MASTER THESIS

TITLE: Predistortion Transmitters for Orthogonal Frequency Division Multiplexing Passive Optical Networks

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AUTHOR: Mireia Liébana Buxó

DIRECTOR: Maria Concepción Santos

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Overview

The aim of this work is to offer different alternatives for an OFDM PON networks, studying and analyzing many systems with their pros and cons and proposing news schematics for a multiuser scenario for the uplink.

The systems analyzed are composed by an optical I/Q transmitter and two types of receivers, a DD and a hybrid 90° coherent receiver. A new technique, called predistortion, that improves the drawbacks of the conventional oI/Q systems is studied. The idea to perform the multiuser scenario is shifting the user data, allowing allocation of each user in a given optical spectral band.

All the simulations have been done using the commercial software VPItransmissionMaker™ and VPIphotonicsAnalyzer™, (VPI) in combination with a code in Matlab for the OFDM coder and decoder.

Also the performance of the optical OFDM systems is measured by means of a script in TCL/TK language that allows changing many parameters, in order to test and obtain results of the systems performance in terms of sensitivity vs. length for a threshold minimum quality BER value of 10⁻³.
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Introduction

Optical fiber networks are emerging as the better solution for access due to two aspects namely:

- Large transmission bandwidths.
- The continuous decline in prices of lasers and optical equipment.

Optical fiber communication is very successful because of the near-perfect characteristics of optical fibers when compared with cooper cables and metallic waveguides. The single mode fiber allows gigabit-rate non-return to zero (NRZ) pulses to be transmitted around a hundred kilometers between regenerators.

The OFDM modulation format is a highly successful technology which has been developed into a popular scheme for wideband digital communication, whether wireless or over copper wires, used in applications such as digital television and audio broadcasting, DSL broadband internet access, wireless networks and 4G mobile communications. That’s because it has many advantages: it can easily adapt to severe channel conditions with a simple equalization process, it is robust against inter-symbol interference (ISI) and has high spectral efficiency compared to other modulation schemes.

Following increases in demand the capacity of the next generation access networks should reach 10 Gb/s and even more. However, as compared to long-haul backbone optical networks, access networks are very cost-sensitive. A Passive Optical Network (PON) is proposed due to its large coverage with large offered capacity per user, improved quality of service and reduced consumption.

The aim of this project is to explore an alternative for a future generation of multiuser PON, based on OFDM technologies and using predistortion schemes.

Towards the goal, the different applications of OFDM technologies as well as optical fiber networks based in PON will be reviewed. Following, new proposals based on predistortion circuits and taking into account the multiple users architecture will be made and analyzed offering new solutions.

The thesis is structured in 5 chapters, containing the next structure and concepts:

Chapter 1 starts with a brief background of OFDM, what it is, how it can be implemented, its advantages and also the most important features to consider when analyzing OFDM systems.
Moreover, the conventional intensity-modulation direct-detection (IMDD) optical transmission systems are reviewed. The operation of the most common and versatile external optical modulator used in most of high-speed optical communication systems will be described in detail. The chapter ends with a brief description of the basic structure and concepts related to PONs.
Chapter 2 explains the basic schemes for optical OFDM systems as applied to point-to-point communications. Three main categories have been identified. The simplest IM-DD systems require some modifications to conventional OFDM schemes, which reduce the efficiency and the performance, while advanced optical transmission systems using an optical IQ transmitter and coherent receivers exhibit the best performances at the expense of complexity and cost. A third alternative are hybrid systems which combine an inexpensive transmitter with a complex receiver or the other way around, thus accommodating the requirements of the PONs uplink and downlink respectively. Also, an introductory description of a new alternative suited for the PONs uplink and based on optical IQ transmitters and coherent receiver is given.

Then there is an introduction to the simulation's tool, based on a combination of Matlab code modules embedded into the optical systems block simulator Virtual Photonics Inc, (VPI). The focus here will be the description of the OFDM coder/decoder modules and the choice of the general setting parameters of the implemented systems. The main goal here has been the definition of a user friendly scenario which at the same time offers flexibility in the numerical tests that can be carried out.

Chapter 3 is devoted to the multiuser case. Based on the basic schemes described in Chapter 2, new approaches especially suited to the PON scenario are described and analyzed in detail. Also predistortion techniques are presented. The underlying mathematical expressions are developed starting from the ideal case, and then moving onto the introduction of a finite Extinction Ratio typical of commercial modulators. General schemes and sketches of the signals spectra found at each key point in the signal’s path are provided for better understanding of the predistortion technique.

Chapter 4 shows the finals results along with a comparative study of all the circuits that are analyzed in this thesis. The main parameters to be analyzed in order to compare the different systems will be the sensitivity and BER as a function of fiber length.

Chapter 5 includes a summary of conclusions and an overview about possible future lines of research.
Chapter 1. Background

1.1 OFDM
Orthogonal Frequency Division Multiplexing is a multi-carrier modulation technique, where a data stream is encoded onto many subcarriers that are then transmitted together on a common path. The orthogonality means that each subcarrier has a sinc-like spectrum, whose nulls align with the peaks of the sinc-like spectra of the adjacent subcarriers. See Figure 1.1.

The condition of orthogonality requires that the sub-carrier spacing is:

\[
\Delta f = \frac{1}{N \cdot T_s}
\]

(1.1)

Where \(T_s\) is the symbol duration and \(N\) the number of subcarriers.

Therefore, with \(N\) sub-carriers, the total pass-band bandwidth will be:

\[
B = N \cdot \Delta f
\]

(1.2)

Figure 1.1 shows the overlapping spectra of the subcarriers, but because of the orthogonally property, as long as the channel is linear, the subcarriers can be demodulated without interference.

An advantage of OFDM is that each subcarrier has a narrow bandwidth as compared with the total data rate, so that the transmission channel is perceived by each subcarrier as a flat channel and therefore equalization is simple.
On the other hand, OFDM transfers the complexity of transmitters and receivers from the analog to the digital domain. For instance, in OFDM any channel response variation with frequency can be corrected at little or no cost in the digital parts of the receiver [1].

1.1.1 OFDM transmitter and receiver

Figure 1.2 shows a general schematic of a digital OFDM transmitter system.

An input serial bit sequence is packed into multilevel symbols, for example, with a QAM modulation format. The symbol serial sequence is parallelized into several outputs which correspond to each of the OFDM subcarriers. The resulting symbol period is \( N \), number of subcarriers, times longer than a serial system with the same total data rate. A training sequence is then added for synchronization and channel response estimation.

Both modulation and multiplexing are achieved digitally using Fourier transforms and as a result, the required orthogonal signals can be generated precisely and in a very computationally efficient way. There is a condition that has to be fulfilled to improve the computational efficiency by using IFFT and FFT algorithms: the whole sequence must have a length equal to a power of 2. If this condition is not met, zeros can be added to the sequence in order to reach the required length (zero-padding).

When the signal is transformed from parallel to serial the Cyclic Prefix (CP) is inserted. The CP main functionality is to provide a guard time that prevents interference between neighboring OFDM symbols (ISI). Finally each of the signal’s components (real and imaginary part) goes through a DAC (to convert it to digital to analog domain) and is low-pass filtered (LPF) to remove spectral replicas and then conditioned for transmission over the channel (usually the optical modulation stage follows).

In reception (figure 1.3), both components of the signal are filtered again (with LPF) for anti-aliasing and digitalized with and A/D conversion (ADC) doing the reverse process applied at the transmitter side. After this, both branches must be added to obtain complex numbers for decoding stage.
After that, an OFDM symbol synchronization process is required before the CP is removed (recovering the orthogonality). The obtained sequence is then parallelized so the demodulation and multiplexing is performed by a FFT. Back in the frequency domain, the training symbols added to each subcarrier are removed. Then the single-tap equalization is done per subchannel.

Consecutively, the phase noise can be compensated (mostly in coherent approaches). After that, each subcarrier is demodulated with its own constellation and, at the end, the restored bit sequences are serialized to recover the information sent [2].

![General OFDM Receiver Scheme](image)

**Figure 1.3 General OFDM Receiver Scheme**

### 1.1.2 Synchronization

Synchronization is one of the most critical functionalities for an OFDM receiver. It can be divided into three levels of synchronization: DFT window timing synchronization where OFDM symbol is properly delineated to avoid intersymbol-interference, frequency synchronization, frequency offset needs to be estimated and compensated, and the subcarrier recovery, where each subcarrier channel is estimated and compensated.

Figure 1.4 shows the time domain structure of an OFDM signal consisting of many OFDM symbols. Each OFDM symbol comprises a guard interval and an observation period. It is mandatory that the receiver FFT window is properly synchronized with the OFDM symbols because otherwise it will result in intersymbol interference (ISI).

![Time domain structure of an OFDM signal](image)

**Figure 1.4 Time domain structure of an OFDM signal**
There are many methods to synchronize a transmission; training symbols are also usually used for synchronization and channel estimation. When working with simulation software, symbol synchronization is not obvious, since chromatic dispersion makes some subcarriers to arrive at the receiver at different times. In terms of the numerical simulation the start of the received time window is set by the choice of the reference frequency which is a simulation parameter of the transmission fiber. An in-depth analysis of the meaning of this parameter is carried out in section 1.2.1.2 in order to understand how it can be properly adjusted to obtain a correct decoding of the sent signal.

1.2 Optical Systems

1.2.1 Optical Fiber

Since transmission loss is low, especially when working in the 3rd transmission window around 1.55um, and in addition in can be compensated using EDFAs, one could say that the main limitation to transmission bandwidth and reach in optical fibers is dispersion. Dispersion can be defined as the effect by which different signal components travel at different speeds causing a temporal spread of the received information, whose most direct consequence is usually ISI.

There are mainly two types of optical fibers: single-mode and multi-mode, the difference between them is the amount of rays of light, also known as modes, which are transmitted through the fiber.

A single-mode optical fiber (SMF) is an optical fiber designed to carry only a single ray of light (mode), because single-mode fiber supports only one transverse mode, intermodal dispersion which is the main source of dispersion in fibers is eliminated. In single-mode fiber performance is primarily limited by chromatic dispersion, which occurs because the index of the glass varies slightly depending on the wavelength of the light.

Single mode fibers are therefore better at retaining the fidelity of each light pulse over longer distances than multi-mode fibers. For these reasons, single-mode fibers can have a higher bandwidth than multi-mode fibers. Equipment for single mode fiber is more expensive than equipment for multi-mode optical fiber, but the single mode fiber itself is usually cheaper in bulk.
1.2.1.1 Chromatic Dispersion

Chromatic dispersion can be defined as the effect by which different spectral components travel at different speeds (group velocity) in the fiber. So the main effect of CD in optical OFDM is a time delay across an OFDM band of subcarriers (Figure 1.5).

