OFDMA network, the bit rate is calculated using a factor that depends on the number of subcarriers assigned to each ONU. This factor is calculated as in Equation 5.1:

$$DBA\ factor_n = \frac{Number\ of\ carriers\ ONU_n}{Total\ number\ of\ carriers}$$

(5.1)

Therefore, if each ONU factor is multiplied by the bit rate, the bit rate for each ONU can be obtained, Equation 5.2.

$$BitRateUser_n = DBA\ factor_n * BitRateDefault$$

(5.2)

5.4. RF frequencies of users

As explained in chapter 3, there is an RF upconversion in the IM/DD system to shift away the information from the intermodulation mixing products.

In a point-to-point scenario, the RF upconversion and downconversion frequencies are the same due to the available electrical bandwidth is completely used for a single user. When multiplexing several ONUs although the electrical band is shared by the ONUs in such a way that the ONU electrical bands are placed one next to the other and, thus, each ONU must be RF upconverted to a different frequency (See Figure 5.2).

In addition, the required guard band needs to be as wide as the sum of the total bandwidth occupied by the totality of ONUs.

The number assigned to each ONU is in increasing order as they are found in the spectrum. Thus, to recover the ONUs at the receiver, the RF frequencies are located in such a way that the ONUs electrical bands not be overlap.

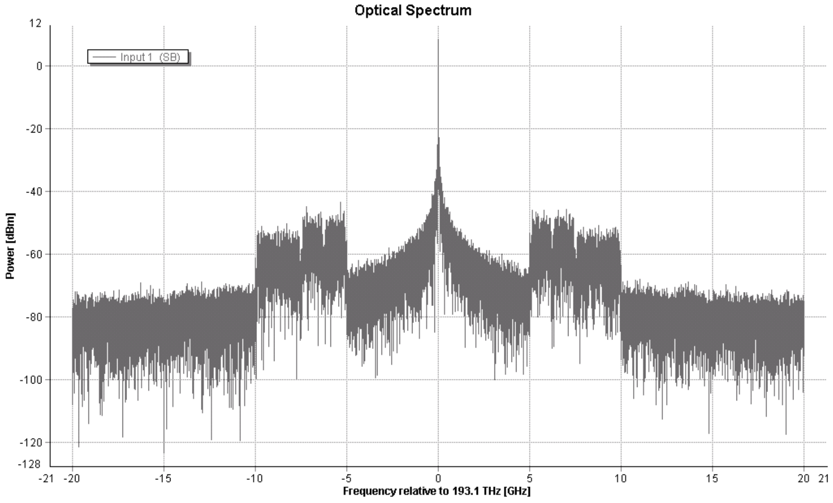


Figure 5.2 Optical spectrum of an optical OFDMA network

As an example, in the Figure 5.2, it can be seen that there are 3 ONUs whose electrical bands are centered at different RF frequencies and one next to the other. The limits of the spectrum occupied by the information of each ONU are identified in the spectrum by subcarriers which are set to zero. The nature of these zeros will be explained in the following subchapter.

The RF frequency is located at the intermediate frequency of the electrical band for each ONU. Due to the fact that for this scenario a 4-QAM modulation is used, the bandwidth is half the bit rate since 2 bits per each symbol are used.

The RF frequency of the ONU depends on the DBA strategy since the bandwidth is provided by the chosen allocation strategy. In addition, the number of ONUs can increase or decrease, therefore, it is very important to obtain an automatically update of the RF frequencies. It can be seen in Equation 5.3 how the RF frequencies are obtained.

$$RFfrequencyONU_x = RFfrequencyONU_{x-1} + \frac{BitRateONU_{x-1}}{2 * BpS} + \frac{BitRateONU_x}{2 * BpS} \tag{5.3}$$

However, when recovering in the OLT, the RF frequency used for the downconversion is placed at the center of the electrical band which is the result of the contribution of all ONUs electrical band.

5.5. The FFT symmetry and the rearranging of subcarriers

In this section, the strategy to rearrange the subcarriers and obtain the information of each ONU at the decoder output will be explained.

In the subchapter 1.2, it was explained that, due to the nature of the IFFT operation, the last half of the samples were shifted to negative frequencies. In addition, the spectrum has to be symmetric since the DC component is also present, so the sample $y_{\frac{N}{2}+1}$ is repeated at both the negative and the positive edges of the spectrum (See Figure 5.3: Separated channels).

As explained in the previous subchapter, at the ONU side, the RF upconversion frequencies are set according to the bandwidth assigned. From the multiuser point of view, the ONUs are placed in the spectra following the RF frequencies, so one ONU is next to the other in an ordered fashion.

To maintain the symmetry in the spectra, the $y_{\frac{N}{2}+1}$ sample of the first ONU is, at the same time, the first sample of the second ONU. It can be seen, thus, an overlapping (See Figure 5.3: Same channel). At the OLT side, the FFT operation is performed for the whole signal. The RF downconversion is located at the intermediate frequency and at the output is obtained, once again, that the signal is shifted in such a way that the last half of the samples are located at the beginning of the sequence.

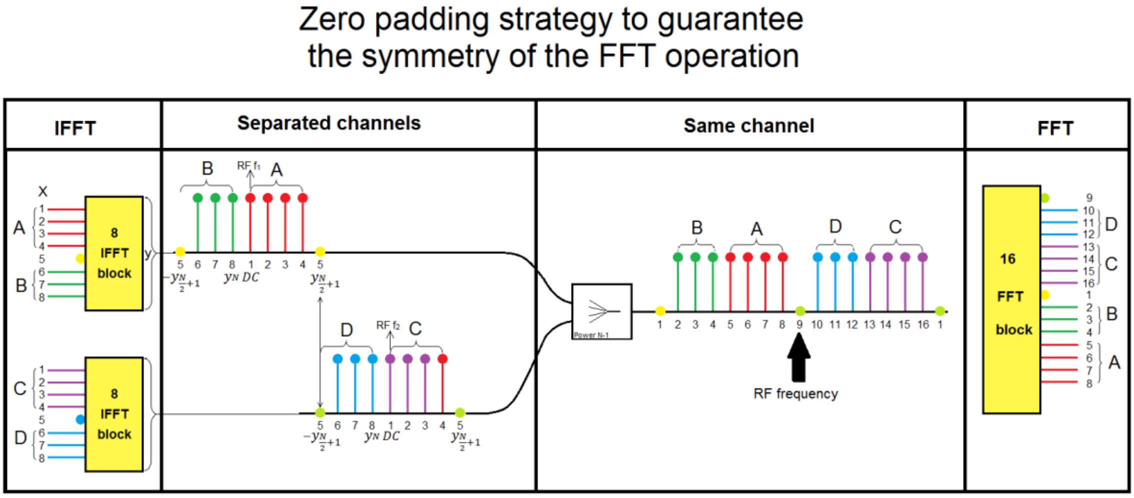


Figure 5.3 Zero padding strategy to guarantee the symmetry of the FFT operation

In a point-to-point scenario, the IFFT and the FFT are performed for the same sequence and the order of the carriers is accomplished because the shift is done twice and the effect is cancelled.

In a multiuser scenario, the IFFT is performed separately for each ONU and the FFT operation is done for the whole sequence of ONUs, so the shift is done twice but in a different way.

To sum it up, it is obtained that the ONUs are disordered and the subcarriers of each user are also disordered.

As seen in the Figure 5.3, the ONUs sequences are divided by letters and colors. Each letter and color corresponds to a group of samples and they are highlighted in order to show the initial and final position of the subcarriers when a signal is transmitted and recovered.

Firstly the letters sequence is ABCD. When the IFFT is performed, the sequence is BADC. Finally, at the FFT output the signal sequence is DCBA.
That needs to be taken into account when calculating the BER of each ONU.

In addition, in order to maintain the symmetry required by the OFDM decoding, each ONU must set its Nyquist subcarrier to zero. The position of these symmetry zeros needs to be tracked for correct extraction in the decoder.

As explained, the OFDM coding provided by VPI does not allow for flexible insertion of zeros. Furthermore, the modules are locked in such a way that changes to coding cannot be applied either. Therefore, the Matlab ODFM coding needs to be used to perform the symmetry Zero Padding insertion in each ONU decoding stage.

Luckily, the Matlab OFDM coding has a flexible Zero Padding insertion, fully explained in subchapter 3.5.1. It is very useful because the code inserts zeros in the positions that are given by a vector in the global parameters, fully tunable for the user.

To rearrange all the subcarriers and order the ONUs the following strategy is carried out.

First, a zero is added at the Nyquist frequency to maintain the symmetry.

Then, the correct arranging of subcarriers at the decoder output is achieved by sequential application of the fftshift function in Matlab, which basically undoes the subcarrier rearranging taking place as a result of the IFFT/FFT operation.

This function recovers the original position of carriers after application of the FFT, that is, when applied over a vector of samples it transfers the second half of the vector samples to the beginning of the vector in the same order.

The subcarrier rearranging in the decoder is undone by applying the *fftshift* operation to the whole decoder output sequence. The ONUs are thus properly arranged in increasing order. The output vector is then split into the ONUs vectors, which are *fftshifted* due to the IFFT performed in the respective coders. By applying the *fftshift* operation individually to each of the ONUs vectors, the *fftshift* in the respective coders is undone and the proper subcarrier rearranging recovered for each ONU.

Note that in a point-to-point connection no rearranging is necessary since the *fftshift* operation in coder and decoder mutually cancel out, so that finally subcarriers are found in the decoder in the same position as in the coder.

