TITLE: Optimization of optical OFDM systems

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Overview

Orthogonal frequency division multiplexing (OFDM) is a well-known modulation technique which is used in broadband wired and wireless communication systems, such as standard 802.11a/b/g/n, digital video broadcasting television (DVB-TV), and Long Term Evolution in the next mobile generation, due to its capacity in solving the problem of the Inter-symbol Interference caused by the effects of a dispersive channel. Since a few years ago, this technique has been used in optical communications which is the aim of this thesis.

In this Master Thesis, the most relevant aspects of optical OFDM communication are described and implemented in optical simulation software called VPItransmissionMaker™ and VPIphotonicsAnalyzer™, (VPI). We find out that the OFDM coder and decoder provided by this program cannot be upgraded. This handicap does not allow modifying the main work algorithm and therefore the system cannot be improved. To solve this problem, it has been designed a Matlab OFDM coder and decoder to study the behaviour of optical OFDM systems using Intensity Modulation (IM) and Direct Detection (DD).

As it will be detailed along the thesis, two different optical OFDM simulation scenarios using IM/DD are developed: an IM/DD RF and Hermitian Symmetry demos. Both of them are optical OFDM systems with an intensity modulation transmission and direct detection. The focus has been set primarily in obtaining a flexible, efficient and user-friendly simulation platform allowing for straightforward setup of advanced simulation of optical OFDM systems.

The performance of these two scenarios is studied, taking advantage from the Simulation Script which VPI software provided in a more manageable mode, specifically, scripts using Tcl/tk language have been developed to derive power budget plots at desired Bit Error Ratio (BER).
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INTRODUCTION

This master thesis is focused on Orthogonal Division Frequency Multiplexing (OFDM) modulation applied in optical systems.

OFDM is a well-known technique in communication systems, since it is used in different applications, for example in wire copper with Digital Subscriber Lines (DSL), Digital Video Broadcasting Television (DVB-TV), in RF systems such as Wireless-LAN, and in the new next generation of mobile system, Long-Term Evolution (LTE).

The wide adoption of OFDM in wireless communications can be explained by its ability to compensate for the radio environment impairments, due to the multipath propagation which produces frequency selective fading, the shadow fading, and interferences from other users. For instance, in ADSL, bit loading algorithms are used to assign more bits to the carriers with better channel behaviour.

In view of the increasing popularity of internet-based services, fiber-optic access is presently regarded as the only technology with potential to cope with the expected bit rate demand of home connections. As a result, Passive Optical Networks have attracted widespread interest and are being deployed worldwide at a breathtaking pace.

For these reasons, the next generation optical networks are expected to require more advanced modulation formats, such as for example OFDM modulation. Furthermore, nowadays the digital processing technology has matured to the point where OFDM signal processing could be performed in a CMOS integrated circuit to digitalize the information at the high bit rates typical of fiber optic communication systems.

OFDM has been already established in long haul high bit data rate fiber applications as a technique to compensate the chromatic dispersion of standard single mode fiber (SSMF) [1]. Now the new challenge is to explore the potential of OFDMA-PON for the next generation of optical networks and determine if it can offer advantages over standard TDMA-PON systems, such as Gigabit Ethernet-PON.

UPC belongs to the European research project called Accordance (A Novel OFDMA-PON Paradigm for Ultra-High Capacity Converged Wireline-Wireless Access Networks). The main objective of this project, which started in 2010 and will finish in 2013, is to take advantage to the optical fiber networks based on OFDMA, the technology of choice for the Next Generation Optical Access. The European project UPC’s main role is the study of the physical layer and simulation of practical scenarios with OFDMA using the software VPItransmissionMaker™ Optical Systems. This Master Thesis will contribute to the project final outcome results.
VPItransmissionMaker™ (VPI) is the software which permits to simulate different optical systems, including an OFDM Long-Haul system. Within this master thesis the behaviour of an OFDM Long-haul scenario offered as a demo inside VPI it will be studied to understand the main features of the system. Unfortunately, the OFDM coder and decoder modules provided by the software, do not give the flexibility required for the intended simulations. Therefore, in this master thesis, we will take advantage of the Co-simulation interface offered by VPI in order to program using Matlab both an OFDM coder and decoder modules with the same characteristics as the ones offered by VPI but improving it with enhanced features and allowing for customization. The designed modules will be integrated into VPI with other modules in order to perform full optical system simulations of optical OFDMA networks.

In order to unveil the potential of OFDM for the optical access provision, assessment of the maximum user count that can be provided is required. Optimization programs that make use of advanced programming in Tcl/Tk language will be developed for automatically determining the maximum number of users that can be supported by each optical OFDM scenario under simulation.

The main goals which this Master Thesis wants to reach are:

- A general study of OFDM system, explaining its advantages and drawbacks.
- Design two more flexible OFDM coder and decoder modules in VPI using Matlab.
- Simulate two different optical OFDM scenarios with a more user-friendly interface in VPI.
- Develop optimization Tcl/Tk scripts for automatic VPI simulation.

The first chapter talks about the theory of an OFDM system, and the evolution from a FDM modulation to the digital OFDM modulation applying the DFT/IDFT to improve the system. In the subsections the main features of an OFDM system such as cyclic prefix, channel estimation and pilot tones are explained, and an overview of the general structure of an OFDM transmitter and an OFDM receiver is given.

The second chapter is about basic concepts of optical communications, focusing on conventional Intensity Modulation and Direct Detection (IM/DD) links. Also, the behaviour of the chromatic dispersion (CD) and its effects such as amplitude fading, nonlinear distortion and phase noise decorrelation, are described.

To avoid one of the CD effects in IM/DD systems, such as non-linearity distortion is necessary to add a guard band between the optical laser carrier
and the OFDM sideband. In chapter 3, two different guard band generation methods are explained. On the one hand, the first technique consists on applying a RF up/down conversion stage using a local oscillator to place the OFDM signal at certain frequency. On the other hand, the second technique called Hermitian Symmetry uses the addition of zero padding in digital domain to emulate the free band.

The fourth chapter analyses the OFDM for Long-Haul simulation provided by VPI software obtaining some constrains such as BER calculation, limited bits per symbol in QAM modulation, inefficiency management of parameters and the equalization stage. Therefore, a new simulation scenario, called IM/DD RF demo, has been developed with a new OFDM coder and decoder, programmed using Matlab language, which permit enhancements in equalization, DAC/ADC stage.

Furthermore, a new OFDM scenario applying Hermitian Symmetry is developed and tested to determine the differences between this technique and the previous one.

Finally in the fifth chapter some Simulation Scripts in Tcl/Tk language are offered in order to optimize the VPI demo parameters. This option gives the opportunity to the user to obtain results without supervision and reducing work time.
CHAPTER 1. GENERAL MULTICARRIER MODULATION CONCEPTS

1.1. Multicarrier Carrier systems

Frequency Division Multiplexing (FDM) is a class of multi-carrier modulations (MCM), which is based on dividing the transmitted signal spectrum into a set of narrow spectrum signals which are sent in parallel. This type of modulation is thus robust against selective frequency fading. The Figure 1.1 shows the process of how a bit sequence is sent with a FDM system, in which the first bits are converted to complex symbols and then assigned to different subcarriers.