![Figure 1.5 Impact of CD on an OFDM symbol](image)

In other words, CD causes ISI producing interference between adjacent OFDM symbols. To prevent the system degradation by ISI the OFDM symbol is extended by a cyclic prefix.

If we consider only relevant the effect of chromatic dispersion, the transfer function of the optical fiber can be described as:

$$H(\omega) = e^{-j\beta(\omega)L}$$  \hspace{1cm} (1.3)

The phase constant ($\beta$), has a nonlinear dependency with the frequency (eq. 1.3) which under the condition:

$$BW \ll \omega_{ref}$$  \hspace{1cm} (1.4)

Can be approximated by its Taylor polynomial (eq. 1.5):

$$\beta(\omega) \approx \beta(\omega_{ref}) + \frac{\partial \beta}{\partial \omega}_{\omega=\omega_{ref}} (\omega - \omega_{ref}) + \frac{1}{2} \frac{\partial^2 \beta}{\partial \omega^2}_{\omega=\omega_{ref}} (\omega - \omega_{ref})^2 + ....$$  \hspace{1cm} (1.5)

Where $\omega_{ref}$ is the center frequency of the signal bandwidth and may be set arbitrarily as the frequency from which all the differential delays are referred to. It is precisely in this sense that in the numerical simulations the choice of this frequency is related to the synchronization of the received symbol.
The group delay is defined as:

\[
\tau_g = \frac{L}{V_g} = \frac{L}{V_g} \left. \frac{\partial \beta}{\partial \omega} \right|_{\omega_{ref}}
\]  

(1.6)

Where \( \beta \) is the propagation constant introduced previously, and \( V_g \) is the group velocity (the speed at which the energy of an optical pulse travels).

In a frame of reference moving at the group velocity the fiber transfer function may be simply written as:

\[
H(\omega) = e^{-\frac{\beta_2 (\omega - \omega_{ref})^2 L}{2}}
\]  

(1.7)

Where:

\[
\beta_2 = \left. \frac{\partial^2 \beta}{\partial \omega^2} \right|_{\omega_{ref}} = \left. \frac{\partial}{\partial \omega} \tau_g \right|_{\omega_{ref}}
\]  

(1.8)

Finally the chromatic dispersion parameter \( D \) [ps/nm·km] is defined as:

\[
D = \frac{\partial \tau_g}{\partial \lambda} \left. \frac{\partial}{\partial \omega} \tau_g \right|_{\omega_{ref}} = \beta_2 \left( \frac{-2\pi c}{\lambda_{ref}^2} \right)
\]  

(1.9)

So that:

\[
\tau_g = D \Delta \lambda \cdot L
\]  

(1.10)

The optical transmission systems considered here are assumed to work in the third spectral window (1.55um), where the chromatic dispersion coefficient is 17ps/(nm·Km).

In the next example (the scenario is a demo for a long haul system included in the commercial software VPI.), can be seen this phenomenon, as figure 1.6 shows, the constellation has the four symbols spread, but inserting a CP this is corrected (figure 1.7).
The best way to quantify the required CP is giving the percentage, then:

$$CP(\%) = \frac{\Delta \tau_{CP}}{T_{OFDM}} = \frac{D \Delta c \lambda L}{B_w N_{FFT}} = D \frac{c}{\lambda_0^2} B_w^2 \frac{L}{N_{FFT}}$$  \hspace{1cm} (1.11)

For instance, in our simulations the modulation used is 4QAM modulation, for a fiber length $L=100$km, $BW=5$GHz and 256 subcarriers. The maximum CP needed can be obtained taking into account the minimum number of subcarriers that will 16. So:

$$CP(\%) = \frac{17 \frac{ps}{nm \cdot km} \cdot 0.04nm \cdot 100km}{16 / 5GHz} \cdot 100 = 2.125\%$$  \hspace{1cm} (1.12)

Later, in section 1.2.4, there is an example of a Long Haul system, with a range of 1000km, using 64 subcarriers and $BW=5$Ghz. So the CP needed is also calculated here:

$$CP(\%) = \frac{17 \frac{ps}{nm \cdot km} \cdot 0.04nm \cdot 1000km}{64 / 5GHz} \cdot 100 = 5.3125\%$$  \hspace{1cm} (1.13)

With result that for the lengths and bandwidths of reference in this work, no CP is required due its low percentage. In practice some CP may be added to relax the synchronization requirements.

### 1.2.1.2 Reference frequency

As explained in the previous section 1.2.1, we may consider that the fiber is basically an element that introduces dispersion, which is a differential delay among all the spectral components of the transmitted signal. This is why the issue of synchronization is very important. The parameter that plays an important role here is the reference frequency. It is important to understand that
this is actually not a physical characteristic of the fiber but it is related with the reference respect to which the dispersion-induced time shifts are considered. It then holds a close relation to the synchronization at the receiver.

Following the analysis in [3], the reference frequency has been set to the central frequency of the signal spectrum. That means that approximately half of the subcarriers will arrive at the beginning of the time window while the rest would have to arrive before the time window starting point and due to the intrinsic periodicity inherent to the FFT numerical algorithms used by VPI to simulate the propagation in fiber (split-step Fourier algorithm), these subcarriers will be found at the end of the time window.

In order to get rid of all the ISI, proper CP extraction at the receiver side needs to take into account the reference frequency choice. In our case, we need to understand that as a consequence of the periodical nature of the numerical algorithms involved, there is ISI between the first and the last transmitted symbol spreading from the beginning of the time window to the end of it, and therefore the CP extraction between these two symbols will need to be split so that half CP time interval will be discarded at the beginning of the time window, and half of it at the end.

1.2.2 Conventional Optical Systems

1.2.2.1 Intensity Modulation - Direct Detection Systems (IM-DD)

Figure 1.8 shows the scheme of a conventional IM-DD optical transmission system. As seen, an electrical signal that varies with the information, is applied to a light generating device (LED or laser) resulting in an optical modulated signal whose intensity or optical power is proportional to the information (Intensity Modulation). A diode detector in the receiver performs the reverse operation (Direct Detection) generating a current proportional to the intensity or optical power received.

The simplicity of the direct intensity modulation of semiconductor lasers made possible the introduction of optical fibre communications at an early date which required the minimum of technical development. These first transmission systems suffer from bandwidth limitations which were overcome with the development of external modulators, such as Mach-Zehnder modulators.
1.2.2.2 DML (Direct modulated laser)

Is based in a laser diode whose feeding current is made to vary according to an electrical signal carrying the information to be sent, for each electron of current injected generates a photon and therefore the optical output power is proportional to the injected current, once the current exceeds the threshold required to produce the laser effect (see figure 1.9).

![Scheme of DML](image)

Figure 1.9 Scheme of DML

In figure 1.10, the intensity characteristic of the laser power is seen. There is a linear zone of interest in work, above the threshold ($I_{th}$). A bias current ($I_b$) is injected to ensure that we always are in the linear region. The slope of this line will be defined as Slope Efficiency (SE).

![Transfer function of a laser](image)

Figure 1.10 Transfer function of a laser

The signal is modulated according to the expression 1.14:

$$P_{OUT} = P_o (1 + m \cdot x(t))$$  \hspace{1cm} (1.14)

Where $P_o$ is the optical carrier power, $x(t)$ is the signal information normalized to 1 and $m$ is the modulation index which is always less than or equal to one to avoid overmodulation and is defined as:
\[ m = \frac{\Delta I}{I_B - I_{th}} \] (1.15)

The electrical field at the output can be defined, just taking the square root of the output power.

\[ E_{OUT} = \sqrt{P_O (1 + m \cdot x(t))} \] (1.16)

There’s therefore a nonlinear conversion involved in the processes of modulation and demodulation which causes that linear channel distortions, such as for example, chromatic dispersion, result in nonlinear distortions from an end-to-end perspective.

1.2.2.3 MZM (Mach-Zehnder Modulator)

A Mach-Zehnder Modulator is an optical device in which a signal-controlled element displaying the electro-optic effect is used to modulate a beam of light.

In a MZM an input laser light beam is split into two paths, one of which has an electro-optically induced phase shift. The beams are then recombined. Changing the electric field on the phase modulating path will then determine whether the two beams interfere constructively or destructively at the output, and thereby a control of the amplitude or intensity of the exiting light is provided.

As shown in 1.11 the output of the electrical field of the MZM is:

\[ E_{OUT} = \frac{E_{IN}}{2} \left[ e^{j\phi(t)} + \gamma e^{j\phi(t)} \right] \] (1.17)

The optical phases in each of the branches come from the combination of the different modulator voltages. On one side, the voltage referring to the electrical
signal and on the other side the DC bias voltage. Taking into account the voltages in each branch:

\[ V_1(t) = V_{DC,U} + V_{RF,U}(t) \]  \hspace{1cm} (1.18)
\[ V_2(t) = V_{DC,L} + V_{RF,L}(t) \]  \hspace{1cm} (1.19)

And therefore:

\[ \phi_1(t) = \phi_{DC,U} + \phi_{RF,U}(t) \]  \hspace{1cm} (1.20)
\[ \phi_2(t) = \phi_{DC,L} + \phi_{RF,L}(t) \]  \hspace{1cm} (1.21)

By definition of half-wave voltage \( V_{\pi} \), applying a voltage of \( V_{\pi} \) to the electrode of an electro-optic waveguide will result in a voltage-induced phase shift of \( \pi \). The electro-optically induced phase shift \( \phi(t) \) can therefore be related to the applied voltage \( V(t) \) according to:

\[ \phi(t) = \pi \frac{V(t)}{V_{\pi}} \]  \hspace{1cm} (1.22)

Where:

\[ \phi(t) = \phi_1(t) + \phi_2(t) \]  \hspace{1cm} (1.23)
\[ V(t) = V_1(t) + V_2(t) \]  \hspace{1cm} (1.24)

Also, in the figure 1.11, the parameter \( \gamma \), indicates the weight of the optical signal to be distributed in each of the MZM's branches. When this parameter is 1 it means that the distribution is equitable between branches. This parameter related directly with the MZM Extinction Ratio (ER) specifying the difference between the maximum and minimum optical power at the MZM output. Their relation is shown in the following equation (1.25).

\[ ER = \frac{(1+\gamma)^2}{(1-\gamma)^2} \]  \hspace{1cm} (1.25)

Typical ER values are between 15-40 dB, the greater ER the better performance of the MZM in terms of achievement of deeper modulation depths and also a higher manufacturing cost.
2.1.1.1 Biasing a MZM

The biasing of the modulator plays an important role in the system performance. In conventional intensity modulation systems, the concern is to achieve a linear transformation between electrical drive voltage and the optical power.