5.6. Normalization at the ONUs output

In section3.5.3, it was shown that an amplitude normalization can be applied to the coder output. When using the Matlab function this normalization depends on the FFT size. The expression of the IFFT performed in the ONUs is depicted in Equation 5.4.

$$\Gamma_{OFDM}(m) = \frac{1}{NFFTONU_x}\sum_{n=0}^{N-1} X_{OFDM}(n)e^{-j\frac{2\pi nm}{N}}$$

(5.4)

Since the decoding will be jointly performed with the same FFT over the combined OFDMA signal, it is important that the amplitude normalizations of the respective ONUs are such that they add with the same amplitude. Since we consider ONUs with different number of subcarriers, the normalization described above leads to erroneous decoding. For this reason, the obtained IFFT samples are multiplied by the ONU subcarriers and divided by the total number of subcarriers, Equation 5.5.

$$\Gamma_{OFDM}(m) = \frac{1}{NFFTONU_x} * \frac{NFFTONU_x}{NFFT\_Total}\sum_{n=0}^{N-1} X_{OFDM}(n)e^{-j\frac{2\pi nm}{N}}$$

(5.5)

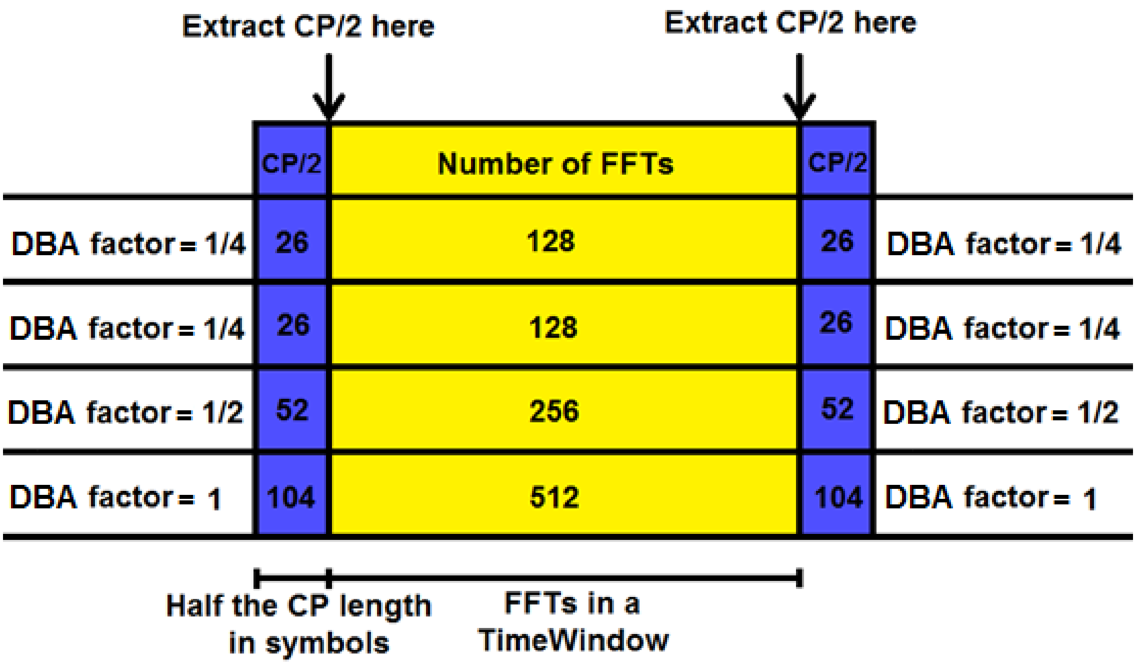
5.7. Cyclic Prefix insertion and extraction in an optical OFDMA

The available OFDM coding and decoding modules specify the CP guard time as a percentage of the total number of subcarriers, i. e. the FFT size, and then it is rounded to the next integer using the ceil operation. In the simultaneous decoding scenario, the OFDM frames coming from each ONU must temporarily match, with the slower ONUs having less but longer symbols in a frame depending on the DBA factor (see Figure 5.4).

As an example, in Figure 5.4, before the FFT, the input sequence of the OFDM decoding can be seen as a sequence with 512 FFTs in a TimeWindow. In a similar form, the signal can be seen as a slower signal with 256 FFT for the same TimeWindow. Therefore, the number of symbols is different but the temporal width is the same.

That means that the guard times have to be equal. Due to the ceil operation, this is not always the case. That is the reason why in the multiuser simulation scenario CP is specified as a number of symbols rather than a percentage
The number of symbols in an OFDM frame depends on the DBA factor.

It has to be taken into account that the length of the CP in symbols is adapted for each ONU depending on its DBA factor, so that the CP has the same temporal width but the length in number of symbols has a different value in each ONU.



	CP/2	Number of FFTs	CP/2	
DBA factor= 1/4	26	128	26	DBA factor= 1/4
DBA factor= 1/4	26	128	26	DBA factor= 1/4
DBA factor= 1/2	52	256	52	DBA factor= 1/2
DBA factor= 1	104	512	104	DBA factor= 1

Figure 5.4 Number of FFT and CP length in a TimeWindow depending on the chosen DBA factor

However, at the OLT the DBA factor is 1. Although the input sequence symbols are faster, the temporal duration is still the same, TimeWindow.

If each ONU CP_length was added respecting its own DBA factor, the cyclic prefix extraction can be done for the whole sequence because, although the number of symbols is different, the CP temporal duration is the same. This can be seen in Figure 5.4.

In the Matlab decoder a half of the CP is extracted at the beginning of the frame and the other half at the end of it [T3]. Due to that, the CP_length must be an even number.

When setting the CP_length value for each ONU, it has to obey two simple rules:

- CP length relation among ONUs must be in agreement with the DBA factor, so that all ONUs have the same guard time interval. (Equation 5.2 in subchapter 5.3).
- CP_length must be an even number.

5.8. PRBS for quality measurements and equalization

In the decoder, the calculation of the equalizer coefficients and of the EVM and BER values requires availability of the sent PRBS sequence.

Furthermore, the OFDM decoding function has to be scalable and capable to perform a variable number of users without changes in the code. Therefore, the PRBS of all the ONUs need to be provided to the OLT as a single input.

The PRBS Joiner cosimulation is a set of modules in the universe of the system. Its main purpose is to provide a single vector with the PRBS of all the ONUs to the OLT. To perform this, a Matlab function has been programmed that concatenates all the PRBSs. In order to provide the function with all PRBS, there are several CosimInputs that collect all ONUs PRBS through Logical Channels. Finally, there is a CosimOutput that sends the vector to the OFDM decoding CosimInput (see Figure 5.5).

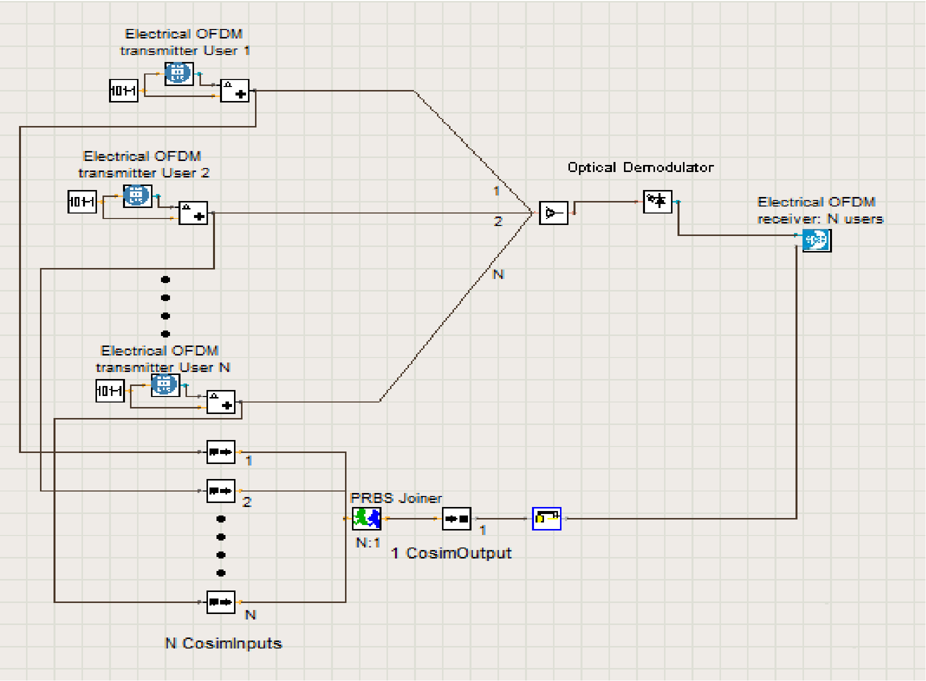


Figure 5.5 PRBS Joiner schema in the universe of the simulation

Once the concatenated PRBS vector is inside the Matlab function, each ONU sequence must be separated and converted from bits to symbols before performing equalization and calculations of both EVM and BER.

In the Figure 5.5, a general schema of the PRBS Joiner cosimulation feature embedded in the scenario can be seen. The Logical Channel of each ONU is connected to the CosimInterface by means of *N*CosimInputs. The CosimInterface takes the input sequences and concatenates them into a single sequence that contains all the ONUs ordered one next to the other. At the output there is only 1 CosimOutput that is sent to the OLT.

5.9. Equalization in optical OFDMA networks

In [T3], the equalization concept and code is explained. If both multiuser and point-to-point strategies are compared, the equalization is done exactly in the same manner. The main idea related to the multiuser strategy equalization is that the sequence used to obtain the channel impulse response is that sent by the PRBS Joiner function explained in the previous subchapter.

The Matlab decoding function obtains the whole transmitted bits sequence only using one Logical Channel owing to the PRBS Joiner function. Therefore, the VPI scenario is optimized because there is only one Logical Channel that contains the whole information pointing to the OLT.

The bits sequence relative to each ONU can be obtained making use of a pointer that depends on the decoding iteration. When ONU *i* is being processed, the pointer matches the position where the ONU *i* sequence begins. Using the global variables, the length of the ONU *i* in bits can be extracted by calculating $\mathrm{BitRateONU}_i$* TimeWindow. In this manner, the ONU *i* vector is extracted starting from the position given by the pointer and with length $\mathrm{BitRateONU}_i$* TimeWindow. Now, the pointer value is updated to the ONU *i+1* using the position for the ONU *i* and adding its length; $\mathrm{BitRateONU}_i$ * TimeWindow.