An FDM transmission signal is represented, in time domain, as the sum of each information symbol at a certain carrier frequency:

\[
\begin{align*}
\infty \\
N
\end{align*}
\]

\[
s(t) = \sum_{k=1}^{N} c_{ki} \cdot g_k(t - iT_F)
\]

(1.1)

\[
g_k(t) = p(t) \cdot e^{j2\pi f_k t}
\]

(1.2)

where the \(c_{ki}\) is the \(k\)th data symbol at the \(k\)th subcarrier, \(g_k\) is the waveform for the \(k\)th subcarrier, \(N\) is the total number of subcarriers, \(f_k\) is the frequency carrier, \(T_F\) is the frame period or symbol OFDM period, and \(p(t)\) is the pulse shaping function which in the ideal case is a rectangular pulse of \(T_F\) width. In simulations it will use a raised cosine function with a certain roll-off factor, \(\alpha\), where \(\alpha = 0\) will correspond to the ideal case [3]. As seen in Figure 1.1, \(T_s\) is the QAM symbol period and it determines the frame period along with number of subcarriers, \(T_F = N \cdot T_s\).
The spectrum of a FDM frame has the shape shown in the next figure.

![Figure 1.2 - FDM signal](image)

Mathematically, the received symbols are obtained by doing

$$
\mathbf{r}_{ik} = \sum_{i=0}^{(i+1)T_F} e^{j2\pi f_k t} \cdot e^{j2\pi f_n t} dt = \begin{cases} 
0 & n \neq k \\
1 & n = k 
\end{cases}
$$

(1.3)

where $i$ is the OFDM frame and $k$ is the number of subcarrier.

This condition is fulfilled when the spectral guard bands between subcarriers are wide enough to avoid interferences between them $f_n \gg f_k$

![Figure 1.3 - FDM transmitter [9]](image)

![Figure 1.4 - FDM receiver [9]](image)

Multiple carrier systems are useful for channels with selective frequency fadings because these will only affect a few symbols, whereas in single carrier systems the whole symbol sequence will be damaged.
The main drawback of the FDM transmission is the excessive bandwidth required to send a signal, due to the guard band needed between subcarriers. This drawback will be solved by using OFDM.

### 1.2. Analogue OFDM

The main advantage of OFDM is the improvement of the spectral efficiency of a FDM. It consists on keeping a subcarriers spacing to fulfil the orthogonality condition.

\[ \Delta f = \frac{1}{T_F} \]  

(1.4)

In the time domain, the orthogonality condition can be understood from the viewpoint that the subcarriers have an integer number of periods inside a frame, therefore, the condition detailed by (1.3) is fulfilled in spite of spectral overlap between sub-channels.

![Figure 1.5 OFDM transmitted signal in Time domain](image1)

![Figure 1.6 OFDM transmitted signal in Frequency domain](image2)

The main drawback in analogue OFDM as well as in FDM, is the requirement of an individual receiver for each sub-channel. Thus, it increases the hardware complexity and cost. The solution for this problem is to use the DFT/IDFT algorithm.
1.3. Digital OFDM

The digitalization of an OFDM signal will be the solution to reduce the hardware complexity increase with the number of channels.

The expression (1.5) represents the transmitted signal $s(t)$, sampled at every interval of $\frac{T_F}{N}$ and assuming only one OFDM symbol.

$$s \left( \frac{nT_F}{N} \right) = \sum_{k=1}^{N} c_k \cdot e^{j \frac{2\pi f_k(n-1)T_F}{N}}$$

(1.5)

From the orthogonality condition (1.4) and the convention that $f_k = \frac{k-1}{T_F}$ and substituting in (1.5) it is obtained that:

$$s \left( \frac{nT_F}{N} \right) = \sum_{k=1}^{N} c_k \cdot e^{j \frac{2\pi (k-1)(n-1)T_F}{N}} = IFFT\ c_k$$

(1.6)

Thus, in the digital domain the OFDM modulation is equivalent to applying the IFFT algorithm over the symbols to be sent. The digital OFDM modulator schematic could then be:

![Figure 1.7 IFFT block [3]](image)

It is interesting to note, that due to the properties of the IFFT algorithm, the order in which the symbols enter to the IFFT block is not the same as the order with which they appear in the spectrum. For example, the symbol assigned to the Nyquist frequency appears twice, at the edges of the spectrum.

In the receiver side an ADC and FFT modulator perform the complementary operations in order to recover the sent signal.
From the spectral viewpoint, the orthogonality condition is represented as the sampling of the FFT, where the targeted subcarriers have the maximum amplitude when the others go to zero.

The DFT/IDFT implementation needs two new devices: the digital to analogue converter, DAC, in the transmitter, and the analogue to digital converter, ADC, in the receiver. The function of the DAC/ADC is the quantization of the input signal depending on the number of levels.

### 1.4. Cyclic Prefix

In communications, either due to the appearance of multipath propagations or chromatic dispersion (CD), as in optical channels which are the focus of this work, there is a temporal overlap between received symbols which is known as Inter-Symbolic Interference (ISI).

The ISI problem can be solved by adding a guard interval, $\Delta_c$, between each OFDM symbol or frame, which must be longer than the delay spread of the channel, to avoid ISI. Another problem closely related with ISI is the inter-carrier interference (ICI), which is the penalty as a result of the incomplete OFDM waveform in the DFT window which thanks to the periodicity of the FFT can be solved by cyclical extension of the symbol into the guard time.

The cyclic prefix (CP) causes the loss of the orthogonality in the transmitted symbols. In order to recover the symbols the CP needs to be removed in the receiver prior to the FFT demodulation.

In the following example (Figure 1.9), the different arrival times at the receiver for each subcarrier are shown. In this case, the CP extension is not wide enough to allow for a complete ISI-free demodulation, since the information from a neighbouring symbol is inside the FFT window.

![Figure 1.8 Cyclic Prefix](image1.png)  ![Figure 1.9 Cyclic Prefix in Optical links](image2.png)
1.5. Channel Estimation: Equalization and Pilot Tones

1.5.1. Equalization

One of the best features of OFDM is its ability to compensate for the channel linear impairments. By means of training sequences, the channel response is estimated and its linear distortions can be balanced in the receiver. For instance, in optical channels CD can be compensated. This technique consists on sending a known bit sequence between transmitter and receiver, which is called training sequence. This training sequence is sent through the channel at the beginning of each transmission and it is repeated each certain time, since the channel never is constant. Then the result is:

\[ Y \omega = X \omega \cdot H_{ch} \omega \]  

where \( Y \omega \) is the received signal, \( X \omega \) is the transmitted signal in the frequency domain and \( H_{ch} \omega \) is the channel’s transfer function.

When the signal is received, it is compared with the original bit sequence to calculate the coefficients of the equalizer to compensate the signal against the channel’s linear distortions and to help to resynchronize the receiver clocks.

\[ \frac{Y \omega}{X \omega} = H_{Eqch} \omega ; H_{ch} \omega \approx \frac{1}{H_{Eqch} \omega} \quad Y_{Eq} \omega = X \omega \cdot H_{ch} \omega \cdot H_{Eqch} \omega \approx X \omega \]  

where \( H_{Eqch} \omega \) is the estimated channel response which will compensate the real channel response \( H_{ch} \omega \), and \( Y_{Eq} \omega \) is the received signal with equalization.

1.5.2. Pilot Tones

In OFDM systems not all the subcarriers are used to send information, but there are some specific subcarriers which are used to resynchronize and help to compensate the channel, called pilot tones.

The main goal of pilot carriers is the compensation of frequency drifts, since if an OFDM signal is affected by frequency drifts due to the channel, the received demodulated sequence will be modified.

In optical systems, when pilot tones are used for phase noise compensation, around these ones several subcarriers are left unmodulated to create a guard band and avoid spectral overlap with the OFDM subcarriers [5].

The simulations of the optical transmission systems of this thesis do not use pilot carriers, just training sequences and cyclic prefix, since as they are based on IM/DD formats, they do not significantly suffer from spectral frequency drifts or phase noise.
1.6. TX/RX OFDM

To obtain an OFDM communication system, the signal has to undergo different stages from the transmitter to the receiver. In this section, this process is described.