Figure 1.12 shows the transfer function for both the optical intensity and optical field (I/Q component) against the drive voltage.

![Figure 1.12 The transfer functions for the optical intensity and the optical field against the drive voltage](image)

To get the most linear part of the intensity response, a bias voltage of $V_x/2$ is required. This is the optimal intensity modulation point or the quadrature point (QP). However, if the MZ is biased at quadrature, the driving amplitude still has to be chosen low to avoid nonlinear distortion.

The optimal bias point for a field or amplitude modulation is the null point (NP), with a required bias voltage of $V_x$, allowing getting a higher modulation depth and suppressing the carrier for CO detection.

The QP has been widely adopted for DD systems because the optical carrier is needed for detection. Reducing the carrier produces significant distortion upon photo-detection due to the intermixing of OFDM subcarriers. But if there is a bandgap between the carrier and the OFDM signal, these products fall mostly in this bandgap. The NP for CO-OFDM signifies a fundamental difference between the optical intensity modulation and optical field modulation [1].

2.1.1.2 MZM configuration for optical OFDM systems

It has been seen in the previous section that by biasing the Mach–Zehnder modulators (MZMs) at null point, a linear conversion between the RF signal and the optical field signal can be achieved. That’s why from now on we will work
with systems that include a MZM. Many signal modulations are possible using electro-optical modulators, see figure 1.13, but here the focus is on those that allows obtaining AM signal or IQ modulation.

<table>
<thead>
<tr>
<th>Device structure</th>
<th>Phasor diagram</th>
</tr>
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<tbody>
<tr>
<td><img src="image_url" alt="Device structure" /></td>
<td><img src="image_url" alt="Phasor diagram" /></td>
</tr>
</tbody>
</table>

Figure 1.13: Table relating different device structures with its output modulation

As seen in figure 1.13, optical amplitude modulation (AM) can be achieved by using phase modulators in a Mach-Zehnder configuration, which are driven in a push–pull mode of operation. Optical IQ modulation, on the other hand, can be realized with Mach-Zehnder type push–pull modulators in parallel, between which a π/2 phase shift is applied. The IQ components of the optical carrier are modulated independently with the IQ modulator, enabling any kind of modulation formats.

### 1.2.3 Advanced Optical Systems

#### 1.2.3.1 Optical IQ (In-Phase/Quadrature)

It consists in two MZMs that are themselves embedded into a Mach-Zehnder interferometer structure (figure 1.14). The incoming light is equally split into two arms, in-phase \( u_i(t) \) and quadrature \( u_q(t) \) arms, respectively.

In both paths, a field amplitude modulation is performed by operating the MZM in the push-pull mode at the minimum transmission point. An additional static phase shift of \( \pi / 2 \) between the two arms of the interferometric superstructure is furthermore introduced.
Figure 1.14 Principle of operation of the optical IQ modulator.

Figure 1.14 shows the configuration of the MZM for an oIQ modulation and also the points in the complex plane (I, Q). Any constellation point can be reached in the complex I/Q plane after recombining the light of both branches. So it becomes possible to generate any optical field, and thus any modulation format, provided the driving signals $u_I(t)$ and $u_Q(t)$ can be synthesized.

The signal is transmitted without carrier, thus the Mach-Zehnder modulator (MZM) is biased at power null point, which is the point of most linearity in E-field characteristic.

With this method the transmitted power is reduced because the carrier is not sent, but instead of this, a higher complexity in transceiver design is required (using a local oscillator laser at the receiver).

1.2.3.2 Coherent Receiver

Different types of CO-OFDM receivers (OTR) are presented below.

- Homodyne

The homodyne receiver was essentially a baseband receiver; however, the complexity in stable locking of the carrier phase drift had prevented its practical applications.

In a homodyne receiver, the LO frequency and its phase are controlled so that they are always equal to the frequency and phase of the received signal carrier.

$$f_{LO} = f_{carrier} \quad (1.26)$$

- Heterodyne

In a heterodyne receiver, the received signal is, mixed with a local oscillator (LO) power. The obtained difference frequency signal, called intermediate frequency ($f_{IF}$) signal, is then amplified and detected.
This intermediate frequency should be higher than the signal bit rate. The maximum bit rate of the heterodyne receiver was always less than the half of that the square-law detector could achieve.

Note that:

$$f_{IF} = |f_s - f_{LO}|$$

(1.27)

The resulting signal has to be down converted to base band for being ready to be introduced in the receiver’s OFDM Block.

Figure 1.15 illustrates the difference between the spectra of the homodyne detection and heterodyne detection.

![Figure 1.15 Spectrum of a (a) heterodyne and (b) homodyne downconverter measured at the output of the balanced photodetector.](image)

- **Hybrid 90°**

The main purposes of coherent detection are linearly recover the I and Q components of the incoming signal, and to suppress or cancel the common mode noise.

![Figure 1.16 Hybrid reception scheme](image)

It mixes two input signals (an incoming signal and an optical local oscillator reference signal) and generates four optical signals with a 90-degree phase difference for I and Q components, and 180-degree phase shift for balanced
Detection. In figure 1.16 it is represented its operational scheme. With an ideal optical hybrid, the output signals $E_1$ to $E_4$ can be expressed as:

$$E_1 = \frac{1}{\sqrt{2}}[E_S + E_{LO}]$$

$$E_2 = \frac{1}{\sqrt{2}}[E_S - E_{LO}]$$

$$E_3 = \frac{1}{\sqrt{2}}[E_S - jE_{LO}]$$

$$E_4 = \frac{1}{\sqrt{2}}[E_S + jE_{LO}]$$

(1.28)

(1.29)

Where $E_S$ and $E_{LO}$ are respectively, the incoming signal and local oscillator (LO) signal. Then, we can analyze how the I component of the photo-detected current is generated, and the Q component can be derived accordingly. The I component is obtained by using a pair of the photo-detectors, PDP1 and PDP2 in figure 1.16, whose photocurrent $I_{1-2}$ can be described as:

$$I_1 = |E_1|^2 = \frac{1}{2} \left( |E_S|^2 + |E_{LO}|^2 + 2 \text{Re} \{E_S E_{LO}^*\} \right)$$

(1.30)

$$I_2 = |E_2|^2 = \frac{1}{2} \left( |E_S|^2 + |E_{LO}|^2 - 2 \text{Re} \{E_S E_{LO}^*\} \right)$$

(1.31)

Where:

$$|E_S|^2 = |E_r|^2 + |n_o|^2 + 2 \text{Re} \{E_S n_o^*\}$$

(1.32)

$$|E_{LO}|^2 = I_{LO} (1 + I_{RIN}(t))$$

(1.33)

Where $I_{LO}$ and $I_{RIN}(t)$ are the average power and relative intensity noise (RIN) of the LO laser. So the I component of the photocurrent becomes:

$$I_I(t) = I_1 - I_2 = 2 \text{Re} \{E_S E_{LO}^*\}$$

(1.34)

In a similar manner, the Q component from the other pair of balanced detectors can be derived as:

$$I_Q(t) = I_3 - I_4 = 2 \text{Im} \{E_S E_{LO}^*\}$$

(1.35)

1.2.4 Dispersion effects

Owing to the special nature of conventional optical IM-DD systems, based on optical-electrical signal nonlinear transformations, the effect of chromatic dispersion results in several kinds of signal degradations. In this section we discuss and analyze the main effects of chromatic dispersion over conventional IM-DD optical systems, and examine techniques to overcome the identified effects, with the aim of elucidating how these conventional systems can be adapted for transmission of a wideband optical OFDM signal.

A first effect is due to the optical double sideband spectrum. When image frequencies mix with the carrier upon photodetection, amplitude fading takes
place owing to the differential phase shifts caused by CD. A solution to this issue is single-band modulation, where one of the sidebands is removed by optical filtering.

On the other hand, as discussed in section 1.2.1.1, the dispersive channel will cause a relative time delay between the subcarriers which will shift a subcarrier from one OFDM symbol time frame to the adjacent symbols; it will thus pollute adjacent OFDM symbols, causing Inter-Symbol Interference (ISI). A solution to this problem is to add a guard band in which the OFDM symbols is cyclically extended (Cyclic Prefix (CP)) to each OFDM symbol.

Another signal degradation effect related to the impact of CD in IM-DD systems is the Intermodulation Dispersion (IMD), it stems from the amplitude modulation of signals containing two or more different frequencies in a system with nonlinearities. The intermodulation between each frequency component will form additional signals at frequencies that are not just at harmonic frequencies.

This is due to the fact that the detection process has a square-module relation with the incident optical field. This quadratic detection produces three important spectral components, one is the product of the optical carrier, which appears as a DC component in the electrical detected spectrum, the other is the product of the sideband multiplied by the optical carrier, which is the useful data signal and finally the product of the sideband multiplied by itself gives unwanted mixing products.

The solution to this problem is to offset the sideband in frequency with respect to the optical carrier, to leave a frequency guard band between them of width equal to that of the band, so that after detection, the unwanted mixing products do not overlap with the OFDM band and can be filtered out. See figure 1.17.

![Figure 1.17 Frequency guardband for IMD.](image)

Another consequence of chromatic dispersion is a phase shift among spectral components of a signal; equalizers are required to adjust the amplitude and phase of each subcarrier before thresholding. They can also compensate for amplitude errors in a channel with fading.
Figure 1.18 and 1.19 shows an example of the received constellations for an IM-DD based optical OFDM transmitted signal of 10 Gbps with 4-QAM with N=64 subcarriers over 1000 km of fiber. Optical modulation is based on a MZM biased at QP and an electrical IQ RF stage at a carrier frequency of 7.5GHz has allowed to locate the required 5 GHz frequency guardband so that IMD products can be filtered out after detection. An optical filtering stage after the MZM has removed the lower sideband to prevent amplitude fadings. By application of it can be found that the differential time shift among subcarriers is and therefore a CP guardtime of 0.125 has been used to eliminate ISI. As seen, in the constellations in figure 1.18 the rotation of the different decoded symbols in the constellation prior to equalization is indicative of the differential phase shift among subcarriers due to CD. After the equalization based on training sequences, the differential phase shifts have been removed and a correct QAM symbols constellation is obtained (figure 1.19).

This simulation proves that OFDM optical systems may allow for efficient CD impairments compensation and thus constitute a good option for an advanced generation of optical transmission systems.

1.3 Software

This section provides a quick overview of the main features of the software used to perform the simulations and how its parameters need to be understood and set in order to obtain successful simulations.