Equalization is then applied to each of the ONU vectors using the joint PRBS for comparison, as it is explained below. As explained in subchapter 3.5.4, both transmitted and received symbols are compared using a matrix with the number of subcarriers in the rows and the number of symbols in the columns obtaining, thus, the channel impulse response.

5.10. ONUs matrix

To obtain a scalable system, a single output of the cosimulator must contain inside all the ONUs sequences. The way to accomplish this requirement is to store all the ONUs in a matrix with as many rows as ONUs. Furthermore, the matrix must be fixed according to the number of ONUs. Thus, the cosimulator

output should be scalable, meaning that the cosimulator feature may guarantee expansion capacity without changing either the code, the inputs or the outputs.
In addition, as will be explained in the following subchapter, some calculations are performed to test the system performance. Therefore, two more matrixes are obtained to store the BER and EVM calculations.

5.11. Simulation scenario

5.11.1. Universe

The universe of the simulation is composed by the users' ONUs, the power combiner, the OLT and the PRBS Joiner. See Figure 5.6.

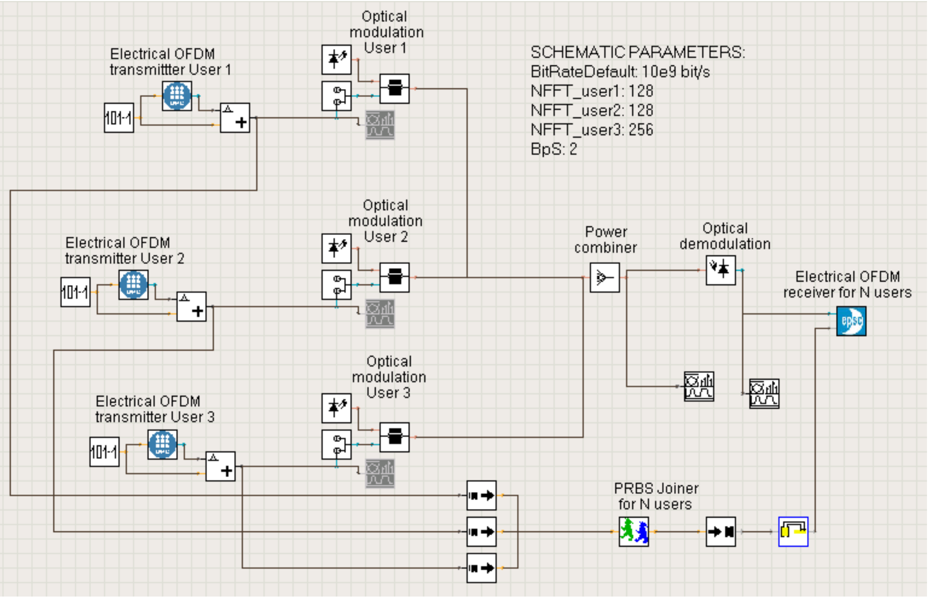


Figure 5.6 Universe of the OFDMA network in the uplink

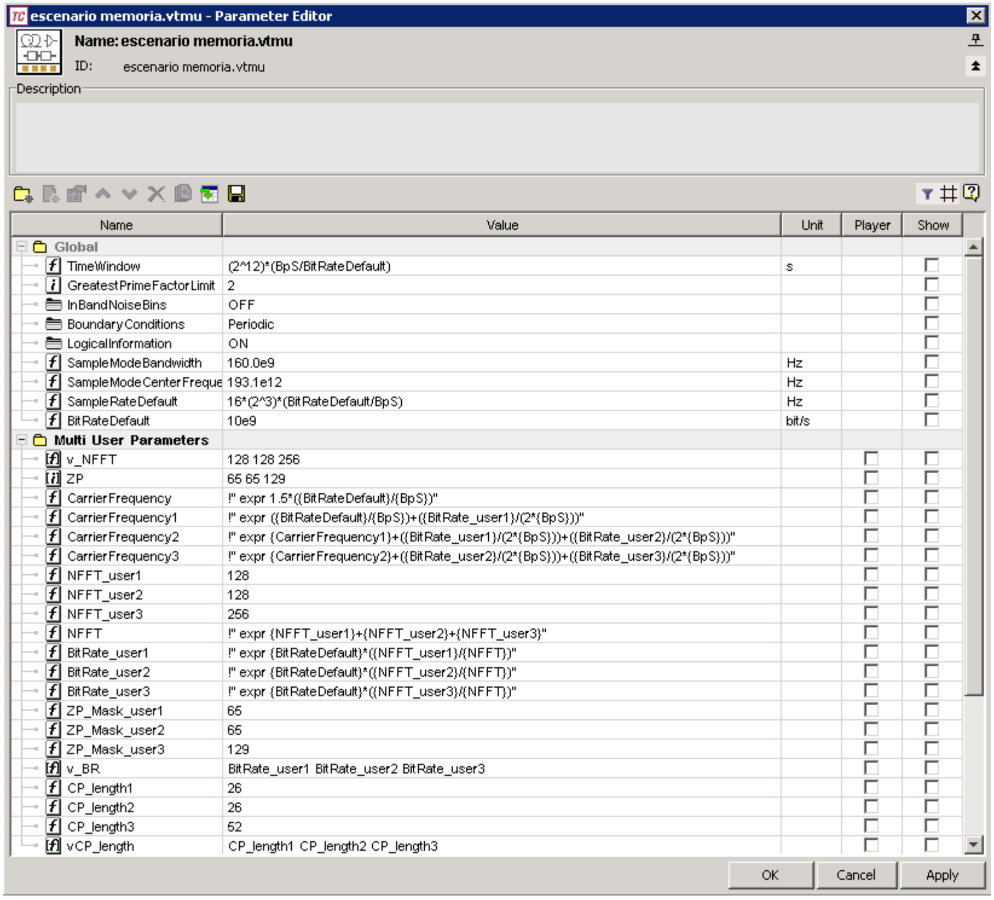
5.11.2. Global parameters of the demo

In order to make a friendly-user scenario, some ONU parameters are calculated automatically. All the equations are programmed according to the number of carriers because it determines the portion of bit rate destined for each ONU (DBA factor). The portion of bit rate obtained determines the bandwidth of each ONU.

The parameters of this scenario can be organized in two groups: the group of global parameters that are necessary for OFDM simulations and the global parameters for a multiuser scheme. Furthermore, the parameters for a multiuser scheme are divided in two groups: those parameters that are relative to the ONU and those that are used in the OLT.

The parameters used for the ONU are numerated according to the user, for example, the parameter called BitRate_user1 is referred to the user 1, the BitRate_user2 corresponds to the user 2 and the BitRate_user3 is relative to the user 3.

The general parameters for the multiuser schema are shown in the Figure 5.7.



escenario memoria.vtmu - Parameter Editor

Name: escenario memoria.vtmu

ID: escenario memoria.vtmu

Description

Name	Value	Unit	Player	Show
Global				
TimeWindow	(2^12)*(BpS/BitRateDefault)	s		☐
GreatestPrimeFactorLimit	2			☐
InBandNoiseBins	OFF			☐
BoundaryConditions	Periodic			☐
LogicalInformation	ON			☐
SampleModeBandwidth	160.0e9	Hz		☐
SampleModeCenterFreque	193.1e12	Hz		☐
SampleRateDefault	16*(2^3)*(BitRateDefault/BpS)	Hz		☐
BitRateDefault	10e9	bit/s		☐
Multi User Parameters				
v_NFFT	128 128 256		☐	☐
ZP	65 65 129		☐	☐
CarrierFrequency	!" expr 1.5*({BitRateDefault}/{BpS})"		☐	☐
CarrierFrequency1	!" expr ({BitRateDefault}/{BpS})+({BitRate_user1}/(2*{BpS}))"		☐	☐
CarrierFrequency2	!" expr {CarrierFrequency1}+({BitRate_user1}/(2*{BpS}))+({BitRate_user2}/(2*{BpS}))"		☐	☐
CarrierFrequency3	!" expr {CarrierFrequency2}+({BitRate_user2}/(2*{BpS}))+({BitRate_user3}/(2*{BpS}))"		☐	☐
NFFT_user1	128		☐	☐
NFFT_user2	128		☐	☐
NFFT_user3	256		☐	☐
NFFT	!" expr {NFFT_user1}+{NFFT_user2}+{NFFT_user3}"		☐	☐
BitRate_user1	!" expr {BitRateDefault}*({NFFT_user1}/{NFFT})"		☐	☐
BitRate_user2	!" expr {BitRateDefault}*({NFFT_user2}/{NFFT})"		☐	☐
BitRate_user3	!" expr {BitRateDefault}*({NFFT_user3}/{NFFT})"		☐	☐
ZP_Mask_user1	65		☐	☐
ZP_Mask_user2	65		☐	☐
ZP_Mask_user3	129		☐	☐
v_BR	BitRate_user1 BitRate_user2 BitRate_user3		☐	☐
CP_length1	26		☐	☐
CP_length2	26		☐	☐
CP_length3	52		☐	☐
vCP_length	CP_length1 CP_length2 CP_length3		☐	☐

Figure 5.7 Universe parameters

- **Main global parameters for OFDM scenarios:**
  - ***BitRateDefault***: 10 Gbps.
  - ***TimeWindow***: 8,192 µs.

  - ***SampleRateDefault***: 4 times the BitRateDefault.

- Parameters relative to the ONU:
  - ***NFFT_user$_n$***

    It can be seen in Figure 5.1 a scenario of three users. These users have 128, 128 and 256 information carriers respectively. Thus, the number of carriers in the simulation is the sum, 512.