1.6.1. OFDM Transmitter

In Figure 1.10, all the different blocks stages of a transmitter, are detailed.

![Figure 1.10 Block Diagram of an OFDM transmitter [10]](image)

Starting from a bit sequence, the first stage divides it in packets of length equal to the number of QAM bits to form a QAM symbol, and then it assigns them to each subcarrier. This process is called Serial to Parallel. The second stage is a reorganization of the subcarriers. After that, a training sequence is added to allow for synchronization and calculate the coefficients of the equalizer.

Before the IFFT stage, an oversampling is applied to make it easier to remove the spectral alias due to non-ideal DAC conversion, and at the receiver it will help in synchronization [4]. When the oversampling is added the next step is to apply the IFFT algorithm. Then, the information of each sub channel returns to a vector form, applying Parallel to Serial, the inverse process which has been applied in the transmitter.

After the CP insertion stage, the signal is divided in real part, in-phase I, and in imaginary part, quadrature Q. These two parts have to be converted from digital to analogue to be sent over the channel, in this case an optical fiber. In order to further reduce the alias due to imperfect digital to analogue conversion a low pass filtering is used.
1.6.2. OFDM Receiver

In the receiver, the block stages diagram is similar to the transmitter but in the reverse way, Figure 1.11:

![Block Diagram of an OFDM receiver](image)

Figure 1.11 Block Diagram of an OFDM receiver [10]

After the signal detection, through an antenna or by a photodiode, the first stage is the filtering process of the in-phase and quadrature components of the received signal, to avoid aliasing problems.

The next stage is the digitalization process of the received signal, which needs two ADC devices, one per each branch. Once the signal is digitalized, the next stage is the synchronization. When the synchronization is completed the CP is removed from the received signal and so the orthogonality is recovered. The resulting signal is parallelized to calculate the FFT. After FFT, the zero padding and the training sequence are extracted. The training sequences are used to estimate the coefficients which are needed to restore the signal in the single-tap equalization block. Consecutively, the phase noise can be compensated, and each subcarrier is demodulated. The final block is the serialization of the information carried out in each sub-channel to obtain the final bit sequence.
CHAPTER 2. OPTICAL COMMUNICATIONS

This chapter focuses in low cost optical OFDM systems and therefore the simplest, conventional IM-DD types of optical modulation and detection are targeted. This chapter reviews the basis of IM-DD systems.

2.1 Conventional IM/DD Systems

The phenomena of light generation and detection are based on one to one conversions between electrons and photons, and therefore electrical currents are converted to optical power and vice-versa. That makes Intensity Modulation and Direct Detection Systems the most natural way of sending electrical information over an optical carrier.

The intensity modulation is usually accomplished by direct modulation of the feeding current of a diode laser. Alternatively, external modulation in the form of MZM in the quadrature bias point or electro-absorption modulation can be used [5].

Mathematically an IM signal takes the form:

\[ P_{out} = P_o (1 + m \cdot s(t)) \]  

(2.1)

where \( P_o \) is the power corresponding to the optical carrier produced by the laser, \( m \) is the modulation index, which depends on the configuration used to send the information, and finally the \( s(t) \) is the information signal.

In the receiver side the complementary function, performed by a photodiode, recovers the electrical information signal as a detected photocurrent proportional to the intensity of the received optical signal.

\[ I_R(t) \propto E(t)^2 \]  

(2.2)

When the transmitted signal, with optical power \( P_{out} \) as defined in expression (2.1), is sent through the fiber, the low-pass equivalent of the electrical field is:

\[ E_{out} = \frac{P_o}{1 + m \cdot s(t)} \]  

(2.3)
And applying a Taylor series to the field the result is the next one:

\[ E_{\text{out}} = 1 + \frac{m}{2} s^t - \frac{m^2}{8} s^2 t + \frac{m^3}{16} s^3 t + \cdots \]  

(2.4)

This means that the optical spectrum of an IM modulated signal will contain harmonics and also mixing products (or intermodulation products) of the information signal, whose value decreases as the powers of the modulation index, \( m \). In absence of channel distortions these nonlinear components are compensated by the square-law transfer function of the photodiode so that the original information signal is exactly recovered. On the contrary, linear channel distortions, such as CD, will give rise to nonlinear distortion in the received signal.

### 2.2 Chromatic Dispersion

When a signal is propagated over a single mode fiber (SMF) the main effect is the chromatic dispersion, which mathematically can be described by:

\[ X_{\text{out}}(\omega) = X_{\text{in}}(\omega) \cdot e^{-j\beta(\omega)z} \]  

(2.5)

where \( X_{\text{out}}(\omega) \) is the Fourier Transform output of the transmitted signal, \( X_{\text{in}}(\omega) \), \( \beta \) is the phase constant, and \( z \) is the length of the fiber.

If a signal is centred at a reference frequency, considering that \( \Delta \omega \ll \omega_{\text{ref}} \), and it is introduced in a dispersive channel the phase constant, \( \beta \), can be expressed as a Taylor series:

\[
\beta(\omega) \approx \beta_{\omega_{\text{ref}}} + \frac{\partial \beta}{\partial \omega} \Delta \omega_{\omega=\omega_{\text{ref}}} + \frac{1}{2} \frac{\partial^2 \beta}{\partial \omega^2} \Delta \omega^2_{\omega=\omega_{\text{ref}}} + \frac{1}{6} \frac{\partial^3 \beta}{\partial \omega^3} \Delta \omega^3_{\omega=\omega_{\text{ref}}} + \cdots
\]

(2.6)

Taking into account that \( \Delta \omega \ll \omega_{\text{ref}} \), the terms of 3 order or higher can be considered negligible. So the final expression can be written as:

\[
\beta(\omega) \approx \beta_{\omega_{\text{ref}}} + \Delta \omega \beta_1 + \frac{\Delta \omega^2}{2} \beta_2 + \frac{\Delta \omega^3}{6} \beta_3 + \cdots
\]

(2.7)
where the coefficients are:

- $\beta_{\omega_{ref}} = \beta_0$ is related to phase velocity, that is the speed at which the phase of a pure tone at frequency $\omega_{ref}$ would be propagate.

$$\beta_0 = \frac{\omega_0}{v_{ph}}$$  \hfill (2.8)

- $\beta_1$ is related to the group velocity, at which changes in the envelope of the wave propagate.

$$\beta_1 = \frac{\partial \beta}{\partial \omega}_{\omega=\omega_{ref}} = \frac{1}{v_g} = \tau_g$$  \hfill (2.9)

- $\beta_2$ is the group delay dispersion given by:

$$\beta_2 = \frac{\partial^2 \beta}{\partial \omega^2}_{\omega=\omega_{ref}} = \frac{\partial}{\partial \omega} \frac{1}{v_g} = \frac{\partial \tau_g}{\partial \omega}$$  \hfill (2.10)

This parameter measures the variation of group delay over the frequency of the different spectral components near the central frequency $\omega_{ref}$, thus it is responsible for the widening of the transmitted pulse. The group delay dispersion, GDD, can also be related to the chromatic dispersion parameter $D = \frac{\partial \beta_1}{\partial \lambda}$ of an optical fiber by:

$$D = \frac{\partial \beta_1}{\partial \lambda} = \frac{\partial \tau_g / L}{\partial \lambda} = \frac{\partial \tau_g / L}{\partial \omega} \frac{2\pi c}{\lambda_{ref}^2} = -\frac{2\pi c}{\lambda_{ref}^2} \beta_2$$  \hfill (2.11)

being $c$ the speed of light and $\lambda_{ref}$ the corresponding centre wavelength.