The VPIphotonics gathers a set of software applications designed for running optical simulations. The ones that are used in this thesis are:

VPItransmissionMaker™: It is required to design, implement and simulate the optical systems. It has a huge data base with electrical/optical devices with typical default values and also many demos with different types of optical systems.

VPIcomponentMaker™: It allows designing active and passive devices and abstracts their performance for simulations with VPItransmissionMaker™.
VPI is based on software has a graphical user interface, which allows intuitive design by using interconnectable blocks which simulate devices (such as optical fibers, modulators, lasers, spectrum analyzers, etc...). Each one of these blocks has a list of settings or parameters that can be adjusted for different behaviors like voltages, frequencies, rates, etc. A convenient characteristic is that the most common values are provided as default, so that the user does not need to bother about how to set them and test simulations can quickly set up.

For more structured as well as well-organized designs, VPI is provided with a hierarchical organization. It has up to three levels of elements or hierarchies: universes, galaxies and stars.

Stars: Unit modules with specific functionality.

Galaxies: A composition of several stars and galaxies interconnected. The galaxies, if they are not encrypted, have a “Look inside” option in its drop-down menu that allows for inspection and modification of its internal design.

Universe: First and top-most level, is the simulation scenario level. It is composed by stars and galaxies interconnected.

The most relevant features that make this program one of the best for optical systems simulations are:

- **Demos**: A large library of demos with detailed explanations is available providing the user with a good base of knowledge on the software. Work with the demos helps to understand how the software works and how to create an optical transmission system.

- **Cosimulation**: Allows the use of standard programming languages as Matlab code, Python or libraries c / c++ to create new functions and obtaining more numerical results besides the graphics. This is one of the most interesting attributes of VPI, letting the user to go beyond the blocks that the software has available. In our case this feature has been key for development of the coder/decoder OFDM block and the Predistortion block.

- **Definition of global variables**: used in all modules within a simulation scenario sharing common variables which are repeatedly used within the universe. Just setting and modifying the common variables in the global parameters is enough to have the variable, in all the blocks that use it, updated to the new value.

- **Default values**: Most parameters have standard values set by default giving us a big advantage because it allows us to modify only those parameters that are of our interest without having to bother about those that are not specifically relevant for our simulations.

- **Programming of simulation sequences**: Through the use of TCL language code, a conditional sequence of simulations using results of previous simulations to set the values of parameters in succeeding simulations may be setup. This functionality has been exploited in order obtain the sensitivity values for different values of the propagation fiber length in Chapter 5.
1.4 Passive Optical Network (PON) Paradigms

The focus of this Thesis work is application of optical OFDM technologies to a PON scenario. That is why after reviewing the basic features of both OFDM and optical transmission systems, a quick look into the basic structures and concepts related to PONs is here provided.

A passive optical network (PON) is a point-to-multipoint bidirectional topology based on an optical fiber network which substitutes conventional cable-based access networks. With the optical fiber used as the transmission media, PON can offer much higher bandwidth while supporting various communication services.

A PON consists of an optical line terminal (OLT) at the service provider’s central office and a number of optical network units (ONUs) near end users through the optical division network (ODN) (see figure 1.20). In the ODN the fiber is ‘passively’ split into many end user connections; this implies that the optical network devices (between the transmitter and receiver) are non-powered, so no electrical devices are used and therefore this reduces the cost of installation and maintenance significantly.

While the cost of the OLT and the fiber is shared by many users and more costly equipment can be afforded, the ONUs are deployed for every end user should be kept simple and low cost.

As said before, the PON structure can be divided into four parts: optical line terminal (OLT), feeder link, optical distribution network (ODN) and optical network unit (ONU). The remote Nodes are the network points where the signal is split, and depending on the network architecture, several splitting levels can be present [4].
Depending on the direction of transmission we talk about the downstream link, when the signal is transmitted from the OLT to the ONUs, whereas in the upstream link the transmission is from ONUs to OLT. It is generally easier to set the downstream link because it is just a broadcast transmission; the problems begin when many users want to transmit data at the same time to the OLT, which requires an efficient multiplexing technique.

There are three main types of PONs depending on the data multiplexing scheme, TDM, WDM and OFDM. The currently deployed PON technology is time division multiplexing (TDM) PON, where traffic from/to multiple ONUs are TDM multiplexed onto the upstream/downstream wavelength. TDM is the multiplexing scheme for all PONs which have been standardized until now, but for the increased capacities required in future PONs the use of TDM is subject to limitations and it also lack flexibility in protocols and networks resource management.

By contrast, wavelength division multiplexing (WDM) PON uses multiple wavelengths to provision large capacities to ONUs. An interesting feature is protocol transparency since each ONU uses an independent wavelength channel. In the downside are the lack of granularity for efficient dynamic bandwidth allocation and the complexity of the optics, OFDM PON employs a number of orthogonal subcarriers to transmit traffic from/to ONUs. It therefore shares the desirable protocol transparency feature of WDM, while offering at the same time fine granularity for efficient dynamic allocation of resources and allowing to shift complexity from the optics to the electronics where more mature technology is currently available.

OFDM PON has therefore received intensive research attention in recent years and is considered as a promising alternative for future PON deployments.
Chapter 2. Optical OFDM Systems

A generic optical OFDM system can be divided into five functional blocks: 1) the Radio Frequency (RF) OFDM transmitter to generate baseband OFDM signal, 2) the RF-to-optical (RTO) up-converter to up-convert the baseband signal to the optical domain, 3) the optical link, 4) the optical-to-RF (OTR) down-converter to down-convert the optical OFDM signal to baseband, and 5) the RF OFDM receiver to perform OFDM baseband processing and demodulation. In figure 2.1 we show an example of the OFDM optical system basic structure with an oIQ transmitter as RTO module and coherent receiver as the OTR. The baseband OFDM transmitter and receiver follow the scheme presented in section 1.1.1, in this section the blocks corresponding to the optical- to-RF and the RF-to-optical conversion are explained with more detail.

Figure 2.1 Scheme for a generic CO-OFDM system with a direct up-/down-conversion architecture

Dependent on how the O/E down-conversion is performed; optical OFDM can be classified into two broad categories: Coherent Optical OFDM and Direct Detection OFDM. In general CO-OFDM will have major role where the receiver sensitivity, PMD sensitivity and spectral efficiency are of critical importance, whereas DD-OFDM may has a broader range of applications due to its lower cost.

In the next section we present a summary of the basic features of the alternatives presently being considered for optical OFDM point-to-point systems implementations.
2.1 Point-to-point OFDM

2.1.1 Low cost / Low performance Systems

Due the enormous market volume it is essential that the cost level of communication systems is lowered to the bare minimum.

As a first approach to optical OFDM systems focused on simplicity and cost-efficiency, optical OFDM systems based on IM-DD optical transmission techniques require several modifications, which were briefly outlined in the previous chapter and are next analyzed in deeper detail.

2.1.1.1 IM-DD DMT (Discrete multitone modulation)

Discrete multitone modulation (DMT) is a popular low-cost scheme that has been exploited in XDSL copper access links. It consists on imposing the hermitian symmetry on the subcarriers so that the resultant OFDM signal is purely real.

IQ modulation and demodulation are not necessary. As a result, only a single digital and a single analog-to-digital (A/D) converter are needed to respectively generate and capture a DMT sequence but sensitivity values increase fast with distance and bit rate [5]. See figure 2.2.

![Figure 2.2 Basic scheme for IM-DD DMT system.](image)
2.1.1.2 RF-IMDD

Another configuration for adapting optical OFDM systems to IM-DD systems is possible taking into account the limitations of IM-DD systems due its square root detector. When performing the E/O conversion through the MZM, double side band appears causing frequency fading, so one of the two resulting sidebands must be suppressed in presence of dispersion.

So, an optical band-pass filter can be used for the separation of both bands, requiring also the allocation of a guard band (to filter out IMD) with respect to the carrier (used to detect the optical signal). If the size of this guard band is equal to the OFDM signal’s bandwidth, direct detection can be used at the receiver.

The optical spectrum of a DD-OFDM signal at the output of the Optical OFDM transmitter is a linear copy of the RF OFDM spectrum plus an optical carrier that is usually 50% of the overall power (figure 2.3).

This is the technique used in the RF up-conversion based on Intensity Modulation for optical OFDM (RF-IMDD) systems.

2.1.2 High cost / High performance Systems

On the other hand, if we want a more robust system we must integrate the more advanced optical systems to conventional OFDM systems, obtaining better performances at the expense of cost and complexity.

Figure 2.4, shows an example of such an advanced optical OFDM system, formed by an oIQ transmitter with a Hybrid 90° Coherent Receiver. The basic characteristics of these advanced optical transmission system have been reviewed in section 1.2.3.
Basically, this system generates a sequence of bits, which are encoded into OFDM symbol frames in the OFDM coder module (see section 2.3.1); then the signal obtained is divided into in-phase (I) and quadrature (Q) signals and introduced each one in a different MZM to modulate it into the optical domain.

Since the two MZM are biased at the null point, the modulated optical signal amplitude into each branch is proportional to the driving voltage applied to it.

In relation to operation of this device it is important to note that it requires careful adjustment of a total of 3 DC biases, one for maintaining each of the MZMs into their null point and another for the $90^\circ$ additional phase shift between branches.

Now the signal is ready to pass through the transmission channel (optical fiber) and to be detected and demodulated with the coherent receiver. Finally the received signal is introduced into the decoder block and the symbols are recovered.

Figures 2.5 and 2.6 serve to illustrate the effect of a finite ER in the nested MZM configuration in the RTO module. Due to the complex nature of the integrated circuit required for the nested MZMs a technological challenge featuring a trade-off between performance and cost, is to ensure high enough ER in each of the nested interferometers. Practical attainable values are around ER=30dB. Figure 2.6 shows the constellations obtained in an oIQ-COH optical OFDM system in back to back configuration respectively with a practical and an ideal ER value. As it can be seen, for ER values of practical relevance, the constellation features replicas of the symbols reducing the transmission quality. By contrast an almost perfect constellation is obtained in an ideal case.

Analyzing these results, the conclusion is that these conventional oIQ systems are not good enough for lower values of ER. The technological solution given to this problem is using predistortion systems, explained below in section 3.2.
2.1.2.1 Hybrids

Between the high (oIQ-COH) and low performance (IM-DD) systems for an optical OFDM system it is possible to find hybrids systems, combining simple transmitters with more complex receivers or the other way around. Two hybrid options are presented next.

2.1.2.1.1 RF + COH Receiver

In these systems, in the transmitter, an electrical IQ mixer is used to first up-convert the OFDM signal to an intermediate frequency before modulating the optical carrier with a single-ended optical. At the receiver side, an optical 90° hybrid is used for coherent optical detection (see section 1.2.3.2). Taking into account the cost of every transceiver, these type of systems are more suitable for uplink, and have been proposed for the uplink of the Accordance OFDM network paradigm [6].