- ***BitRate_user*** $_n$

  The optical access network bit rate is 10 Gbps, so the users are sharing the bit rate. A Dynamic Bandwidth Allocation strategy has been used. It is explained at subchapter 5.3.

$$BitRateUser_n = BitRateDefault * \frac{Number\ of\ FFT\ user_n}{Total\ number\ of\ FFT} \tag{5.6}$$

- ***Number of symbols user*** $_n$

  Another important parameter is the number of symbols for each user, Equation 5.7. Although it is not shown in the global parameters, it will be useful to explain for the following subchapters. The sum of them determines the total number of symbols in the simulation.

$$Number\ of\ Symbols\ User_n = \frac{BitRateUser_n * TimeWindow}{BpS} \tag{5.7}$$

- ***CP_length*** $_n$

  The cyclic prefix is set by the user taking care of the restrictions explained in the subchapter 5.7.

- ***ZP_mask_user*** $_n$

- ***CarrierFrequency*** $_n$

- **Parameters relative to the OLT:**
  They are organized in vectors. Each vector position is relative to each user. This is useful because the users can be selected by shifting the vector positions.

  - ***v_NFFT***
    This vector contains the NFFT of each user.

  - ***v_BR***
    This vector contains the BitRate of each user.

  - ***vCP_length***
    This vector contains the number of symbols for the CP overhead of each user.

  - ***ZP***
    This vector contains the Zero Padding positions of each user.

- ***CarrierFrequency***
  The RF frequency downconverted in the OLTis obtained obeying the Equation 5.8.

$$CarrierFrequency = 1.5 * \frac{BitRateDefault}{BpS} \tag{5.8}$$

5.11.3. Electrical OFDM transmitter galaxy

As said previously, the coding module provided by the software is not as scalable as desired. For this reason a new coding block is programmed by means of the cosimulation feature. It can be seen in Figure 5.8.

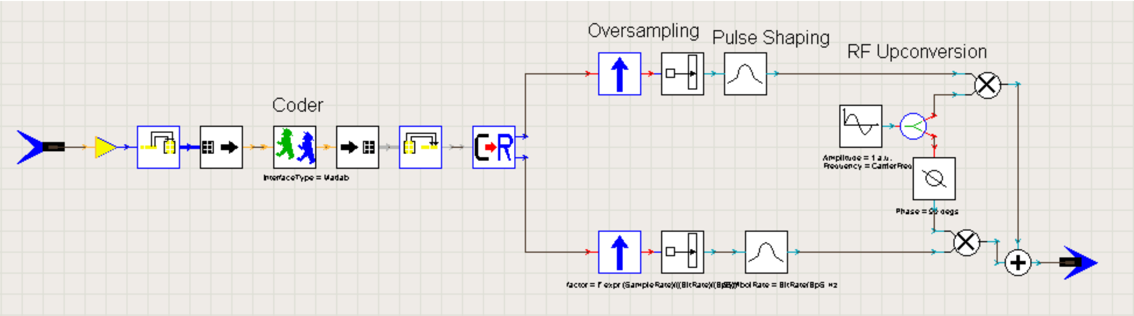


Figure 5.8 Electrical OFDM transmitter galaxy

5.11.4. Electrical ODFM receiver

In the Figure 5.9, it can be seen the electrical OFDM receiver galaxy. Although the e-OFDM receiver operation seems the reverse than in the transmitter, the decoding block in the galaxy realizes some new operations to deal with the strategy used for multiple user connection.

Up to the decoding stage, the system performs the same operations as in the Long-Haul demo explained in subchapter 3.4. However, the decoding is programmed in Matlab.

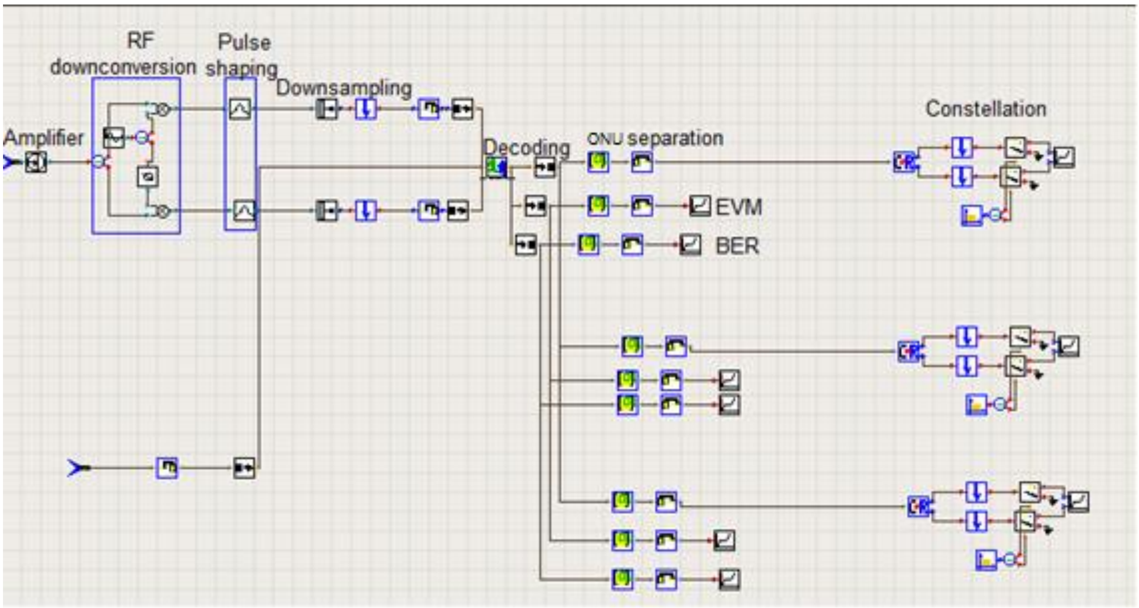


Figure 5.9 Electrical OFDM receiver galaxy

Three different outputs are obtained after the decoding process. Each output corresponds to a matrix, which rows are related to a different ONU respectively. The matrixes contain:

- ONU sequence
- Bit Error Rate
- Error Vector Magnitude

It can be seen in the Figure that there is a green module that performs the ONU separation. This module is a sub_matrix finder and is in charge of extracting the vector related to each ONU.

Finally, analyzers are embedded to show the final outputs. For the constellation constructor, there are several modules that collect the symbols and print them in the constellation diagram.

5.12. Results for different strategies

The strategies studied in chapter 4 can be tested with the multiuser demo. Therefore, the two strategies tested in the multiple user connection demo are the same wavelength and the different wavelength at a safety distance approaches.

5.12.1. Same wavelength

The scenario for this simulation is an optical access network with three independent users using a correlated optical carrier at 193.1 THz. Its total Bit Rate is 10 Gbps, so, as a 4 QAM modulation is used, the bandwidth is 5 GHz.

The settings for this strategy are depicted as follows in Table 5.1:

	ONU 1	ONU 2	ONU 3
Number of carriers	128	128	256
BitRate	2.5 Gbps	2.5 Gbps	5 Gbps
RF CarrierFrequency	5.625 GHz	6.875 GHz	8.75 GHz
CP_length	26	26	52
ZP positions	65	65	129

Table 5.1 Simulation settings

The optical spectrum in Figure 5.10, shows the optical carrier and the information carriers. It can be seen that a 5 GHz gap is created among the optical carrier and the information carriers. The information bandwidth is 5 GHz.

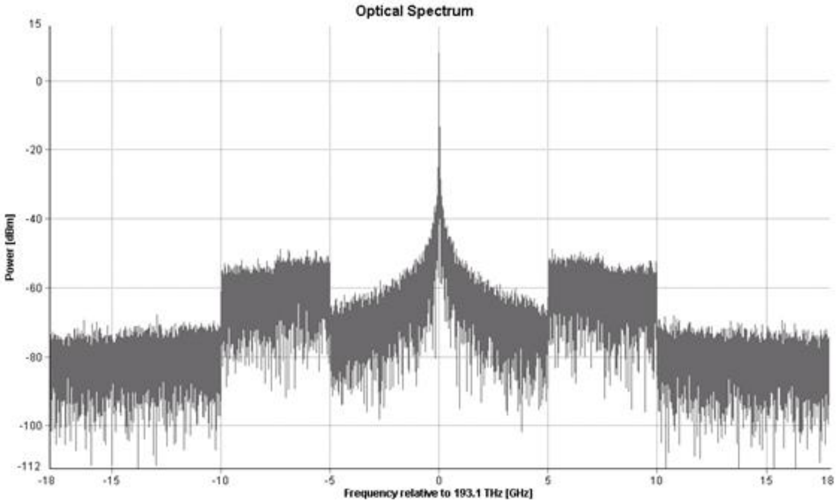
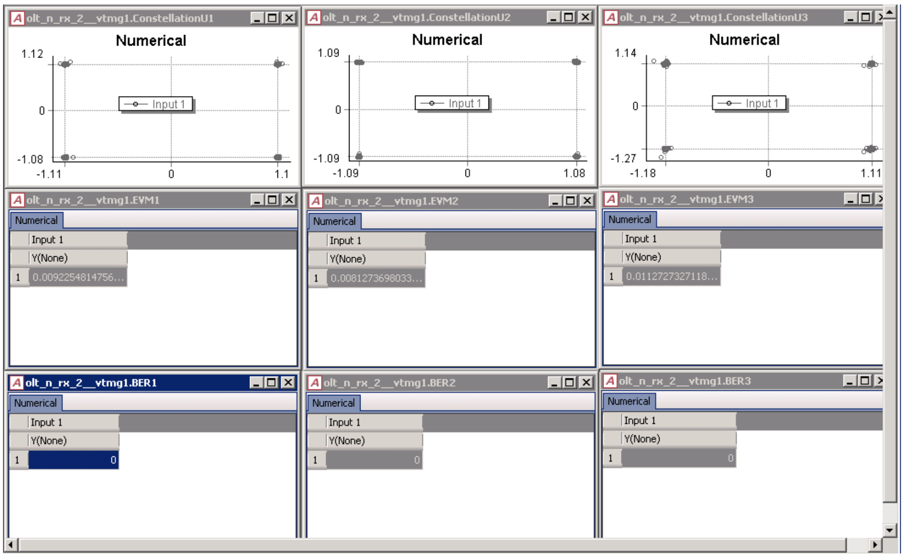


Figure 5.10 Optical spectrum for the same optical carrier

The final results are depicted in Figure 5.11. It can be seen the constellation, EVM and BER for each ONU. The four symbols of the constellation are near the ideal points, so the EVM is very small. The BER calculations results that there is not any bit with error.



```
olt_n_rx_2__vtmg1.EVM1
Numerical
Input 1
Y(None)
1 0.0092254814756...

olt_n_rx_2__vtmg1.EVM2
Numerical
Input 1
Y(None)
1 0.0081273698033...

olt_n_rx_2__vtmg1.EVM3
Numerical
Input 1
Y(None)
1 0.0112727327118...

olt_n_rx_2__vtmg1.BER1
Numerical
Input 1
Y(None)
1 0

olt_n_rx_2__vtmg1.BER2
Numerical
Input 1
Y(None)
1 0

olt_n_rx_2__vtmg1.BER3
Numerical
Input 1
Y(None)
1 0
```

Figure 5.11 Constellation, EVM and BER for each user

5.12.2. Different wavelengths at a safety distance

Now the same scenario is simulated with different optical carriers at a safety distance. In Figure 5.12 it can be seen the optical spectrum. It can be noted that the three optical carriers are separated 30 GHz to avoid OBI.