If the references for phase and time are set at a certain reference frequency which usually is conveniently situated at the centre of the signal’s bandwidth, the transfer function of the fibre can be expressed as:

$$H(\omega) = e^{-j\beta_2(\omega-\omega_{ref})^2L}$$  \hfill (2.12)

where $L$ is the fiber length.
2.3 Effects of CD over IM/DD systems

Mainly, there are three different important effects that have to be taken into account when a signal is sent through an optical link: amplitude fading, nonlinear distortion and phase noise decorrelation. To study the effects of CD in fiber optic systems with IM/DD, some examples are shown.

2.3.1 Amplitude fading

On one hand, the transmission of double side band modulations, in optical links are limited due to the CD, since it produces different phase shifts for the upper and the lower sidebands.

In the next example, the received constellation of an optical OFDM system is represented with a double side band signal (DSB), Figure 2.1. Due to CD, the upper and lower sidebands are affected by different phase shifts provoking that the symbols suffer attenuation, and even might be cancelled, Figure 2.1Figure 2.2. This effect can to some extent be alleviated using equalization as seen in Figure 2.3.

![Double Side Band Signal](image1)

**Figure 2.1 Double Side Band Signal [3]**

![Constellation](image2)

**Figure 2.2 Constellation of a DSB signal affected by Amplitude fading.**
(NFFT=64;BR=10GHz; L=40km)

![Constellation](image3)

**Figure 2.3 Constellation of a DSB signal affected by Amplitude fading equalized.**
(NFFT=64;BR=10GHz; L=40km)
On the other hand, using an optical single sideband (SSB) modulation, Figure 2.4, there is only one photo-detected component at each electrical frequency, so there are no carriers cancelled at certain frequencies, just a phase shift, Figure 2.5, that can be recovered with equalization, Figure 2.6.
### 2.3.2 Nonlinear distortion

When an IM modulated pure-tone signal $s(t)$ of frequency $\omega$ is transmitted through an ideal optical fiber link, Figure 2.7, the signal is decomposed into a series of deltas, where the deltas are the harmonics of $s(t)$ separated between them a multiple of frequency $(n \cdot \omega)$. In the receiver applying the DD process, expression (2.2), the signal is recovered without any modification or loss of information.

![Figure 2.7 IM/DD system with ideal channel](image)

If the signal is sent by a dispersive channel, as a fiber optic, Figure 2.8, the harmonics of the signal will be affected and introduce non-linearities when the signal is received by the photodiode, as it is shown in the next figure.

![Figure 2.8 IM/DD system with dispersive channel](image)

This effect, known as dispersion-induced nonlinear distortion, gives rise to intermodulation products in the received signal. This is the reason behind the spectral band-gaps between the optical carrier and the signal sideband required in IM-DD optical OFDM systems [5].
2.3.3 Phase noise decorrelation

In IM/DD systems the phase noise (PN) fluctuation of the light source is not so critical, since the optical carrier and the sideband are phase noise correlated. This is the case, when the fiber length between transmitter and receiver are not too far away. Unfortunately, when the fiber distance is long a phase noise decorrelation appears between optical carrier and sideband. [8] In the next Figure 2.9, the phase noise impact is shown.

This effect is largely dependent over the lasers linewidth and can be compensated by making use of pilot tones [8]. In our simulations we have used typical DFB laser linewidths in the range of 1 MHz and for the distances and data rates used, we have not observed significant signal degradation coming from this effect. Thus, pilot tones based phase noise compensation has not been considered.

![Phase Noise Impact on DD-OFDM Systems](image)

**Figure 2.9** Phase Noise Impact on IM/DD systems [8]
2.4 IM with Direct Modulated Laser (DML)

The simplest optical link is based on the use of a laser diode directly modulated by an electrical signal through its bias current and demodulated with a photodiode. The bias current sets the operating point in the linear zone of the laser transfer function, above its current threshold; Figure 2.10, where the slope of the function is called slope efficiency and it is usually given in \( \frac{W}{A} \).

As it is shown in Figure 2.11, a DML is used to send the information and a PIN diode in the receiver to convert the optical signal in an electrical signal. The expression, which the DML fulfils, is the same as it is used in any IM/DD, (2.1):

\[
P_{out} = P_o (1 + m \cdot s(t))
\]

(2.13)

where \( P_o \) is the power corresponding to the bias current applied to the laser \( P_o = SE(I_{Bias} - I_{th}) \), Figure 2.10, and \( m \) is the index of modulation which is related to between the modulated bias current and the bias current \( m = \frac{I_{RF}}{I_{Bias} - I_{th}} \).

In the reception of an IM/DD system, the PIN diode detects the optical signal that the laser sends through the fibre, and converts from optical to electrical domain as:

\[
I_R(t) = R \cdot G \cdot P_{out}
\]

(2.14)

being \( R \) the Responsivity of the photodiode in \( \frac{A}{W} \), and \( G \) the gain of the receiver amplifiers.

This detected intensity will be proportional to the square modulus of the electrical field, as it is shown in the expression (2.2), and the behaviour will be the same as explained in the section 2.1.1.
2.5 IM with Mach Zehnder Modulator (MZM)

In advanced applications, involving high data rates or long distance links, a DML is not able to provide the required performances. In those cases an external modulator called Mach-Zehnder modulator (MZM) can be used.

The MZM is an integrated-optic amplitude external modulator. These kinds of modulators are based on the electro-optical principle that occurs in certain materials, such as LiNbO₃. The electro-optical effect means that an optical signal is sensitive to the refractive index changes with respect to the voltage applied across electrodes.

A MZM is composed by two pairs of electrodes: one pair for the RF signal to represent the modulation data signal, and the other pair to bias voltage, as it is shown in the next figure.

\[
E_{\text{out}}(t) = E_{\text{in}} \cdot \cos \left( \frac{\pi}{2V_{\pi}} V_{RF}(t) + V_{B} \right)
\]

(2.15)

where \( V_{RF}(t) \) is the voltage of the modulation data (OFDM signal) and \( V_{B} \) is the bias voltage that specifies the configuration point in the transfer function of the MZM, Figure 2.13. \( V_{\pi} \) is the differential drive voltage resulting in differential phase shift of \( \pi \) rad between the two waveguides, see Figure 2.13. In order to
obtain an IM, a voltage bias of $\frac{V_\pi}{2}$ is required to operate in the linear part of the optical power function.

Therefore, the optical power at the output of the MZM depends on the phase difference between the two arms of the modulator, which can be changed by varying the bias voltage of the MZM, resulting:

$$P_{out} = P_0 \cdot \cos^2 \left( \frac{\pi}{2V_\pi} V_{RF}(t) + V_B \right) = \frac{P_0}{2} \cdot 1 + \cos \left( \frac{\pi}{V_\pi} V_{RF}(t) + V_B \right)$$  \hspace{1cm} (2.16)

Then considering quadrature point and small signal condition: $\sin x \approx x$, the result is:

$$P_{out} \approx P_{IN} \cdot 1 + \cos \left( \frac{\pi}{V_\pi} V_{RF}(t) + \frac{V_\pi}{2} \right) = \frac{P_0}{2} \cdot 1 - \sin \left( \frac{\pi}{V_\pi} V_{RF}(t) \right)$$

being $m$ the index modulation defined as $m = \frac{\pi}{V_\pi}$.

An appropriate bias must be applied in order to work into each one of the interest working points, Figure 2.13:

- $V_B = \frac{V_\pi}{2}$, Quadrature Point: IM systems, used in conjunction with DD mainly.

- $V_B = V_\pi$, Null-point: Amplitude Modulation (AM) systems with suppressed carrier, used mainly in combination with coherent detectors.