2.1.2.1.2 oIQ + RF (DD Receiver)

Figure 2.7 shows the configuration of this optical system composed by an oIQ transmitter combined with a low cost/performance detector, the DD receiver.

![Figure 2.7 Conventional oIQ system with DD receiver](image)

Since the MZMs are biased at the null point which is the point that provides linearity in E-field characteristic the signal is transmitted without carrier and therefore an optical carrier must be provided for direct detection. In order to filter out IMD products the optical carrier is spectrally offset from the OFDM signal sideband by a spectral guardband of width equal to the OFDM bandwidth.

![Figure 2.8 and figure 2.9 Constellation for ER=30dB and ER=120dB for DD receivers respectively in back to back configuration.](image)
As it is seen in figure 2.8 a low system performance is found when a replica constellation appears in the case of having an ER=30dB. This does not occur for an ER=120dB (figure 2.9).

2.2 OFDM-PON Architectures

While the basic concept of the OFDMA-PON is to assign a different electrical frequency band to each user, there's no specific assumption about the carrier wavelength that should be used. Initial SCMA-PON proposals which could be considered as precursors of OFDMA-PON [7], assumed local lasers with the same wavelength at each ONU and direct detection at the OLT. It was rapidly recognized that such a proposal is of reduced practical relevance as the required wavelength precision and stability of lasers is unattainable with present technologies.

Here, two lines of research in OFDMA-PON topology are discussed. The first one is based on ONUs signal’s remodulation and it is the one being researched within the ACCORDANCE consortium [6]. The OLT broadcasts an optical carrier that is used by all ONUs to modulate its upstream information in its assigned electrical frequency band (figure 2.10). Since they originate from the same optical carrier, the relative spectral distances can be maintained accurately. For cost and complexity reasons, better than MZM, the preferred external modulator option is electro-absorption. These kind of modulators do not allow for carrier suppression and therefore every ONU will insert its optical carrier, which if used for detection will result in catastrophic OBI effects. The use of coherent modulation is thus advised.

The second option is known by statistical OFDMA-PON [8] and it is based on ensuring that a wide enough spectral gap is maintained between the optical signals coming from different ONUS so that by direct detection of the whole upstream signal, independent detection of every user is accomplished so that their respective information occupies a different electrical band after detection (figure 2.11). The stock problem of having every ONU emitting at a different wavelength is solved by equipping every ONU with identical laser sources which when installed lock to a wavelength which is random in a broad optical bandwidth. Due to the random nature of the emission wavelength, when the number of plugged in users in an OFDMA-PON is low, there’s a low probability
that the wavelength of the new incoming user overlaps with one of the existing wavelengths and therefore the new user can be successfully added to the PON. In the event of spectral collision of the new user in the PON, the OLT activates a thermal control of the emission wavelength of the involved ONUs so to thermally shift their wavelengths at a 0.1nm/degree rate.

Figure 2.11 Optical spectrums for distributed ONU with Direct Detection.

2.3 Simulation Scenario

In this section we present an overview of the characteristics of the simulation scenario used throughout the thesis work.

A first useful tool has been an optical OFDM system demo contained in the software, based on a 10 Gbps OFDM IM-DD long-haul system for 1000 km of fiber and 16 subcarriers. While allowing understanding the basic structure and concepts of this kind of simulation scenarios, the demo does not provide enough detailed information about the basic functions performed in the coding/decoding stages, nor does it allow for flexibility on the setting up of different modalities of OFDM systems.

We have when exploited the Cosimulation feature of VPI to design our own OFDM coding and decoding stages programmed in Matlab code.

In addition, we have added to our simulation scenario other useful characteristics such as a structured definition of the main simulation parameters to allow for an easy and user friendly management of variables. In the simulations carried out within this thesis work, there’s a great quantity of different parameters whose values need to be controlled and set up to the right quantity in order to carry out successful and correct simulations. The structure of global parameters designed greatly simplifies the task of controlling the values of the main parameters in a simulation.

The list of parameters that control a simulation has been reduced to a minimum by automatic establishment of necessary relationships, but also taking into account that the maximum flexibility for simulating a great variety of different optical systems by only acting upon the scenario parameters and not having to look into the Matlab code needs to be ensured.
Nevertheless, the user is always granted total control over the simulation through access to the Matlab coding, for manipulating every feature not available through changes in the parameter values, and also for adding new simulation parameters and functionalities.

As an example, BER calculations have been included, and a different strategy for CP extraction at the receiver that takes into account the reference frequency choice has been shown to give better results than the one used in the long-haul demo. [9] [10]

In the following section we go into deeper detail into the structure of the developed VPI simulation scenarios.

2.3.1 OFDM Coder / Decoder
This module (figure 2.12) is responsible of performing OFDM encoding in the simulation tool.

By clicking ‘look inside’ the blocks composition of the galaxy is viewed. Its operation was explained in more detail in section 1.1.1.

For the OFDM Coder, the same idea is used, just one block (figure 2.12) that contains the entire scheme for the decoding operation.
As shown in figure 2.13 the decoder is composed by different blocks as a Cosimulator block, a logical channel input, a constellation block and different outputs (signal in symbols, BER, EVM and the signal in bits).

### 2.3.2 General Parameters

The most important parameters are set in the general parameters list (figure 2.14). Some parameters that are common to several stars or galaxies are conveniently defined as general parameter, such as for example:
**TimeWindow**: Sets the duration of a block of samples. If the time window is large, the simulation will take longer. But at the same time it is important to take into account that reliable BER calculations require a statistically significant number of errors to be detected. For the typical $10^{-3}$ before FEC threshold BER, we have used $2^{16}$ bits.

**SampleRateDefault**: Is the rate at which the samples are sampled. According to the Nyquist theorem we need this value to exceed twice the maximum frequency in the signals which are relevant to our simulation. Care should be taken when selecting this number because allocation of guardbands or extended optical spectra due to intensity modulation of signals can cause the relevant optical spectrum to simulate to go beyond expectations.

**SampleModeCenterFrequency**: Sets a global carrier frequency of the simulation, in this case we are working in third window, so the frequency will be $193.1 \times 10^{12}$ Hz.

**BitRateDefault**: Specifies the velocity of the transmitted bits through the system. In the simulations it will be set to 10Gbps.

**CyclicPrefix**: Gives the possibility of adding a cyclic prefix in percentage value between 0 and 1. In the systems studied this value has been set to 0 since maximum fiber lengths of 100km and 5GHz bandwidth signals have been simulated. In section 1.2.1.1 the differential time shift for calculating the CP shows that no relevant signal degradation steaming from ISI is expected in these systems.

**N_FFT**: Is the number of carriers available to build an OFDM signal. This parameter must be a power of two value, since represents the number of inputs of the IFFT/FFT algorithm. This value has been fixed to 256.

### 2.3.3 Simulation limits

Some parameters have to be properly set to fulfill certain conditions so VPI can run the simulations. Otherwise, problems may occur and the simulations cannot be carried out. That is a direct consequence of the fact that VPI bases its numerical calculations in FFT based algorithms.

A condition that needs to be fulfilled is that the temporal and the spectral windows widths and their respective resolutions are interrelated. Specifically the total number of samples to be simulated must be a power of two.

$$SampleRateDefault \cdot TimeWindow = N_{samples} = 2^N$$  \hspace{1cm} (2.1)

By establishing relationships among the involved parameters, the simulations setup has been designed so that these necessary conditions are automatically met.
We have thus defined the number of bits as a general variable that must be set
to a power of two.

\[
N\text{bits} \approx \frac{100}{BER} \approx 2^M
\]  

(2.2)

Also an integer number of bits are to be accommodated into the Time Window
and therefore we have set the Time Window to:

\[
TimeWindow[s] = \frac{N\text{bits}}{BitRate}
\]  

(2.3)

Taking into account that to get a viable result, we consider that the BER (Bit
Error Rate) is 10e-3, in order to get a significant number of errors in our
simulations we have set \(N\text{bits}=2^{17}=131.072\).

In the VPI software according to the bit rates, for a total simulated bits of \(2^{17}\) the
time window will be:

\[
TimeWindow[s] = \frac{2^{17}}{10^{10^9}} = 131.072 \mu s
\]  

(2.4)

Also the sample rate needs to be chosen carefully taking into account the
Nyquist theorem determining the maximum simulation frequency limited by the
Nyquist rate. Therefore if the sampling frequency is higher, the resolution in the
time domain is better.

\[
SampleRateDefault[Hz] = 2^S \frac{BitRate}{BitsPerSymbol}
\]  

(2.5)

For the case of \(BitRate = 10\text{Gbps}\):

\[
SampleRateDefault[Hz] = 2^S \frac{10^{10^9}}{2} = 40\text{GHz}
\]  

(2.6)

Thus, we can ensure that the product \(TimeWindow\) by \(SampleRateDefault\) will
always be a factor of two.
2.3.4 Other Parameters

There are several components of the simulation schemes that also have important parameters to take into account.

As said a good feature of VPI is that it provides default values with the most common values of parameters. Unless otherwise specified the default values have been used in our simulations. Following are remarks about the parameter values used in some of the more relevant modules in the simulations.

2.3.4.1 Fiber Module

Into this module (figure 2.15), parameters are related to the most important characteristics of the fiber.

![Figure 2.15 Setting configuration window fiber module](image)

**Length:** The length of the fiber span, we have used lengths from 0km to 100 km.

**Attenuation:** The attenuation per unit length of the fiber span, this depends on the type of fiber we are using, normally is $0.2 \times 10^{-3} \text{dB/m}$.

**ReferenceFrequency:** Is the reference frequency for the fiber dispersion parameters. As we saw in section 1.2.1.2, it is related to a proper symbol synchronization at the receiver. For the different cases studied in this thesis, the reference frequency must be different in each case.

A study about the proper setting of the reference frequency for each optical OFDM system can be found in [3]. As a general rule, for the systems simulated in this Thesis, the reference frequency needs to be set at the center of the OFDM band being detected.
Dispersion: The dispersion coefficient of the fiber, working in third window is 17ps/nm-km.

The rest of fiber parameters have been left at their default values.

2.3.4.2 MZM Module
The most important parameters here are $V_{piDC}$ and $V_{piRF}$. In the discussion in 1.2.2.3 no difference is made about the two voltages and therefore we will set them to the same value $V_{pi}$, defined as a general parameter for convenience.

![Figure 2.16 Setting configuration window for general MZM module](image)

$V_{pi}$: Set to 3.1416 in order to simplify the calculations of predistorter circuits.