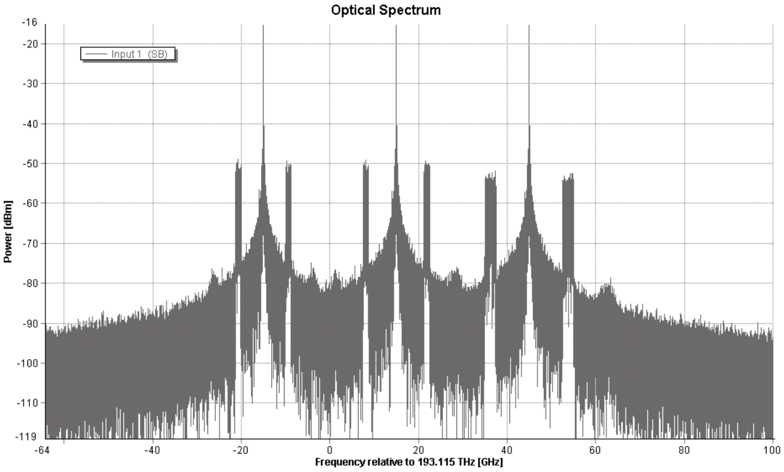
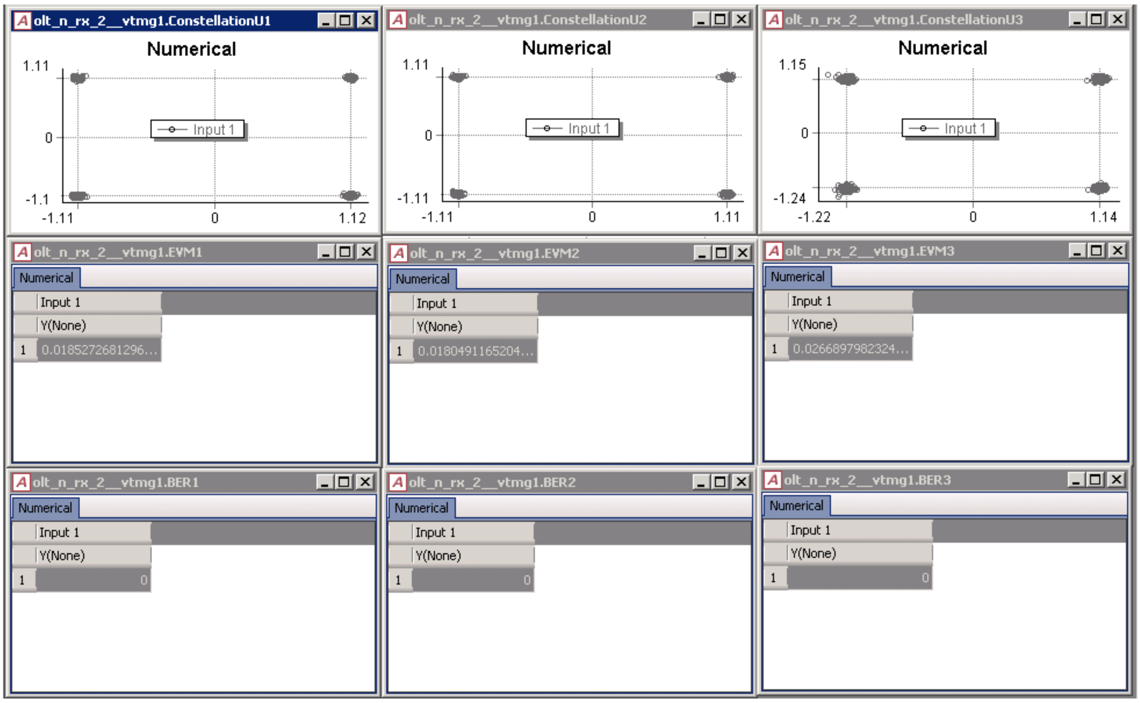


Figure 5.12 Optical spectrum for different optical carriers

The result in Figure 5.13 is worse than in the other case because the EVM is higher and the constellations are more spread out than in the above case. However, it is enough to recover the signal due to the EVM is also very small. In addition, the BER is 0 again, so there are not bit errors.



olt_n_rx_2__vtmg1.EVM1

Numerical

Input 1
Y(None)
1 0.0185272681296...

olt_n_rx_2__vtmg1.EVM2

Numerical

Input 1
Y(None)
1 0.0180491165204...

olt_n_rx_2__vtmg1.EVM3

Numerical

Input 1
Y(None)
1 0.0266897982324...

olt_n_rx_2__vtmg1.BER1

Numerical

Input 1
Y(None)
1 0

olt_n_rx_2__vtmg1.BER2

Numerical

Input 1
Y(None)
1 0

olt_n_rx_2__vtmg1.BER3

Numerical

Input 1
Y(None)
1 0

Figure 5.13 Constellation, EVM and BER for each user

In order to take the most of the available spectrum, it is very interesting to know the minimum safety distance in order to conclude the number of ONUs that can be multiplexed inside a given bandwidth.

VPI allows for swept testing. In other words, it can be done as many simulations as loops inserted. For this test, 30 loops with 1 GHz step change in the optical carrier distance for each loop are simulated. The scenario is depicted in Figure 5.14.

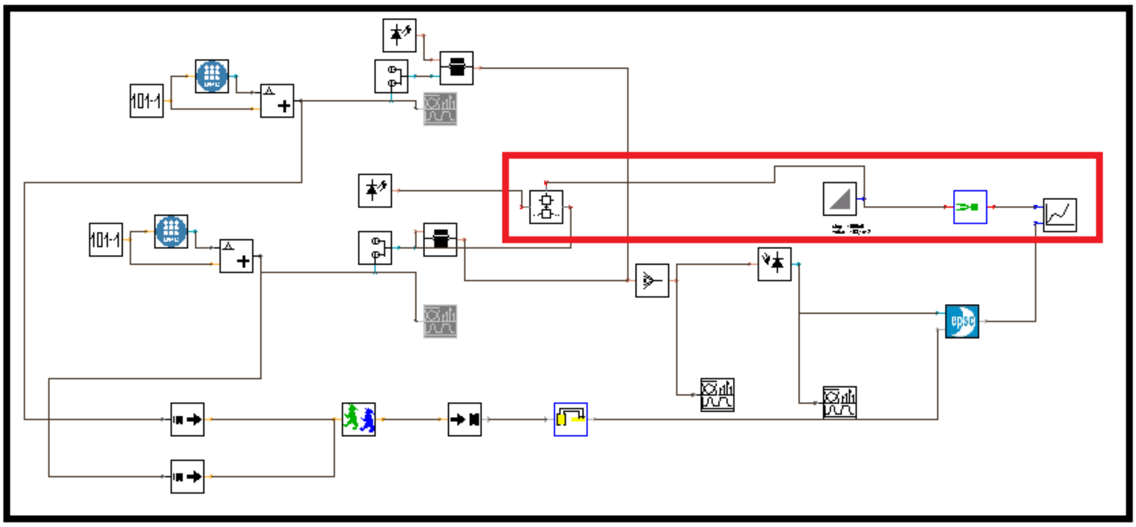


Figure 5.14 Two ONUs scenario with 30 GHz space with 1 GHz resolution

It can be seen that this new test is done with two ONUs. From left to right inside the red box can be seen the parameter controller, the ramp and the chop (See Figure 5.14).

The parameter controller determines the parameter that will be changing in each loop. The changed parameter is referred to the block that is connected with it, in this case the Emission Frequency of the laser. The ramp is the block that determines the initial value of the parameter and the resolution for each loop. The chop determines the number of loops in the iteration.

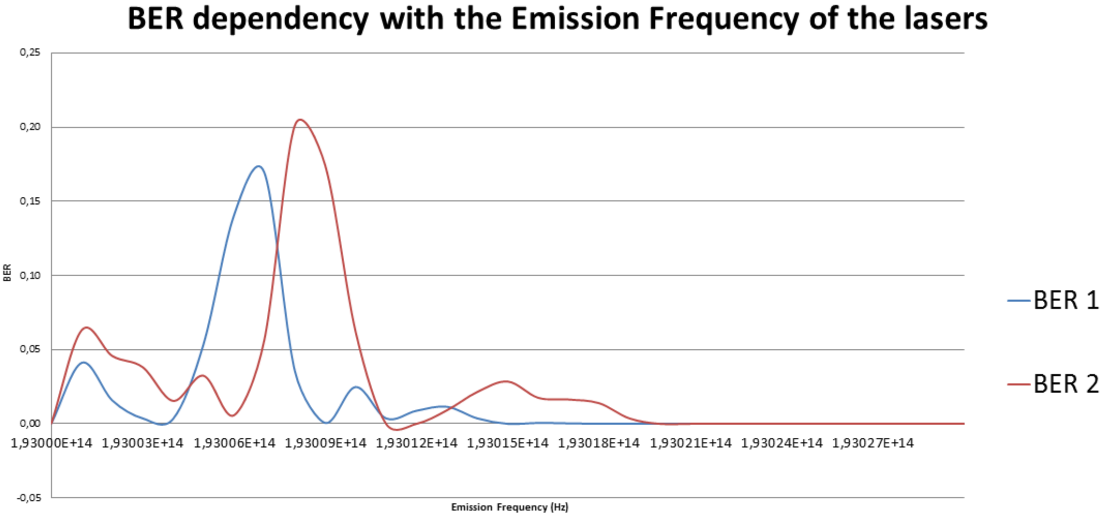


Figure 5.15 BER evolution

In the Figure 5.15, the BER evolution with the Emission Frequency for the two users is depicted.