In this project, the operating point is situated in the quadrature point (QP), because the IM/DD technique to modulate and demodulate the optical signal is used.

All the simulations of this thesis use an external modulator MZM in QP. The results would not change significantly if another kind of IM modulator would have been used.
CHAPTER 3. OPTICAL OFDM TECHNIQUES

In order to define an optical OFDM system based on IM/DD, two points are to be considered: firstly, the OFDM signal has two components (Inphase-Quadrature) while only the intensity of the optical signal is modulated in IM/DD, and secondly, a linear channel is required in order to apply equalization, while the IM/DD system is inherently nonlinear in the presence of CD.

The first problem can be solved using two different techniques: electrical IQ or Hermitian Symmetry.

The second problem is solved by using guard bands between the optical carrier and the OFDM signal to leave the CD nonlinear distortion that introduces the optic fiber out from the detected signal's bandwidth.

In Figure 3.1, a general classification of different strategies for o-OFDM systems is represented [9].

This work has been focused in intensity modulation (IM), using a MZM in quadrature point to transmit the signal, and the direct detection (DD) using a photodiode in the receiver.

As it is explained in section 2.3, the main problem of an IM/DD optical system, due to the chromatic dispersion of the fiber, is the unwanted mixing products among the subcarriers, since they may interfere with other subcarriers in the electrical domain affecting the complete transmitted signal.
To prevent these interferences, a frequency gap may be allocated between the optical carrier and the OFDM spectrum, which width must be at least equal to the OFDM signal’s bandwidth.

In the next section two strategies to create a spectral gap between the carrier and the OFDM spectrum are described, namely the RF up-down conversion (electrical IQ) and the zero padding using discrete multi-tone modulation, DMT.

### 3.1 RF-up conversion (electrical IQ) in IM/DD systems

The RF-up conversion technique is based on converting a baseband OFDM signal into an OFDM pass-band signal centred at a carrier frequency ($f_c$), as it is shown in the Figure 3.2. This carrier frequency must be at least 1.5 times the bandwidth of the OFDM signal to create a guard band equal to the OFDM bandwidth between the optical carrier and the OFDM signal.

The addition of the guard band equal to the OFDM bandwidth signal, avoids the problem of the intermodulation products allowing that the main OFDM signal is not affected. In this technique, the system needs an electrical IQ mixer with a local oscillator between the OFDM coding block and the optical modulator. The function of the IQ mixer is to sum up the real part (in-phase) with the imaginary part (in-quadrature) of the OFDM signal at an RF carrier frequency generating a double side band signal. After that, this signal can be IM modulated over the optical carrier to be transmitted over the fiber.

![Figure 3.2 RF-up conversion (eIQ)](image1)

![Figure 3.3 eIQ OFDM transmitter](image2)
In the receiver, with direct detection, the signal is down-converted by another IQ mixer with the opposite function, returning the OFDM signal to baseband before the OFDM decoding block.

### 3.2 Hermitian Symmetry (DMT) in IM/DD systems

In this section, the technique is the discrete multi-tone modulation (DMT) which permits to send only the real part of the OFDM signal applying Hermitian Symmetry.

The main advantage of this kind of systems is that the RF blocks are not needed because the guard bands are generated in digital domain with zero padding before the IFFT.

Hermitian Symmetry method allows the transmission of just the real part of the OFDM signal at the expense of reducing in half the effective bit rate. It can be seen that if the upper half subcarriers are set to the complex conjugate of the lower half subcarriers, the resulting OFDM signal has only real part. This one component of the OFDM signal can directly be IM modulated over the optical carrier. For a mathematically explanation see Annex.

In the receiver, the photo-detected signal will be connected to the real part input of the decoder, and the imaginary part will be grounded.

As a drawback, in order to generate a guard band between the optical carrier and the signal sideband, half of the active subcarriers, those spectrally located closer to the optical carrier, must be set to zero, with a further reduction by two the effective bit rate.

The number of subcarriers, which is needed in IFFT/FFT block to transmit/receive the signal to obtain the same efficiency than the eIQ system, is thus four times higher. Even so, the HS system will only be transmitting half of the effective bit rate and will just be requiring one DAC, instead of two. The capacity of the DAC required for transmitting the same effective bit rate in both systems will be eight times higher in the Hermitian Symmetry plus guard band system but the eIQ will be requiring two DAC units. Thus, the output signal is
Optimization of optical OFDM systems composed by the active sub channels and their respective complex conjugate and a zero padding to create the guard band, see Figure 3.4

It is important to note that both designs, electrical IQ and Hermitian Symmetry, can be used without any kind of guard band, thus the adding of this one is just an option to avoid the errors provided by mixing products, as it has been explained in several parts of the thesis. This depends on how much CD is present (hence how severe is the nonlinear distortion). For short distances of fiber, therefore, the guard band requirement is not so strict.

In the next chapter, different scenarios have been developed to be used for advanced simulations of optical OFDM systems based on IM/DD.
CHAPTER 4. O-OFDM Simulations

This chapter is organized into 3 main sections. Sections 4.1 and 4.2 are devoted to the IM/DD with RF-up/down conversion optical OFDM system. In section 1, a VPI built-in demo is analysed in detail to understand the basics of VPI simulations of optical OFDM systems. After the study in section 4.1, some limitations have found, since the VPI demo does not allow for the required flexibility, especially with regard to the OFDM coding and decoding stages. For this reason, in section 4.2, a new scenario has been designed in which the VPI OFDM coding and decoding have been replaced by modules programmed in Matlab.

In section 4.3, a complete new simulation scenario based on the Hermitian Symmetry has been designed using the new OFDM coders and decoders built.

4.1 VPI Optical OFDM demo

The objective of this section is to analyse in detail the OFDM for Long-Haul Transmission Demo provided by VPI. This demo consists in a transmission over 1000km optical fibre link following the IM/DD techniques described in chapter 3.1.

Firstly, a general scenario of an OFDM Long Haul transmission system is shown in Figure 4.1, and its global parameters (Figure 4.2) are analysed in detail. Secondly, with the aim to study their behaviour, a specific view is offered within the transmitter and the receiver blocks. Finally the optical channel is analysed.

Figure 4.1 OFDM Long Haul System provided by VPI
Analysing the whole demo, three important blocks can be seen: transmitter block, channel block and receiver block.

The global parameters and their values of this demo and their default values are shown in Figure 4.2. The most relevant parameters are the *Time Window*, *Sample Rate*, *Bit Rate* and *Bits per Symbol of the QAM* modulation, in this case 2, because the modulation is a 4-QAM.

![Figure 4.2 Global Parameters of OFDM Long Haul System](image)

As it is seen in figure 4.2, the parameters are related to each other so that the *TimeWindow* and the *SampleRateDefault* must be:

\[
\text{TimeWindow} = \frac{2^m}{\text{BitRateDefault}} ; \quad \text{SampleRateDefault} = 2^n \cdot \text{BitRateDefault}
\]

where \( m \) and \( n \) are integer numbers. The reason for that is due to VPI simulations are based on FFT algorithms which are more effective when \( \text{TimeWindow} \cdot \text{SampleRateDefault} = 2^k \), with \( k \) an integer number. If either of these two parameters change, they always must respect those relationships.

A limitation found is that only QAM levels which are also a power of two can be simulated.

In section 4.2, more generic relationships are given which involve the *BitsPerSymbolQAM* value so that any level of QAM can be accepted.
4.1.1 Optical OFDM Transmitter

Focusing in the OFDM transmitter block, if we look inside this block we will see the different sub-blocks to generate an OFDM signal, Figure 4.3. These sub-blocks are: the PRBS generator, OFDM coder, pulse shaping, RF-up conversion, and a mixer block.