ExtinctionRatio: As explained, it is a critical parameter in the performance of the MZM. We have set it to 120 dB to simulate an ideal case and to 30 dB for a more realistic scenario.

LowerArmPhaseSense: It can be set to NEGATIVE for a push pull operation or POSITIVE, so that the phase change in the MZ’s lower arm is the same sign as that it the upper arm.
Chapter 3. Advanced OFDM systems for PONs

After the review study carried out in previous chapters, the main goal of this chapter is to analyze new proposals for optical OFDM systems for PONs. A first proposal is based on oIQ transmitters for the uplink. Given the cost and complexity of current implementations of these kind of transmitters this constitutes a research topic which could be considered in a long-term PON evolution scenario.

An issue solved here is that of dynamically changing the band where the information of each user is allocated by providing control over the frequency of an RF oscillator in each ONU. The bandshifted oIQ scheme is analyzed in section 3.1.

Next, and given the limitations of current oIQ transmitters, mainly related to finite ER values, as seen and analyzed in previous chapters; proposals based on the use of predistortion circuits prior to optical modulation are made. The advantage related to the new predistortion optical transmitters is two-fold. On the one hand, they simplify the modulator structure since instead of a nested MZM architecture a single MZM in dual-drive configurations is required. And on the other, through proper design of the predistorter circuit transfer function, a limited value of ER may be overcome.

All simulations here are proof-of-concept to verify that the new schemes work properly and comply with the expectations in the analysis. Therefore no fiber propagation has been considered, i.e. they are for the back-to-back case.

3.1 oIQ + BandShifting

3.1.1 Band Shifting oIQ

The aim of the bandshifted oIQ is to obtain a modulated optical signal such that:

\[
(I + jQ)e^{jw_{RF}t} = (I + jQ)(\cos(w_{RF}t) + j\sin(w_{RF}t))
\]

(3.1)

Developing it:

\[
I' = I\cdot\cos(w_{RF}t) - Q\cdot\sin(w_{RF}t)
\]

(3.2)

\[
Q' = jQ\cdot\cos(w_{RF}t) + jI\cdot\sin(w_{RF}t)
\]

(3.3)

Where \(w_{RF}\) is the angular frequency corresponding to the electrical band allocated to the specific ONU.

The equation 3.1 shows how it should be the phase and quadrature of the OFDM signal generated by adding a shift frequency to the desired frequency before the modulation block.

In the simulation tool, the shifting is carried out using multipliers, combining the In-phase and Quadrature signal with the cosine and the sine (formed by the
same cosine with a phase shift of 90 degrees) and then added or subtracted according to equations 3.2 and 3.3 obtained above. Below are shown in more detail the simulated systems with the obtained results.

The real part of the desired signal must go into the real branch of the nested MZM structure of the oIQ transmitter (upper branch in Fig 3.1), while the imaginary part must be fed to the imaginary branch. The scheme is thus as displayed in figure 3.1.

![Figure 3.1 Conventional oIQ system with Band Shifting and Direct Detection receiver.](image)

The optical spectrum obtained at the optical transmitter output is shown in figure 3.3, confirming the spectral shift of the OFDM band by the RF frequency value. In the OLT side, direct as well as coherent detection of the whole user band may be employed.

To verify the correct performance of the new bandshifted oIQ transmitter, system simulations using DD and COH receivers have been carried out.

The simulation scenario for the bandshifted oIQ with a DD receiver is shown in figure 3.1. An optical carrier with the same laser wavelength as the one in the ONU is provided to the OLT for DD.

In practice, remodulation schemes such as those proposed in the Accordance OFDM-PON network paradigm could be used to ensure the same wavelength at both ONU and OLT sides.

Phase noise issues have been left out of this proof-of-concept study and therefore correlation between the two wavelength sources is imposed by setting the RandomNumberSeed property of both laser modules to the same numerical value.

As seen, in figures 3.5 and 3.6 correct constellations for the back-to-back case are obtained and BER=0.
Chapter 3. Advanced OFDM systems for PONs

Figure 3.2 and 3.3 OFDM electrical input signal and OFDM signal shifted.

Figure 3.4 Optical signal after MZM

Finally the signal is demodulated and symbols are recovered, as figures 3.5 and 3.6 shows.

Figure 3.5 and figure 3.6 Constellation for ER=30dB and ER=120dB respectively in back-to-back configuration.

Figure 3.7 shows the advanced optical system (oIQ transmitter with a coherent receiver) with the frequency shift stage. As a fundamental difference with the DD receiver scheme, the optical carrier for the coherent detection is located at the center of the OFDM band.
The same process than before is carried out in the transmitter side. In the receiver, hybrid 90° coherent detection is used. Two photodiodes are needed for the In-phase signal and other two for the quadrature signal. Then the two splitted branches (IQ) are decoded in the OFDM decoder, the constellation received is shown in figures 3.8 and 3.9.

As in the case with the DD receiver, the constellation is recovered perfectly for both cases, ER=30dB and for ER=120dB.

### 3.2 Predistortion oIQ

This type of modulation’s technique aims to improve some of the restrictions of the conventional oIQ systems as well as to reduce the final cost of the transmitter’s implementation.

The idea is to obtain an equivalent oIQ modulator by making use of predistortion circuits over a simpler optical modulator device structure.
In a first section the basic structure of a predistortion-oIQ (p-oIQ) modulator is derived and tested through point-to-point transmission simulations using different receiver types: a DD with auxiliary carrier injection and a coherent receiver.

After the basic performance of the new p-oIQ transmitter has been verified with the two kinds of receivers, a proposal to include the bandshifting feature as required in the OFDM-PON uplink is analyzed and simulated.

### 3.2.1 Mathematical foundation

A mathematical development can be done in order to derive the proper input-output transfer characteristic for the predistorter circuit. [11]

From the equation of the electric field output of the MZM (seen in section 1.2.2.3):

\[
E_{OUT} = E_{IN}[e^{j\Delta \phi}e^{j\phi(t)} + \gamma e^{j\Phi}e^{j\phi(t)}]
\] (3.4)

\[
E_{OUT} = E_{IN}e^{j\Delta \phi}[e^{j\phi(t)} + \gamma e^{j(\phi(t)-
\Delta \phi)}e^{j\phi(t)}]
\] (3.5)

If \( \Delta \phi = \phi_2 - \phi_1 \)

\[
E_{OUT} = E_{IN}e^{j\Delta \phi}e^{j\frac{(\phi(t)+\phi(t))}{2}}[e^{j\frac{(\phi(t)-\phi(t))}{2}} + \gamma e^{j(\Delta \phi)}e^{j\frac{(\phi(t)-\phi(t))}{2}}]
\] (3.6)

The condition that we are looking for is that this output field contains the oIQ combination of the real and imaginary signals generated by the OFDM coding stage. We will carry out this analysis starting from the easier ideal case, when \( \gamma = 1 \), and then moving out to the more complicated case of a finite ER where \( \gamma \neq 1 \).

#### 3.2.1.1 Ideal case

Considering an ideal case, where \( \gamma = 1; \Delta \phi_b = 0 \) and \( C = E_{IN}e^{j\Delta \phi} \)

\[
E_{OUT} = C \cdot e^{j\frac{(\phi(t)+\phi(t))}{2}} \cdot \left[ e^{j\frac{(\phi(t)-\phi(t))}{2}} + e^{j\frac{(\phi(t)-\phi(t))}{2}} \right]
\] (3.7)
\[ E_{OUT} = C \cdot 2 \cdot \cos \left( \frac{\phi_1(t) - \phi_2(t)}{2} \right) \cdot e^{j \frac{\phi_1(t) + \phi_2(t)}{2}} = I + jQ \]  

(3.8)

Doing the module and the phase:

\[ |E_{OUT}| = 2 \cdot \cos \left( \frac{\phi_1(t) - \phi_2(t)}{2} \right) = \sqrt{I^2 + Q^2} \]  

(3.9)

\[ \varphi_{E_{OUT}} = \left( \frac{\phi_1(t) - \phi_2(t)}{2} \right) = \tan^{-1} \left( \frac{Q}{I} \right) \]  

(3.10)

So the MZM branches driving functions \( \phi_1(t) \) and \( \phi_2(t) \) are:

\[ \phi_1(t) = \cos^{-1} \left( \frac{\sqrt{I^2 + Q^2}}{2} \right) + \tan^{-1} \left( \frac{Q}{I} \right) \]  

(3.11)

\[ \phi_2(t) = \tan^{-1} \left( \frac{Q}{I} \right) - \cos^{-1} \left( \frac{\sqrt{I^2 + Q^2}}{2} \right) \]  

(3.12)

And the functions needed for the predistortion module will be:

\[
\begin{align*}
f(I, Q) &= \frac{\Delta \phi(t)}{2} = \cos^{-1} \left( \frac{\sqrt{I^2 + Q^2}}{2} \right) \\
g(I, Q) &= \frac{\sum \phi(t)}{2} = \tan^{-1} \left( \frac{Q}{I} \right)
\end{align*}
\]  

(3.13)

In this case a very high ER is required for a proper performance of the predistorter, i.e. values around ER=120. This is not a commercial value for a MZM that’s why to prove that for lower values of ER the predistorter system works, we must recalculate the equations.