Note that when the optical carrier is located at the RF upconversion frequency of the ONUs, the BER increases dramatically because the shifted optical carrier is interfering in the mix of both the fixed optical carrier and the electrical band of the ONUs.

Finally, it can be considered that 20 GHz is a big enough safety distance in this case because from that value up, the BER is under the 10^{-3} threshold

5.13. Scalability and user friendliness

Scalability can be defined in networks as the possibility of being able to guarantee the capacity of growth and expansion.

When a demo can be modified in a rapid and straightforward form without having to do many calculations and changes, it is possible to say that is user-friendly.

The customized demo presented in this chapter is done taking into account these two good recommendations.

So that the simulation scenario be invested with the required scalability, the OFDM coding and decoding have to be prepared for any ONU configuration.

Provided that there are some restrictions in the system, the OFDM coding and decoding modules are ready to carry out the ONUs expansion.

5.13.1. The loop performance

This subchapter is focused onto scalability and user friendliness. In addition, special emphasis has been put in designing a simulation scenario where the user can set and tune all the parameters and setup a variety of configurations without changing any code of the OFDM coding and decoding modules. In order to achieve scalability without changing any code, there is a loop implementation inside the OFDM decoding.

The loop starts after the FFT operation because here the users are previously ordered with the fftshift strategy. However, the subcarriers arranging is done inside the loop because the fftshift to arrange the subcarriers have to be done ONU by ONU. It is important to ensure the correct order because all the vectors relative to the ONUs are used in the loop and the order of their positions is also the order of the location of the ONUs in the optical spectrum. Therefore, the Matlab code performs the decoding of each ONU sequence separately using an iteration where each ONU *i* is decoded using the vectors in the global parameters also at position *i*.

An example of the use of these vectors and the iteration is given in subchapter 5.9 during the equalization process. Inside the loop it is performed a fftshift to rearrange the ONUs subcarriers, the zero padding extraction, the equalization process, the sequence arrangement and the EVM and BER calculations. So, it can be noted that the loop has to carry out many vectorial operations and an special emphasis is provided when performing both the calculations to shift the vectorial pointers to the next ONU sequence and finding a subvector inside a greater vector.

To conclude, the loop performance is exploited from the view point of the simulation time. Although the simulation time depends on the number of samples in the network, if the SampleRateDefault is stablished 4 times the BitRateDefault, the system is simulated in 15-20 seconds for 1024 subcarriers.
When the SampleRateDefault is very high, the run time increases a lot. For example, for a SampleRateDefault 64 times the BitRateDefault, the system is simulated in 4 minutes for the same number of subcarriers than above.

However, the usual SampleRateDefault is 4 times the BitRateDefault so the system optimization is visible.

5.13.2. Sub-matrix finder at the output

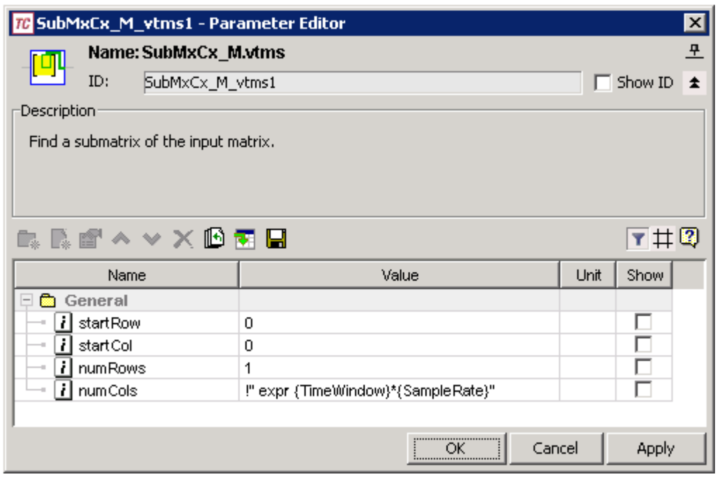
The optimization of the code does not allow to obtain at the output of the cosimulator as many ONUs as CosimOutputs because this implies changes in the galaxy module when the scenario grows. For this reason, the cosimulator has three CosimOutputs, one for each calculation: constellation, EVM and BER.

The OFDM decoding outputs are a matrix and two vectors: the matrix is for the ONUs sequences and the vectors for the EVM and BER calculation. Each matrix or vector row is relative to an ONU. They are constructed dynamically according to the number of ONUs. However, when the cosimulator module outputs the matrix and vector, a VPI module has to separate each ONU row to send the values to the analyzers.

The VPI module that is in charge of find a submatrix inside the whole matrix is the SubMatrix Finder.

Figure 5.16 SubMatrix finder module

The global parameters of the module can be seen in Figure 5.17.



Name: SubMxCx_M.vtms

ID: SubMxCx_M_vtms1

☐ Show ID

Description

Find a submatrix of the input matrix.

Name	Value	Unit	Show
General			
startRow	0		☐
startCol	0		☐
numRows	1		☐
numCols	!" expr {TimeWindow}*{SampleRate}"		☐

Figure 5.17 SubMatrix finder parameters

The parameters are the starting row and column and the number of positions taken for each row and column.

As a significant note, the first row or column considered by the VPI is located at 0, contrary to Matlab, where the first position of a vector is number one. So, a common error can be putting a 1 to choose the 1st column because it really corresponds to the zero one.

5.13.3. How to add an ONU?

The scalability is demonstrated due to the fact that an ONU can be added by just placing some modules at the input and at the output but without changing any coding and decoding Matlab code.

Some additional actions that have to be carried out at the ONU side: first, it has to be inserted a new ONU. This implies a new PRBS, a new LogicAddChannel, a new e-OFDM transmitter and a new modulation stage, comprising the drive amplitude, the laser and the MZM. Then, it has to be added the ONU in the main parameters taking care of allocating the parameters in the vectors because they are ordered. In addition, they have to accomplish the scenario requirements such as setting an even CP length value according to the DBA factor, etc…The majority of the parameters are calculated automatically since the number of FFT is decided by the user. So, for a new ONU addition, only the FFT and CP_length are chosen by the user. The rest of parameters can be auto-calculated if the user copies the formula of the parameter of other ONU inside the new created parameter and, finally, the user only needs to fill the vectors that would be used in the OLT.

When adding an ONU, some requirements have to be taken into account. The more important fact is the choice of the RF upconversion frequency. Fortunately, the system calculates the correct RF frequency automatically if the parameters are set in a correct form.

To calculate the EVM and BER, the PRBS Joiner code has to be modified to join the new ONU in the final sequence. So that, a new CosimInput must be placed before the CosimInterface.

At the OLT side, a new constellation constructor has to be added at the e-OFDM receiver and new analyzers and sub-matrix finders have to be added at the output of the OFDM decoding.

To sum it up, the next list of steps have to be accomplished:

1. Place an ONU in the universe (PRBS, LogicAddChannel, e-OFDM transmitter and optical modulation blocks).

2. Create the new parameters relative to this new ONU inside the universe parameters. This implies: number of FFT and CP length. The rest of parameters can be automatically calculated if the formula is copied.

3. Relate the parameters inside the e-OFDM transmitter to those refer to the new ONU in the universe parameter.

4. Add a new CosimInput to the PRBS Joiner.

5. Modify the PRBS Joiner function and concatenate the new ONU sequence at the final of the vector.

6. Add three sub_matrix finders, one for each measurement. Remember to change its parameters according to the row position of the new ONU.

7. Add the constellation diagram and the analyzers corresponding to BER and EVM.

8. Run the simulation and check if it fires errors.

CONCLUSIONS AND FUTURE LINES

6.1. Conclusions

This Master thesis has analyzed connection strategies for multiple users in an optical OFDMA network.

First a revision of the basic concepts of OFDM modulation and optical systems has been carried out. Special emphasis has been given to IM/DD systems as a more cost-effective alternative for OFDMA networks. In order to adapt the OFDM modulation formats to travel over an optical fiber, the IM/DD modulation with RF upconversion has been found as the best option.

A revision of the Virtual Photonics (VPI) software designed for the simulation of optical systems has been made. This software includes a demo for simulation of optical OFDM systems which is optimized for the simulation of very long lengths of fiber propagation. The demo allows adjustment of the more typical parameters of OFDM modulations such as for example the inclusion of CP and equalization.

For more advanced simulations though, the OFDM coding and decoding modules offered by VPI do not have the required flexibility.

By taking advantage of the Cosimulation tool of VPI, an OFDM coder and decoder have been programmed in Matlab [T1 and T3]. Here we have described the functionality of the designed coder and decoder and have taken advantage of them to design an extended simulation scenario for the testing of multiuser uplink OFDMA networks.

By using simulations in VPI, two strategies for the user uplink multiplexing have been analyzed: independent lasers with the same optical carrier and independent lasers with optical carriers at a safety distance. It has been concluded that, if a same optical carrier is used, a multiple detection effect occurs due to the decorrelation of the optical carriers coming from each of the ONUs that destroys the signal in detection. A mathematical analysis of the phenomenon has been provided that allows to understand the constellations obtained. A possible solution is to use an auxiliary carrier for detection of the multiuser signal together with pilot tone phase noise cancellation. The study of this proposal is left for future works.