- OFDM coder block, which is the responsible of processing the electrical OFDM signal.
- Laser, which provides the optical carrier.
- Mach-Zehnder modulator block biased at QP which IM modulates the signal over the optical carrier.
- Single Side Band Filter (SSBF) to remove one of the spectral sidebands of the transmitted signal to avoid amplitude fading due to the CD of the fiber.

![OFDM modulator block](image)

**Figure 4.3 OFDM modulator block**

The PRBS block generates a random bit sequence whose length is $TimeWindow \cdot BitRate$. This bit sequence will be the information of the OFDM signal.

The OFDM coder block can generate an OFDM signal as it is explained in section 1.6.

To filter the output of the OFDM coder module a pulse shaping with raised square root with a roll-off factor equal to 0.2 is used. This roll-off factor simulates an imperfection in the DAC conversion characteristics [9]. For ideal simulations it is set to zero.
The RF carrier is chosen at 7.5GHz in order to obtain a guard band equal to the OFDM bandwidth which is 5GHz, between the optical carrier $f_{opt} = 193.1\ THz$ and the OFDM signal.

In the next picture, the parameters of the OFDM transmitter block are shown:

![Figure 4.4 OFDM transmitter block parameters](image)

It is worth noting they are organized into several levels, where the QAM-OFDM signal group is divided into different sub-groups, as DAC, RF, Filter and PRBS Generator, and it has the main parameters to build an OFDM signal.

The main parameters of the QAM-OFDM signal are: OFDMType, Coding, BitsPerSymbolQAM, Number of carriers and CyclicPrefix.

- **OFDMType** selects the OFDM generation technique, where the options are OFDM or DMT.
- **Coding** is the type of modulation which can be mPSK or mQAM.
- **BitsPerSymbolQAM** defines the bits needed to create a symbol QAM. Only powers of two values are accepted in this simulation.
- **Number of carriers** is the number of the IFFT/FFT inputs.
- **CyclicPrefix** fixes the part for the cyclic prefix as a percentage.
In the DAC sub-group, three new parameters are shown: QuantizeOutputValues, QuantizationLevels and HighestQuantizationLevel.

- **QuantizeOutputValues** selects the option to use the DAC/ADC stage.
- **QuantizationLevels** defines the resolution of the DAC/ADC.
- **HighestQuantizationLevel** is the maximum value of the rail.

The RF sub-group includes the *CarrierFrequency* and *Phase* of the RF-up/down conversion stage. The *Filter* sub-group is the pulse shaping stage and gives the option to select the type of the filter with the parameter *NyquistResponse* and *RollOff*.

The *PRBS Generator* sub-group defines the parameters of the information source. The important parameters of this sub-group are: *PreSpaces*, *PostSpaces*, *PRBS_Type*, *MarkProbability* and *RandomNumberSeed*.

- **PreSpaces** is the number of leading zero bits.
- **PostSpaces** is the number of trailing zero bits.
- **PRBS_Type** defines the type of binary sequence. The displayed parameter set depends on the value of this parameter as the following physical parameters are context sensitive.
  - **MarkProbability** is the probability that 1's could be generate if the PRBS is chosen.
  - **RandomNumberSeed** Lookup index for noise generation. A value of zero implies an automatic, unique seed.

All these parameters are directly passed to the different sub-modules of the OFDM transmitter block.

When the OFDM signal is already created, it is connected to the *DriveAmplitude RF* waveguide input of the MZM to modulate the optical signal from the laser. The optical carrier of the laser is 193.1 THz with an average power of 5 mW and linewidth of 1MHz.
4.1.1.1 OFDM coder block

The function of the OFDM coder and decoder blocks in VPI has been studied in detail in this Master Thesis, since one of the goals is to create an open-source alternative about the VPI OFDM coder and decoder blocks.

The OFDM coder block provided by VPI, Figure 4.5, is a locked module, which does not allow the look inside function. The main function of this block is the OFDM modulation process explained in section 1.6. It can be programmed by using the parameter editor of the block, Figure 4.6.

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<th>Parameter</th>
<th>Description</th>
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</thead>
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</tr>
<tr>
<td>SampleRate</td>
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<td>Yes</td>
</tr>
<tr>
<td>QuantizationLevels</td>
<td>1024</td>
</tr>
<tr>
<td>HighestQuantizationLevel</td>
<td>1</td>
</tr>
<tr>
<td>BoundaryConditions</td>
<td>Periodic</td>
</tr>
</tbody>
</table>

Unfortunately, not very detailed information about the functions performed by the module is provided and sometimes it is difficult to understand the outcomes obtained. Furthermore, some of the scenarios to simulate require small modifications of the OFDM modulation/demodulation code that are not possible with the locked OFDM modules provided by the software.

The goal will therefore be designing our own OFDM coder and decoder functions in Matlab and make them work as inter-connectable modules inside VPI by making use of the Co-simulation feature provided by the software.

In [9], the behaviour of this block was analysed, focusing mainly in the equalization and CP properties. Here it has built on the work in [9], to improve
the whole modules performance, with special emphasis on normalization, training, and DAC/ADC conversion.

### 4.1.2 Channel Block

The channel block, represented in the blue square of Figure 4.3, is built by a standard single mode fiber (SSMF) link consisting of a loop circuit where the signal covers 100 km with amplification and filtering stages for each loop. The loop is repeated 10 times to achieve a 1000 km fiber link. The main parameters of these blocks are the attenuation per km, and the chromatic dispersion value with associated reference frequency. The reference frequency concept has been analysed in detail in [9].

### 4.1.3 Optical OFDM Receiver

The demodulation block represents the optical OFDM receiver and it is formed by:

- Photodiode, which converts the optical signal into an electrical one.
- OFDM demodulator block, which decoders the received signal in the reverse way of the OFDM transmitter block.

Studying the OFDM demodulation block, Figure 4.7, it can be seen that it is composed by different stages: RF-down conversion, pulse shaping, OFDM decoder and BER estimation.

The RF-down conversion stage takes the sideband signal located at the RF carrier frequency, \( f_{RF} \), and shifted it to base band.

To recover the signal a pulse shaping filter with a roll-off factor is in place.

After that, an OFDM decoder digitalizes the received signal to process the information which has been sent. The outputs of the OFDM decoder evaluate the system performance characteristics, such as error vector magnitude (EVM), and symbol error rate (SER) using Monte-Carlo approach, but unfortunately no BER results are provided.
Many parameters in the OFDM demodulation block are complementary to those in the OFDM modulation block, but some stages are added, for example: equalization and EVM calculation. The global parameters of the OFDM demodulator block are shown in the next picture:

Figure 4.7 OFDM demodulation block

![OFDM Demodulation Block Diagram](image)

Figure 4.8 OFDM demodulation block parameters
Only two new sub-groups are in the OFDM modulation block parameters, which are the *Equalization*, and *BER estimation*.

- *Equalization* is a parameter that specifies whether sub-barrier equalization should be carried out.
- *EqualizAmp* defines the amplitude equalization array.
- *EqualizPhase* is the phase equalization array, in radians.

It is seen that these modules just provide the option to add a fixed sequence of equalizer coefficients. The demo gives a sequence which is valid only for the specific scenario of the demo and does not give information about how to obtain the equalizer coefficients for other scenarios. In the Matlab demo, the equalizer coefficients are automatically calculated by making use of training sequences. See section 4.2.1.2

The BER estimation group determines the parameters which correspond to the EVM and SER calculations.