### 3.2.1.2 Finite ER case

Considering a practical case, where \( \gamma \neq 1; \Delta \phi_b = 0 \) and from the equation (3.4):

\[
E_{OUT} = \cos(\phi_1(t)) + j \sin(\phi_1(t)) + \gamma \left[ \cos(\phi_2(t)) + j \sin(\phi_2(t)) \right]
\]  

(3.14)
Doing the module:

\[ |E_{OUT}| = \sqrt{\left(\cos(\phi(t)) + \gamma \cos(\phi_2(t))\right)^2 + \left(\sin(\phi(t)) + \gamma \sin(\phi_2(t))\right)^2} \]  \hspace{1cm} (3.15)

\[ |E_{OUT}| = \sqrt{1 + \gamma^2 + 2\gamma \cos(\phi(t) - \phi_2(t))} = \sqrt{I^2 + Q^2} \]  \hspace{1cm} (3.16)

For the phase, from the equation (3.6):

\[ E_{OUT} = Ce^{\frac{\phi_1(t) + \phi_2(t)}{2}} \left[ \cos\left(\frac{\phi(t) - \phi_2(t)}{2}\right)(1 + \gamma) + j\sin\left(\frac{\phi(t) - \phi_2(t)}{2}\right)(1 - \gamma) \right] \]  \hspace{1cm} (3.17)

\[ \varphi_{E_{OUT}} = \frac{\phi_1(t) + \phi_2(t)}{2} + \tan^{-1}\left[\frac{1 - \gamma}{1 + \gamma} \tan\left(\frac{\phi(t) - \phi_2(t)}{2}\right)\right] = \tan^{-1}\left(\frac{Q}{I}\right) \]  \hspace{1cm} (3.18)

Again, the two MZM branches driving functions \( \phi_1(t) \) and \( \phi_2(t) \) are:

\[ \phi_1(t) = \frac{1}{2} \left[ 2\tan^{-1}\left(\frac{Q}{I}\right) - \tan^{-1}\left(\frac{1 - \gamma}{1 + \gamma} \tan\left(\frac{1}{2}\cos^{-1}\left(\frac{I^2 + Q^2 - 1 - \gamma^2}{2\gamma}\right)\right)\right) + \cos^{-1}\left(\frac{I^2 + Q^2 - 1 - \gamma^2}{2\gamma}\right) \right] \]  \hspace{1cm} (3.19)

\[ \phi_2(t) = \frac{1}{2} \left[ 2\tan^{-1}\left(\frac{Q}{I}\right) - \tan^{-1}\left(\frac{1 - \gamma}{1 + \gamma} \tan\left(\frac{1}{2}\cos^{-1}\left(\frac{I^2 + Q^2 - 1 - \gamma^2}{2\gamma}\right)\right)\right) - \cos^{-1}\left(\frac{I^2 + Q^2 - 1 - \gamma^2}{2\gamma}\right) \right] \]  \hspace{1cm} (3.20)

And finally the functions needed for the predistortion module will be:

\[
\begin{align*}
    f(I, Q) &= \frac{\Delta \phi(t)}{2} = \text{real} \left[ \cos^{-1}\left(\frac{I^2 + Q^2 - 1 - \gamma^2}{2\gamma}\right) \right] \\
    g(I, Q) &= \frac{\sum \phi(t)}{2} = 2\tan^{-1}\left(\frac{Q}{I}\right) - \tan^{-1}\left(\frac{1 - \gamma}{1 + \gamma} \tan\left(\frac{1}{2}\text{real} \left[ \cos^{-1}\left(\frac{I^2 + Q^2 - 1 - \gamma^2}{2\gamma}\right) \right]\right)\right)
\end{align*}
\]  \hspace{1cm} (3.21)

To take the real part in the \( \text{acos} \) function is necessary so that when the OFDM signal takes very low amplitude values, the minimum value possible at the output of the finite ER modulator is obtained. Of course this means some distortion in the optical modulated signal, but as seen in the results, this distortion is kept to reasonable levels for practical ER values.
3.2.2 Simulations

Simulations confirming a proper performance of the new p-oIQ with both types of receiver, DD and COH, are presented next.

Next are some details of the basic structure of the p-oIQ in the simulator.

In the simulation tool, a Python block called $f(x)$ where two driving functions named $f(I,Q)$ and $g(I,Q)$ have as their inputs the Inphase and Quadrature signal components. These functions are obtained by means of the mathematical development of the MZM (section 1.2.2.3). In figure 3.10 the galaxy that composes this block is shown.

![Figure 3.10: Internal Block of the Real Predistortion Module](image)

The two OFDM signals (inphase and quadrature) go through the predistorter where two new functions are obtained, then combined and introduced to the modulator. In the figure 3.11 the schematic composition for an overall transmitter system can be seen.

![Figure 3.11: Scheme of the predistortion block.](image)

The value for gamma is given by the ER of the MZM. Taking into account the relationship as given by the VPI manual, the correct gamma value to compensate for a finite ER should be calculated as:
\[ \gamma = \sqrt{ER/2 - 1} \]

\[ \gamma = \sqrt{ER/2 + 1} \]

3.2.2.1 \( p\text{-oIQ} / \text{Direct detection} \)

This system is composed by a transmitter that includes the Matlab block where the predistortion is configured and just one MZM, to modulate the electrical signal into the optical domain. In this first system the receiver will be a DD.

According to figure 3.12 the Input bit sequence is introduced into the OFDM Coder Block in order to map, modulate and encode the input signal into an OFDM sequence with associated real and imaginary signal.

The real (I) and imaginary (Q) OFDM signal outputs are fed to the predistortion block so that the f and g signals following the expressions 3.2.3 and 3.2.4 are obtained at the output. As seen, these outputs are combined to be inserted into each of the branches of the dual-drive-MZM as follows:

\[ \phi_1(t) = f(I,Q) + g(I,Q) \]

\[ \phi_2(t) = f(I,Q) - g(I,Q) \]

Care should be taken so that the branchesigns feature of the MZM is set to POSITIVE.

The optical base band signal at the output is ready to be introduced into the channel or SM optical fiber.

Once the optical signal arrives at the receiver side is introduced into a photodiode together with an auxiliary carrier or local oscillator at a wavelength with a frequency offset with respect to the OFDM single so that after DD, IMD
products can be filtered out (figure 3.13). In order to introduce this signal into the OFDM Decoder Block, it has to be down-converted to base band with an RF stage.

![Optical Spectrum](image)

Figure 3.13 Spectrum before detection including the carrier.

Then the signal is prepared to enter inside the OFDM Decoder Block in order to recover the original sent signal. When analyzing the constellation diagrams obtained in back-to-back (figures 3.14 and 3.15), we may conclude that the system is working properly.

![Constellation Diagrams](image)

Figure 3.14 and 3.15: Constellation for ER=30 and ER=120

3.2.2.2 p-oIQ / Coherent detection

According to the figure 3.16, this system is composed by the same p-oIQ transmitter, changing this time the receiver block for a coherent detector.
Figure 3.16 Complete system of the predistortion transmitter with coherent detection.

Figure 3.17 and figure 3.18: OFDM electrical signal and OFDM optical signal before MZM.

Once the optical signal arrives at the receiver side (figure 3.18) is introduced inside the hybrid 90° coherent receiver.

Then the signal (figure 3.19) is prepared to enter inside the OFDM Decoder Block in order to recover the original sent signal.

Figure 3.19 Signal before being decoded.
Finally the constellation received is shown in figure 3.20 and 3.21 for the ideal and the real case.

![Figure 3.20 and figure 3.21 Constellation for ER=30 dB and ER=120dB respectively.](image)

### 3.3 Predistortion oIQ + BandShifting

After verifying the proper performance of point-to-point systems based on p-oIQ transmitters, as a natural next step, we analyze in this section an oIQ transmitter with band shifting as a proposal for the uplink of future generation OFDM-PONs.

#### 3.3.1 Band Shifting p-oIQ / Direct detection

The next figure (figure 3.22) shows the configuration for the band shifting with direct detection circuit.

![Figure 3.22 Simulated circuit in VPI for band shifting with predistortion transmitter with DD receiver](image)

As seen, a band-shifting stage based on RF oscillators has been added, in a similar way as in the conventional bandshifting oIQ.
In this case, the receiver is a direct detection system meaning that an optical carrier is needed to detect the signal, figure 3.23 shows the signal with the carrier inserted. Then sends this signal to the electrical domain (figure 3.24). It is worth noting here the great amount of IMD generated shown at the lower frequency band.

Finally the decoding is performed, but before converting the signal into symbols again, it must be down-converted using the same shifting frequency in the transmitter. In the figure 3.25, all the stars that compose the receiver are shown.

The symbols received are shown in the figures 3.26 and 3.27 which are the constellation with an Extinction Ratio equal to 30 dB representing a real case and 120 dB for and ideal case.
3.3.2 Band Shifting p-oIQ / Hybrid 90° Coherent Detection

The next figure (figure 3.28) shows the configuration for the band shifting with coherent detection circuit. As seen the p-oIQ transmitter with bandshifting property is employed in combination with a coherent receiver.

In the figures 3.29 and 3.30 it can be seen the transmitted OFDM signal and the signal shifted, placed at 15GHz.
Figure 3.29 and figure 3.30: Coded OFDM input signal and the signal placed at 15GHz.

The optical signal obtained after the MZM goes through the channel or the SM optical fiber. In the receiver side there is the OTR block formed by a hybrid 90° coherent receiver. It should be noted that the OFDM signal was moved up to 15 GHz in the transmitter so to detect it correctly in the receiver, a local oscillator at an optical frequency of 193.1THz+15GHz (figure 3.31) is required.

![Figure 3.31 Parameters of the detector photodiode](image)

In the figure 3.32 it can be seen the signal after the MZM, placed at 15 GHz. Also the figure 3.33 shows the recovered signal, exactly equal than the original one, ready for being decoded.

Finally demodulating and demultiplexing the signal is performed in the OFDM decoder.

![Figure 3.32 and 3.33: Optical signal after the MZM and the signal before being decoded.](image)

As a result of the overall simulation, the signal is detected and recovered correctly, therefore we can see below the symbols corresponding to the 4QAM modulation. The figures 3.34 and 3.35 shows the constellations obtained for a practical and an ideal case, where the ER is equal to 30dB and 120dB, respectively.
Figure 3.34 and figure 3.35: Constellation using an extinction ratio (ER) of 30dB and 120dB respectively.
Chapter 4. Results

In the previous chapter, new proposals for optical OFDM systems, with special emphasis on new optical transmitter designs were investigated and the proper performance of several end-to-end transmission systems verified in back-to-back configuration through numerical simulation scenarios developed in VPI. In this chapter we focus on the behavior for a certain length of propagation though fiber of several of these end-to-end systems.

To this aim, the performance in terms of required power levels at the receiver input for a threshold before FEC BER of $10^{-3}$, for different fiber propagation length have been obtained.

By means of an automatic program based on TCL language we have programmed a sequence of simulations that automatically find the required attenuation value at the receiver input for a decoded BER of $10^{-3}$. The script code can be found in annexes A.

Implementing the band shift in the conventional oIQ transmitters with both receivers (DD and COH) for an ideal case, the results obtained are displayed in figures 4.1 and 4.2.

![Sens vs length (Conventional oIQ with Band Shift, ER=120dB)](image1)

Figure 4.1: Sens. vs. length graph for conventional oIQ with bandshift in an ideal case.

![BER vs length (Conventional oIQ, with Band Shift ER=120dB)](image2)

Figure 4.2: BER vs. length graph for conventional oIQ with bandshift in an ideal case.
As seen in figures 4.1 and 4.2, for an oIQ + coherent receiver with frequency shifting the sensibility and the BER values are almost constant giving to the system stability and a good performance, and reaching lengths of up to 130km with a sensitivity of -50dBm. For a typical launching power of 3 dBm, that means a total power budget of 53 dB. Fiber loss for 130 Km in the third window amount to 130km*0,2dB/km=26dB and therefore there are 27 dB left for splitting loss. The number of users in the PON is doubled for every 3 dB of power splitting budget, so a maximum $2^9=512$ users can be served on the PON.