For the case when different optical carriers are used for each ONU we have checked that correct detection is obtained for spectral distances around 20 GHz between optical carriers.

A simulation demo for an OFDMA network in the uplink has been built. The demo offers a user friendly simulation scenario that allows for the straightforward addition of users in a simple and scalable way. The global variables concept of VPI has been taken advantage of in order to automatically calculate a great number of parameters.

So that the information coming from each user is correctly allocated in the spectrum, the ONU RF frequency is calculated taking into account the individual bandwidth of each user and respecting the guard band requirements.

A zero padding technique is performed before the IFFT operation so that the resulting compound signal can be correctly jointly demodulated in a bigger size FFT. A zero is placed at the edge of each user (Nyquist frequency) to respect the symmetrical nature of the FFT operation.

Furthermore, in a point-to-point scenario, the shift of the samples is cancelled because the FFT is done twice, one at the transmitter and another in the receiver. However, in the multiuser scenario, the IFFT is performed separately for each user and, then, the reverse FFT is done for the whole sequence of users obtaining, thus, a different shift that, at the FFT output, provokes disordered users and disordered subcarriers for each user. The strategy carried out to order both users and subcarriers is as follows. First, the users' order is rearranged by performing the same FFTshift at the output so both shifts are cancelled. Once the users are ordered, the FFTshift has to be done separately for each user. For this reason, there is an iteration that performs the subcarriers rearranging in each loop. Furthermore, the operations to recover the sequence at reception are carried out inside this loop, providing, thus, scalability.

Once the users are ordered, then, the subcarriers can be shifted another time for each user individually because it is known the number of samples and the shift kind.

The CP insertion and extraction is done as in [T3]. However, the multiuser demo allows the flexibility when choosing the CP length. Furthermore, the CP length is inserted as a number of symbols to make it easier the temporal matching of the OFDM frames coming from the different users.

In order to obtain transmission quality measurements, the BER and the EVM are calculated for each user.

The optical OFDMA network simulation demo is the most important contribution of this work. The demo has been optimized so that it offers a user friendly and flexible platform. It is also easily scalable to the number of ONUs.

To allow the required scalability, the ONUs configuration is done in the same way so that in order to add new ONUs is simple and direct. Furthermore, the OLT is designed in such a way that it can process many ONUs as required without changing any programmed code and by only selecting the appropriate parameters and modules.

Related to the friendliness, the main parameters are calculated by itself, so it is very easy to test the performance of the system when the number of ONUs is increasing. Furthermore, the bandwidth of each ONU can be modified by the user to adapt the simulations to the number of subcarriers desired. The DBA factor related to the fraction of the total bandwidth used by each ONU has been defined. It is a useful parameter to understand how the ONUs share the total bandwidth.

Regarding the quality measurements (EVM, BER, constellation), the calculations are done by comparing the transmitted PRBS with the sequence at the output of the OLT. This operation is based on the VPI software functionality Logical Channels to send the PRBS. Once again, so that no changes in code are required, there is a function, the PRBS Joiner, that takes all the PRBS, concatenates them and, finally, sends a vector through a single Logical Channel to the OLT, so a dynamic number of PRBS vector can be concatenated inside the PRBS Joiner to be used inside the OLT without suffering any change in the OLT.

6.2. Future lines

In this subsection, several future lines of research that can be followed to extend the work of this Master Thesis are given.

First, the designed multiuser uplink simulation setup can be taken advantage of for testing a variety of users multiplexing strategies, some of which already discussed here, such as the addition of an auxiliary carrier to overcome the multiple detection effect due to the decorrelation of subcarriers or the OLT tone remodulation at the ONU.

This thesis work has used the MZM biased in quadrature as the optical IM modulator in the ONU. Although it can be convenient for the purposes of testing the fundamental effects, at present this is not a very cost-effective alternative for the ONU. Simulation of direct modulation lasers or electro-absorption modulators as optical IM modulators in the ONU will render more realistic simulations of the multiuser uplink problem, and the effect on performance of impairments such as for example DML or EAM chirp could be tested.

Here, all ONUs have been considered to use a 4-QAM modulation. It would be interesting to adapt the multiuser simulation scenario to support different modulation levels for each ONU.

Finally, an equivalent simulation scenario as the one given here for the uplink can be designed for the downlink to provide a complete simulation setup for optical OFDMA networks.

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ACRONYMS

- **ASE** – Amplified Spontaneous Emission
- **B2B** – Back-to-Back
- **BER** – Bit Error Rate
- **CFO** – Carrier Frequency Offset
- **CO-D** – Coherent Detection
- **CP** – Cyclic Prefix
- **CW** – Continuous Wave
- **DBA** – Dynamic Bandwidth Assignment
- **DD** – Direct Detection
- **E/O** – ElectricaltoOptical
- **EVM** – Error Vector Magnitude
- **e-OFDM** – Electrical OFDM
- **FFT** – Fast Fourier Transform
- **FTTB** – Fiber To The Building
- **FTTH** – Fiber To The Home
- **ICI** – InterCarrier Interference
- **IFFT** – Inverse Fast Fourier Transform
- **IM** – Intensity Modulation
- **IM/DD** – Intensity Modulation/Direct Detection
- **IQ** – In-phase and in-Quadrature
- **ISI** – InterSymbolic Interference
- **MZ** – Mach-Zehnder
- **MZM** – Mach-ZehnderModulator
- **O/E** – OpticaltoElectrical
- **OBI** – Optical Beat Interference
- **OFDM** – Orthogonal Frequency Division Multiplexing
- **OLT** – Optical Line Terminal
- **ONU** – Optical Network Unit
- **o-OFDM** – Optical OFDM
- **PRBS** – Pseudo-Random Bit Sequence
- **QP** – Quadrature Point
- **SER** – Symbol Error Rate
- **SSB** – Single SideBand
- **VPI** – Virtual Photonics Inc
- **ZP** – Zero Padding

APPENDIX A: PULSE SHAPING, OVERSAMPLING AND GAP GENERATION

A.1. Pulse shaping and oversampling

The pulse shaping is the manner for VPI to introduce non-idealities into the DAC. Thus, the pulse shaping is modeled using a raised-cosine factor with a certain roll-off factor to vary the non-ideality.

However, in this thesis master the roll-off factor is zero so the pulse shaping does not introduce any non-ideality.

Oversampling is useful to correct the aliases appeared by means of the pulse shaping. When sampling with a non-ideal DAC, some alias appear and it is impossible for any practical filter to separate it from the sampled signal. The solution is to shift the aliases away from the OFDM signal by means of a combination of both zero padding and oversampling, as can be seen in the Figure A.1. The employed technique is fully explained in [B3].

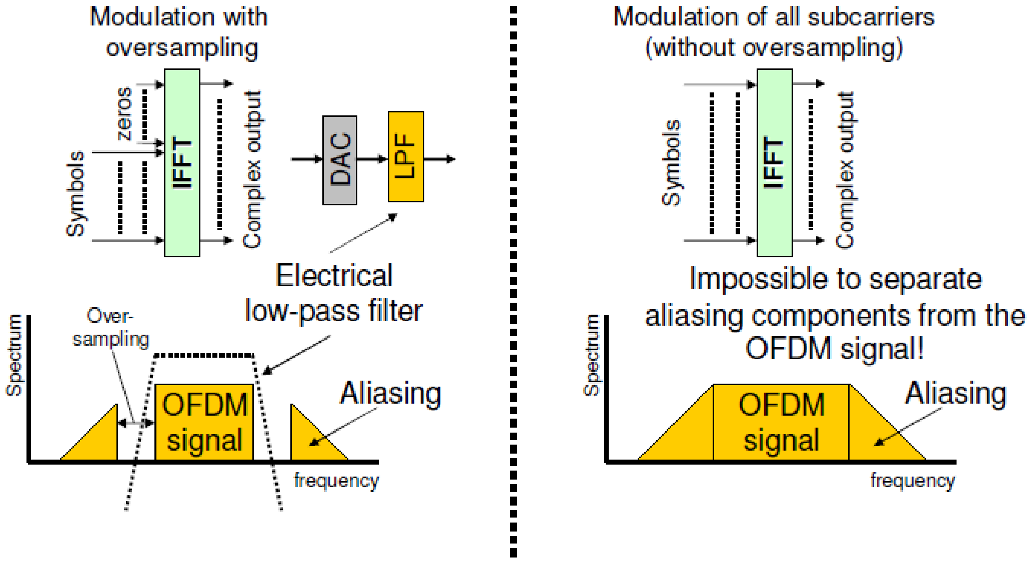

Figure A.1 Aliases shifted away by means of oversampling

A.2. Zero padding strategy to create a gap between the optical carrier and the information subcarriers

The other way to create a gap between the OFDM signal and the DC component is using a zero padding technique.

The zero padding strategy is to add zeros at the edges of the IFFT input sequence. A gap is created, though bitrate efficiency decreases, as can be seen in the FigureA.2. In fact, to generate a gap between the optical carrier and the information subcarriers with the minimum required length, the half of the subcarriers is zero. In other words, if 128 IFFTs are required, the double is necessary to perform the zero padding technique.