- *UseSymmetry*: permits whether constellation symmetry will be used to improve statistics estimate.
- *SampleType*: specifies the method used to determine the sampling instant.
- *SampleTime*: defines the sampling instant as a fraction of the symbol time slot.
- *ClockRecovery*: enables an internal clock recovery. It should be activated.
- *Outputs*: is the result of the EVM or SER.
- *ChannelLabel*: is the label of the logical channel containing the information on modulation format and transmitted bit sequence.
- *ChannelIndex*: is the index of the logical channel containing the information on modulation format and transmitted bit sequence. A value of -1 specifies that the logical channel with the highest index should be used.
- *IgnoreSymbols*: Allows a group of consecutive QAM symbols to be excluded from the calculation.
- *MultipleBlockMode*: in *IndependentBlocks* mode, a new SER calculation is performed for each input block received in a multiple-block simulation. In *AverageOverBlocks* mode, statistics are accumulated over all blocks received, and cumulative values are output after each block.
4.1.3.1 OFDM Decoder block

The OFDM decoder block is the core of the demodulation module, since it permits to recover the signal as explained in the section 1.7.

![OFDM Decoder Block](image)

Figure 4.9 OFDM Decoder Block

The study of this block helps to mimic the general function and create a new OFDM decoder. Firstly, to start the study, we take a look to the parameters of the block, Figure 4.10, to know the different stages between the OFDM coder block.

- **Pilot tones**: insert the pilot tones at the integer array in this parameter.
- **QuantizedInputValues**: enable the possibility of DAC/ADC use.
- **QuantizationLevels**: is the resolution of the DAC/ADC.
- **HighestQuantizationLevel**: the maximum input/output rail of the DAC/ADC.
- **Equalization**: permits to compensate the channel impairments.

```
+---+----------------+------------------+-------+----------+
|   | Physical       | Equalization     | Enhanced | Scheduler |
+---+----------------+------------------+----------+-----------+
|   | BitRate        | Equalization     | BoundaryConditions | Scheduler |
|   | BitRateDefault| EqualAmp         | Periodic  |           |
|   | SampleRate     | EqualPhase       |           |           |
|   | SampleRateDefault|                |           |           |
|   | OFDMType       |                 |           |           |
|   |                 | OFDM            |           |           |
|   | BitPerSymbolGAM|                 |           |           |
|   |                 | 4               |           |           |
|   | NumberOfCarriers|                 |           |           |
|   |                | 16              |           |           |
|   | CyclicPrefix   |                 |           |           |
|   |                | 0               |           |           |
|   | PilotTones     |                 |           |           |
|   |                | Off             |           |           |
|   | QuantizedInputValues|         |           |           |
|   |                | Yes             |           |           |
|   | QuantizationLevels|        |           |           |
|   |                | 1024            |           |           |
|   | HighestQuantizationLevel| |           |           |
|   |                | 1               |           |           |
|   |                 |                 |           |           |
```

Figure 4.10 OFDM decoder block parameters
4.1.4 Results of Long-Haul simulation

The results of a Long-Haul system are the transmitted signal, the received signal, the constellation, the EVM or SER. In the next figures some examples are shown:

![Optical Spectrum RX](image)

**Figure 4.11** Received OFDM signal

![Signal Constellation for slice 5](image)

**Figure 4.12** Received Constellation

The EVM of this Long-Haul system simulation is 0.178, and the main parameters are:

- Fiber Length=1000 Km.
- Fiber Attenuation=0.2dB/Km
- Bit Rate= 10 Gbps.
- Sample Rate= 40 Gbps.
- Time Window=6.5536 µs.
- Modulation: 4-QAM.
- Number of FFT carriers=64.
- Cyclic Prefix = 20%
- Carrier Frequency (RF) = 7.5GHz.
- Roll-Off=0.2.
- Equalization=Yes.
### 4.1.5 Limitations of OFDM coder/decoder block

After studying the OFDM coder/decoder, some limitations have been found. These limitations are:

- The $BtsPerSymbolQAM$ parameter must be a power of 2.
- The Bit Error Rate is not calculated.
- It does not allow for simulation of OFDM system with DMT.
- Equalization fixed for the parameters of this specific simulation. If a different simulation wants to be tried, no clues are provided as to how can the equalizer coefficients be calculated [9].
- Some common variables between the emitter and receiver are defined as global, such as for example $BtsPerSymbolQAM$, but there are other parameters, which could take profit of this advantage, such as $r\, Frequency, CyclicPrefix$. That would improve the user friendliness of the demo.

In the next section, the design and development of an alternative demo which overcomes the limitations found in the VPI demo has been described. The main aim is to come up with a user-friendly, simple and effective demo which helps to easily reach the goals of the simulation tasks foreseen within the Accordance project.
4.2 Matlab OFDM IM/DD RF demo

A new alternative demo has been developed in which the OFDM coder and decoder modules have been replaced by new modules programmed in Matlab making use of the Co-Simulation tool. Besides that, in order to make it more user-friendly, global variables have been defined for an easy control of the main parameters of the complete system.

4.2.1 General scenario and global parameters

![New IM/DD RF scheme](image)

Figure 4.13 New IM/DD RF scheme

As it can be seen in Figure 4.13, there are the same parts as in VPI Long-Haul demo, the OFDM transmitter, the optical channel and the OFDM receiver.

The OFDM transmitter is composed by the new Matlab OFDM coder, a couple of pulse shaping for the real and imaginary part and the RF-up conversion stage which has a local oscillator and a mixer to sum up both parts.

The optical channel only is a Standard Single Mode Fiber (SSMF) since rather than Long-Haul systems, access networks are targeted in Accordance.

In the OFDM receiver a photodiode detects the optical signal and changes into electrical field. The electrical signal is passed to the RF-down conversion stage and finally it is filtered with a raised cosine filter to send the real and imaginary parts towards the new Matlab OFDM decoder.

The global parameters are divided in different groups depending on their functionalities: coding Parameters, RF Parameters and Global.
These parameters must be set to fulfill certain conditions in order to ensure an acceptable simulation.

The first important condition for the parameters is the choice of the number of symbols, since it must be a power of 2:

\[
SymbolRate = \frac{BitRateDefault}{BitsPerSymbolQAM}
\]

\[
TimeWindow \cdot SymbolRate = N_{Symbols} \Rightarrow N_{Symbols} = \frac{TimeWindow \cdot BitRateDefault}{BitsPerSymbolQAM} = 2^p
\]

The **TimeWindow** and **SampleRate** must be selected to obtain a number of samples equal to a power of two, as it was explained in section 4.1, then:

- **TimeWindow** parameter is the duration of an observation and it must comprise an integer number of bits, and it is calculated as:

\[
TimeWindow = \frac{2^t \cdot BitsPerSymbolQAM}{BitRateDefault}
\]

where \(2^t \cdot BitsPerSymbolQAM\) is an integer number which represents the total number of bits in the simulation.