On the other hand, due to the simplicity of the DD receiver, we can only reach up to 10km accomplishing $\text{BER}=10^{-3}$. The sensitivity for this case is about -47.50dBm the power splitting budget in this case would be 50,50dB (taking into account 2dB of fiber loss) and therefore a maximum of $2^{16}=65.536$ users could be served.

As we saw before in this work, coherent receivers are more robust and have better performance than the DD receiver. This could be a good option for the uplink of a future OFDM-PON provided that prices and complexity of conventional oIQ transmitters are reduced.

The next system to be simulated uses a more common value of ER for the MZM. Results in Figures 4.3 and 4.4 show similar values of sensitivity but more limited reach up to maximum of 15km.

![Figure 4.3: Sens. vs. length graph for conventional oIQ with bandshift in a practical case.](image)

![Figure 4.4: BER vs. length graph for conventional oIQ with bandshift in a practical case.](image)
For the predistortion systems with band shifting using a coherent receiver, the results obtained are seen in figures 4.5 and 4.6:

![Sens vs Length (p-oIQ+BS, COH receiver)](image)

**Figure 4.5:** Sens. vs. length graph for p-oIQ + coherent detector with bandshift for a practical and an ideal case.

![BER vs Length (p-oIQ+BS, COH receiver)](image)

**Figure 4.6:** BER vs. length graph for p-oIQ + coherent detector with bandshift for a practical and an ideal case.

A salient feature of Figure 4.5, is that similar results are obtained for both the practical and the ideal ER cases, showing the ability of the predistorting transmitter to compensate the ER limitation. As seen, the sensitivity increases from -53dBm for the back-to-back case up to -33dBm for a maximum distance of about 15km.

The behavior of the BER is quite better when ER=120dB in the first ten kilometers, then similar values are obtained until it exceeds the $10^{-3}$ BER.

Next the results obtained for the p-oIQ with bandshifting using a DD receiver are given in figures 4.7 and 4.8:
Figure 4.7: BER vs. length graph for p-oIQ + DD with bandshift for a practical and an ideal case.

Figure 4.8: BER vs. length graph for p-oIQ + DD with bandshift for a practical and an ideal case.

Again, the behavior in terms of sensitivity is very similar for both the practical and the ideal ER cases. The maximum reachable distance is around 10km with -45dBm sensitivity.

The power splitting budget in this case would be 46dB (taking into account 2dB of fiber loss for a third window transmission) and therefore a maximum of $2^{15} = 32,768$ users could be served.
Chapter 5. Conclusions

A review of optical OFDM systems and techniques has been carried out with focus on applications to passive optical networks (PONs).

Simulation scenarios based on VPI have been developed for analysis of the basic characteristics of the optical OFDM system properties.

The studied optical OFDM systems have considered receivers with both direct detection as well as optical coherent detectors that employ 90° optical hybrids.

As for the optical transmitters optical IQ modulators based on nested MZM configurations have been analyzed and compared with a new proposal for a simplified optical IQ transmitter based on a single MZM and predistortion circuits.

The mathematical functions that govern the input-output transfer characteristic of the predistortion circuits have been derived, also taking into account the finite value of the Extinction Ratio parameter of the modulator and compensating its detrimental effect on the received signal quality.

The basic OFDM-PON schemes have been reviewed and a proposal for an upstream link has been investigated, based on optical IQ modulators on the ONU s and coherent detection at the OLT side. A technique for the RF shift of the optical band has been proposed and shown to allow for control of the position of the optical spectral band where the ONU information is allocated, so that no collision occur between the bands assigned to each ONU and so that the OLT can correctly demodulate the whole OFDM stream formed by addition of the signals from all the ONUs.

A TCL code has been implemented for automatic obtention of sensitivity vs. fiber length curves with VPI. These curves allow determination of the power budget and thus the maximum reach and number of users that can be served in the PON by each optical OFDM scheme. A maximum reach of 130km and 512 users has been obtained with a system based on conventional oIQ with band shifting. We can thus conclude that OFDMA-PONS are an alternative worth further research for a future generation of PONs.
## Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>4QAM</td>
<td>4 Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>ACCORDANCE</td>
<td>A Novel OFDMA-PON Paradigm for Ultra-High Capacity Converged Wireline-Wireless Access Networks</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue to Digital Converter</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>BER</td>
<td>Bit Error Rate</td>
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<tr>
<td>CD</td>
<td>Chromatic Dispersion</td>
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<tr>
<td>COH</td>
<td>Coherent</td>
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<tr>
<td>COH-OFDM</td>
<td>Coherent OFDM</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic prefix</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital to Analogue Converter</td>
</tr>
<tr>
<td>DD</td>
<td>Direct Detection</td>
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<tr>
<td>DD-OFDM</td>
<td>Direct Detection OFDM</td>
</tr>
<tr>
<td>DL</td>
<td>Down-link</td>
</tr>
<tr>
<td>DML</td>
<td>Direct Modulated Laser</td>
</tr>
<tr>
<td>E/O</td>
<td>Electro-optical</td>
</tr>
<tr>
<td>ER</td>
<td>Extinction Ratio</td>
</tr>
<tr>
<td>EVM</td>
<td>Error Vector Magnitude</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter-Carrier interference</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transform</td>
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<tr>
<td>IM</td>
<td>Intensity Modulation</td>
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<td>IMD</td>
<td>Intermodulation Distortion</td>
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<td>IM-DD</td>
<td>Intensity Modulation - Direct Detection</td>
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<tr>
<td>ISI</td>
<td>Inter-symbol Interference</td>
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<tr>
<td>IQ</td>
<td>In-phase and Quadrature</td>
</tr>
<tr>
<td>LED</td>
<td>Light-emitting Diode</td>
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<tr>
<td>LO</td>
<td>Local Oscillator</td>
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<tr>
<td>LPF</td>
<td>Low Pass Filter</td>
</tr>
<tr>
<td>MZM</td>
<td>Mach-Zehnder Modulator</td>
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<tr>
<td>NP</td>
<td>Null Point</td>
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<tr>
<td>OBI</td>
<td>Optical Beat Interference</td>
</tr>
<tr>
<td>ODN</td>
<td>Optical Division Network</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplex</td>
</tr>
<tr>
<td>OFDM-PON</td>
<td>Orthogonal Frequency Division Multiplex - Passive Optical Network</td>
</tr>
<tr>
<td>OFDMA-PON</td>
<td>Orthogonal Frequency Division Multiple Access - Passive Optical Network</td>
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<tr>
<td>olIQ</td>
<td>Optical In-phase and Quadrature</td>
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<tr>
<td>OLT</td>
<td>Optical Line Terminal</td>
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<tr>
<td>ONU</td>
<td>Optical Network Units</td>
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<td>OOFDM</td>
<td>Optical Orthogonal Frequency Division Multiplex</td>
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<tr>
<td>OSNR</td>
<td>Optical Signal to Noise Ratio</td>
</tr>
<tr>
<td>OTR</td>
<td>Optical-to-RF</td>
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<tr>
<td>PMD</td>
<td>Polarization Mode Dispersion</td>
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<td>PON</td>
<td>Passive Optical Network</td>
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<td>p-oIQ</td>
<td>Predistortion Optical In-phase and Quadrature</td>
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<tr>
<td>QP</td>
<td>Quadrature Point</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------</td>
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<tr>
<td>RB</td>
<td>Rayleigh Backscattering</td>
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<td>RTO</td>
<td>RF-to-Optical</td>
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<tr>
<td>RX</td>
<td>Receiver</td>
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<td>SCMA-PON</td>
<td>Subcarrier Multiple Access - Passive Optical Network</td>
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<td>SE</td>
<td>Slope Efficiency</td>
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<td>SMF</td>
<td>Single Mode Fiber</td>
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<td>Signal to Noise Ratio</td>
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<td>Time Division Multiplexing</td>
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<td>TDM-PON</td>
<td>Time Division Multiplexing - Passive Optical Network</td>
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<td>TX</td>
<td>Transmitter</td>
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<td>UL</td>
<td>Up-link</td>
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<td>VPI</td>
<td>Virtual Photonics Inc.</td>
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<td>WDM</td>
<td>Wavelength Division Multiplexing</td>
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<td>WDM-PON</td>
<td>Wavelength Division Multiplexing - Passive Optical Network</td>
</tr>
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</table>
Bibliography


Annexes

A. Tcl/tk Script

# tcl-script for Optimization

# get platform
set OS $tcl_platform(os)

# save file name
set saveFile1 p:/Mireia/Prueba.dat

# initialization
set prec 6e-4
set lim 1e-3

# clean the save file
set fileID1 [open $saveFile1 w]
close $fileID1

# search for the laser power until a BER <= 1.0e-3
for {set L 0} {$L<=15000} {incr L 5000} {
    setstate UniversalFiberFwd_vtmg1 Length $L
    set a 0
    set b 0
    set startAtt 20
    set deltaAtt 5.
    set cont 0

    # set the laser power
    initialize Attenuator Attenuation
    setstate Attenuator Attenuation $startAtt

    # execute the simulation
    run 1
    wrapup
    # get the BER value

    set BER [statevalue BERcalculator InputValue]
    set EVM [statevalue EVMcalculator InputValue]
set PRX [statevalue PRXcalculator InputValue]

while {($BER>$lim + $prec/2 || $BER<$lim - $prec/2} {
  if { $BER>$lim + $prec/2 } {
    set startAtt [expr $startAtt - $deltaAtt];
    set b -1;

    initialize Attenuator Attenuation
    setstate Attenuator Attenuation $startAtt

    run 1
    wrapup

    set BER [statevalue BERcalculator InputValue]
    set EVM [statevalue EVMcalculator InputValue]
    set PRX [statevalue PRXcalculator InputValue]
  } elseif {$BER<$lim - $prec/2} {
    set a 1;
  } elseif {$BER<$lim - $prec/2} {
    set startAtt [expr $startAtt + $deltaAtt];
    set a 1;

    initialize Attenuator Attenuation
    setstate Attenuator Attenuation $startAtt

    set prova $BER

    run 1
    wrapup

    set BER [statevalue BERcalculator InputValue]
    set EVM [statevalue EVMcalculator InputValue]
    set PRX [statevalue PRXcalculator InputValue]
  }
}
if {$a*$b<0} {
    set deltaAtt [expr $deltaAtt / 2];
    set a 0;
    set b 0;
}

set fileID1 [open $saveFile1 a]
puts $fileID1 "$L $startAtt $PRX $BER $EVM"
#puts $fileID1 "$startAtt $PRX $BER $EVM"
close $fileID1