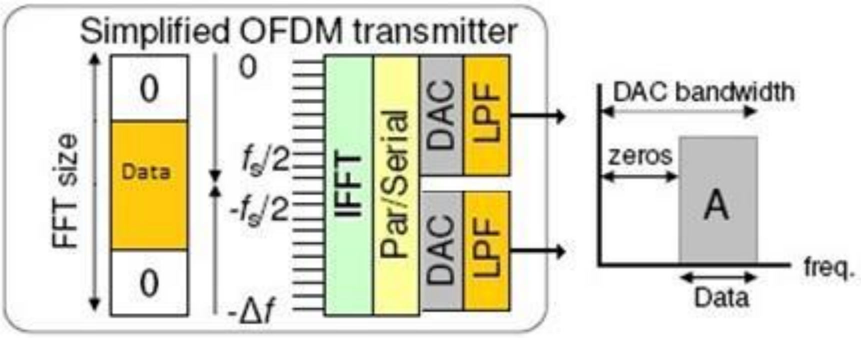

Figure A.2 Zero padding at the edges to create gap

APPENDIX B: OFDM CODING MATLAB CODE

```
function [y]=ofdm_coder1(x1,TW,BR,BpS,N_FFT,CP,ZP_Mask,NFFT)
%% Parameter initialization
Nc=N_FFT-length(ZP_Mask);
OFDM_LENGTH=N_FFT+CP; % total QAM symbol length of OFDM symbol
(including overheads)

NTS_OFDM=floor(length(x1)/(BpS*OFDM_LENGTH)); %Total number of OFDM
symbols in input sequence

NTS_QAM=NTS_OFDM*OFDM_LENGTH; % total number of QAM symbols,
including overheads

NTS_QAM_INFO=Nc*NTS_OFDM; % total number of QAM symbols carrying
information (without overheads)

NTB_INFO=NTS_QAM_INFO*BpS; %Total number of information bits

tabla_4qam = [ -1.0000 - 1.0000*j , 1.0000 - 1.0000*j ,  -1.0000 +
1.0000*j,   1.0000 + 1.0000*j];

%% Gathering the information bits

xx1=x1(1:NTB_INFO); % Vector containing the information bits to
transmit

xx1_QAM=tabla_4qam(bi2de(reshape(xx1,BpS,NTS_QAM_INFO)')+1);

xx1_OFDM_INFO=reshape(xx1_QAM,Nc,NTS_OFDM);

%% insert one zero at the spectrum edges (for mutiuser integration)

A_ones = ones(1,N_FFT); % Vector of ones with length N_FFT

A_ones(ZP_Mask) = 0; % Insert in the ones vector the zeros
introduced by the user in ZP_Mask

Nc_Mask = find(A_ones); % Generate a new vector Nc_Mask with the
positions where it has to be information

xx1_OFDM_ZP = zeros(N_FFT, NTS_OFDM); % Generate a zeros matrix of
N_FTT x NTS_OFDM

xx1_OFDM_ZP(Nc_Mask,:) = xx1_OFDM_INFO;

%% IFFT is applied

xx1_IFFT=ifft(xx1_OFDM_ZP,N_FFT);

%% Cyclic prefix is added to each OFDM symbol

xx1_CP=[xx1_IFFT(1+N_FFT-CP:N_FFT,:);xx1_IFFT];
```

```
%% Serialization and adaptation to the SampleRate

xx1_serial=reshape(xx1_CP,1,NTS_QAM);

y=zeros(1,TW*BR/BpS);

y(1:NTS_QAM)=xx1_serial;

% Normalization at the output of the OFDM coder

h = modem.qammod('M',BpS);

const = h.modulate(0:BpS-1); % “const” are all the values that can
%take the constellation and depends on the chosen modulation choose
%by means of the BpS parameter

y = y./max(abs(const));

y = y./sqrt(2);

modul = sqrt(real(y).^2+imag(y).^2);

maxmod = max(modul);

y_real_mod = real(y)./maxmod;

y_imag_mod = imag(y)./maxmod;

% Electrical data packet send to the MZM

y = y_real_mod + y_imag_mod*1i;

saveC:\Saul\matlab_outputs\Coder1
```

APPENDIX C: OFDM DECODING MATLAB CODE

```
function
[yy,EVM,BER]=olt_n_rx(y_real,y_imag,sumaPRBS,TW,SR,BR,BpS,v_NFFT,ZP,
vCP_length)

%%Initialization of single variables and vectors

tabla_4qam = [ -1.0000 - 1.0000*j , 1.0000 - 1.0000*j ,  -1.0000 +
1.0000*j,   1.0000 + 1.0000*j];

N_users=length(v_NFFT); % Number of users

N_FFT=sum(v_NFFT);% Total number of carriers

Nc=N_FFT-length(ZP);% number of total carriers without overheads

vBR=(BR.*v_NFFT)/N_FFT;  % vector of BRs of each user
BR_user1=v_BR(1)

CP_length=sum(vCP_length);% CP length of the whole input sequence

FrameLength=N_FFT+CP_length; % Total Length of the frames, including
overheads

N_Frames=floor(TW*BR/(BpS*FrameLength));% Number of symbols in each
frame

N_Symbols=N_Frames*FrameLength; % Total number of symbols (includes
overheads, excludes single symbols)

N_Symbols_Info=Nc*N_Frames; % number of symbols that carry info
x=y_real+j*y_imag;

yy1=x(1:N_Symbols); % from input sequence remove single symbols,
consider only info+overheads

yy1_SP=reshape(yy1,FrameLength,N_Frames);

%% Remove CP

% move the last half CP at the start of string (before or after
removing

% CP_length/2 related to fiber f_ref issues
yy1_CP_OUT= yy1_SP(CP_length/2+1:FrameLength-CP_length/2,:);

% take FFT

yy1_FFT=fft(yy1_CP_OUT,N_FFT);
```

```
% assign each part of the spectrum to one ONU
% first takefftshift so that the users are deliberately disordered
%to recover the order after the FFT

yy1_FFT_ordered=fftshift(yy1_FFT,1); %To rearrange the users' order

inicio=0;

inicio_t=0;

fori=1:N_users

      final=inicio+v_NFFT(i);  % Pointer related to the final of the
      %user sequence

      inicio=inicio+1;

Nci=v_NFFT(i)-1; % remove ZP

      y_user=fftshift(yy1_FFT_ordered(inicio:final,:),1);%To
      rearrange the subcarriers inside NFFT

%% remove ZP
% retrieve ZP mask of user i

ZP_user=ZP(i);

y_user_ZP_removed=y_user([1:ZP_user-1,ZP_user+1:v_NFFT(i)],:);
      %training

      FrameLength_user=v_NFFT(i)+vCP_length(i);%  Frame  length  of
      %the corresponding user

      N_t=floor(vBR(i)*TW/(BpS*FrameLength_user));%Number         of
      %symbols in each subcarrier for training

      N_Symbols_user=N_t*FrameLength_user;  %Number  of  symbols  for
      %training

      final_t=inicio_t+(vBR(i)*TW);

      inicio_t=inicio_t+1;

      Bits_training=sumaPRBS(inicio_t:final_t);%  Extract  the  PRBS
      %in the transmission

      inicio_t=final_t;

      Symbols_training=tabla_4qam(bi2de(reshape(Bits_training(1:N_t*
      Nci*BpS),BpS,N_t*Nci)')+1);% Bit to symbols and reshape to a
      %vector

      Training_matrix=reshape(Symbols_training,Nci,N_t);    %  Vector
      %to matrix

      input_Training_matrix=Training_matrix;

      output_Training_matrix=y_user_ZP_removed(:,1:N_t);
```

```
      ch_response=sum((output_Training_matrix./input_Training_matrix
      ),2)/N_t;% Channel response

      channel_inv= diag(1./ch_response); % Inverse of the channel
      response

      y_user_equalized=channel_inv*y_user_ZP_removed;%       Channel
      %response is applied to correct the amplitude and phase levels
      %get the symbol seq

N_symbols_info_user=Nci*N_Frames;

N_bits_info_user=N_symbols_info_user*BpS;

      y_user_info_symbol_seq=reshape(y_user_equalized,1,N_symbols_in
      fo_user);  % Matrix to vector of symbols

      prueba=floor((TW*SR)/N_symbols_info_user); % Calculating the
      number of sequences in a TW*SR

      auxiliar=repmat(y_user_info_symbol_seq,1,prueba);     %     the
      sequence of symbols is repeated prueba times

      repeticiones= (TW*SR)-length(auxiliar); % Searching the number
      %of positions that can not be filled because of the TW*SR
      %requirement

      vector_repeticiones=y_user_info_symbol_seq(1:repeticiones);%Ve
      ctor with repeticiones positions

      y_user_samples=[auxiliar,vector_repeticiones];%    Concatenate
      %bothvectors

      yy(i,:)=y_user_samples; % Matrix with the user samples in the
      rows. In each row it is obtained TW*SR symbols and each row
      correspond to a user

      %% EVM calculation

      yy_dec_user = qamdemod(y_user_info_symbol_seq,2^BpS,pi/2);

      z_user = reshape(de2bi(yy_dec_user)', 1, N_bits_info_user);

      PRBS_TX_user = Bits_training(1:length(z_user));

      PRBS_TX_QAM_user=reshape(PRBS_TX_user,BpS,N_symbols_info_user)
      ';

      PRBS_TX_QAM_matlab_user=qammod(bi2de(PRBS_TX_QAM_user),2^BpS,p
      i/2);

      PRBS_TX_serial_user=reshape(PRBS_TX_QAM_matlab_user,1,N_symbol
      s_info_user);

      TX_EVM_user = PRBS_TX_serial_user;

      RX_EVM_user = y_user_info_symbol_seq;
```

```
      num1_user = (real(TX_EVM_user)-real(RX_EVM_user)).^2;
      num2_user = (imag(TX_EVM_user)-imag(RX_EVM_user)).^2;
      numtotal_user = sum(num1_user+num2_user);
      den1_user = real(TX_EVM_user).^2;
      den2_user = imag(TX_EVM_user).^2;
      dentotal_user = sum(den1_user+den2_user);
      EVM_user = sqrt(numtotal_user/dentotal_user);
      EVM(i,:)=EVM_user;
      % % %% BER calculation
      result_user = xor(PRBS_TX_user,z_user);
      Errors_user= sum(result_user);
      BER_user = Errors_user/length(PRBS_TX_user);
      BER(i,:)=BER_user;
      inicio=final;
      y_user_info_symbol_seq=0;
      vector_repeticiones=0;
      y_user_symbol_seq=0;
end
save c:\Saul\matlab_outputs\testRX2
```