- **SampleRateDefault** parameter is defined by:

\[
SampleRateDefault = \frac{2^s \cdot BitRateDefault}{BitsPerSymbolQAM}
\]

<table>
<thead>
<tr>
<th>Coding Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>i BpS</td>
<td>2</td>
</tr>
<tr>
<td>f CP</td>
<td>0</td>
</tr>
<tr>
<td>i N_FFT</td>
<td>64</td>
</tr>
<tr>
<td>i ZF_Mask</td>
<td>25 27 28 29 30 31 32 33 34 35 ...</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RF Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>f CarrierFrequency</td>
<td>1.5*(BitRateDefault/BpS)</td>
</tr>
<tr>
<td>f Phase</td>
<td>90</td>
</tr>
<tr>
<td>f RollOff</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Global</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>f TimeWindow</td>
<td>((2^16)\cdot(BpS/BitRateDefault)) s</td>
</tr>
<tr>
<td>i GreatestPrimeFactorLimit</td>
<td>2</td>
</tr>
<tr>
<td>i InBandNoiseEins</td>
<td>OFF</td>
</tr>
<tr>
<td>i BoundaryConditions</td>
<td>Periodic</td>
</tr>
<tr>
<td>i LogicalInformation</td>
<td>ON</td>
</tr>
<tr>
<td>f SampleModeBandwidth</td>
<td>1280e9 Hz</td>
</tr>
<tr>
<td>f SampleModeCenterFrequency</td>
<td>1331e12 Hz</td>
</tr>
<tr>
<td>f SampleRateDefault</td>
<td>((2^3)\cdot(BitRateDefault/BpS)) Hz</td>
</tr>
<tr>
<td>f BitRateDefault</td>
<td>13e9 bit/s</td>
</tr>
</tbody>
</table>
where \(2^s\) \(\text{BitsRateDefault}\) is an integer number which represents the total number of samples.

- \(\text{BitRateDefault}\) parameter specifies the velocity of the transmitted bits through the system.

- \(BpS\) parameter defines the bits needed to create a QAM symbol.

The \textit{Coding Parameters} are designed to control the common coder and decoder parameters, to avoid inconsistency between two parameters with the same name. These parameters are:

- \(BpS\): the bits per symbol QAM depending on the type of modulation to simulate.
- \(CP\): gives the possibility to add a cyclic prefix writing a value between 0 and 1. This value can be considered as a percentage, thus to calculate the size of the cyclic prefix it has to multiply this value with the total number of electrical subcarriers (\(N_{FFT}\)).
- \(N_{FFT}\): 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 FFT/IFFT algorithm.
- \(ZP\_Mask\): is an integer array vector which defines the subcarriers that will be cancelled.

The \textit{RF Parameters} defines the values of the RF-up/down conversion stages which are shown in the Figure 4.13.
4.2.2 Design of Matlab OFDM Coder & Decoder

VPI provides a block called *Co-simulatorInterface* which supports simulation with Matlab, Python and dynamic link libraries. In this section, the different OFDM stages using Matlab’s codes in the *Co-Simulator* block are explained.

4.2.2.1 Matlab OFDM Coder

In the next Figure 4.15, the new coder module, which is composed by different VPI blocks such as co-simulation interface, a complex to real&imaginary converter and up-sampling, is shown. The *Co-Simulator* block is able to run a Matlab code which is preprogrammed for all the digital processing of the signal, explained in section 1.6.

![Matlab OFDM coder structure](image)

**Figure 4.15 Matlab OFDM coder structure**

This OFDM coder permits to simulate the digital signal processing of the base band OFDM signal. In Figure 4.16, the main parameters of the Matlab OFDM coder are seen:

<table>
<thead>
<tr>
<th>Coding Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HS</td>
<td>Nc</td>
</tr>
<tr>
<td>ZP_Guardband</td>
<td>On</td>
</tr>
<tr>
<td>N_zeros</td>
<td>(N_FFT-4)/4</td>
</tr>
<tr>
<td>BpsS</td>
<td>BpsS</td>
</tr>
<tr>
<td>CP</td>
<td>CP</td>
</tr>
<tr>
<td>N_FFT</td>
<td>N_FFT</td>
</tr>
<tr>
<td>ZP</td>
<td>Off</td>
</tr>
<tr>
<td>ZP_Mask</td>
<td>Off</td>
</tr>
<tr>
<td>DAC</td>
<td>Off</td>
</tr>
<tr>
<td>Highest_Level</td>
<td>1</td>
</tr>
<tr>
<td>Nbits</td>
<td>10</td>
</tr>
<tr>
<td>Normalization</td>
<td>On</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Global Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TimeWindow</td>
<td>TimeWindow</td>
</tr>
<tr>
<td>BitRate</td>
<td>BitRateDefault</td>
</tr>
<tr>
<td>SampleRate</td>
<td>SampleRateDefault</td>
</tr>
</tbody>
</table>

**Figure 4.16 New OFDM coder parameters**
Where:

- BpS, N_FFT and CP are defined in the global parameters of the whole schematic, explained in the previous section.

- ZP is a Boolean parameter which specifies if the transmitted signal will use zero padding (On/Off). If this parameter is On mode, the parameter ZP_Mask is enabled to insert the array of carriers which will be zero.

In the next figure is represented an example of the ZP_Mask use.

```
16 carriers
1  16

16 carriers

16 carriers
1  16

16 carriers

Figure 4.17 An IM/DD RF signal applied ZP_Mask
```

It is important to know, if the System has the Hermitian Symmetry option in On mode, the order of the subcarriers is different. See next section 4.3.

- DAC is a Boolean parameter to enable or disable the digital to analogue converter block. If the DAC parameter is selected two parameters are enabled Highest Level and the Nbits. The Highest level is the largest output voltage of the DAC. The Nbits is the number of bits of the DAC.

- Normalization permits to fix the output of the coder between 1 and -1. It consists in dividing the input signal by the modulus of the highest sample at the OFDM output, then the maximum value of the output signal is modulus one. This is what was seen to be the case for the VPI OFDM coder and it was a fixed feature. In our scenarios, it provides an option to enable/disable the normalization. This has been found to be useful when simulating multiple-users scenarios [11].
Optimization of optical OFDM systems

*HS* defines which kind of the technique is used, Hermitian Symmetry or RF up/down conversion. If the *HS* is enabled the coder will process the input signal using Hermitian Symmetry. On the contrary, if it is disabled the system will work using RF up/down conversion. In the Hermitian Symmetry demo, this parameters will be explained with more detail.

If a user looks inside the *Cosimulator*, the main parameters are the *InterfaceType* (Matlab/Phyton), and the *RunCommand* which is the function of the Matlab code, which is saved in the input folder of the OFDM coder block.

<table>
<thead>
<tr>
<th>General</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>InterfaceType</td>
<td>Matlab</td>
</tr>
<tr>
<td>LogicalInformation</td>
<td>Yes</td>
</tr>
<tr>
<td>Path</td>
<td></td>
</tr>
<tr>
<td>hcoFile</td>
<td></td>
</tr>
<tr>
<td>intCommand</td>
<td></td>
</tr>
<tr>
<td>RunCommand</td>
<td>y=cfdm_coder_simu_cristoDAC(orbs,Tin)</td>
</tr>
<tr>
<td>WrapupCommand</td>
<td></td>
</tr>
<tr>
<td>ShareInterface</td>
<td>On</td>
</tr>
</tbody>
</table>

Figure 4.18 Co-simulator parameters
4.2.2.2 Matlab OFDM decoder

The OFDM decoder block is a more complex block, since it will be able to reconstruct the signal that has been sent through a dispersive channel, the fiber optic.

The VPI block which represents the open source OFDM decoder is shown in

Figure 4.19 This new decoder is composed by different blocks as Co-simulator block, one logical channel input, a constellation block, and different outputs (signal in symbols, BER, EVM and the signal in bits).
The OFDM decoder has two accesses for the received signal, one for the real part and the other for the imaginary part. The real input always receive a signal, since as both when HS is enabled and disabled the signal has a real part, however, in the case of imaginary input, if HS is disabled, the mode used will be RF up/down conversion and this one will not cancelled, on the contrary if HS is enabled, the mode used will be Hermitian Symmetry and thus, the imaginary part must be zero. This connection doesn’t add information to the system, because it is connected to a switch that depends on the HS parameter; when HS is “Yes” the imaginary input is a vector of zeros.

The two inputs are adapted to the Co-simulator input which will be processed and recovered. In the decoder Matlab code, there are several important stages: down-sample, normalization, clipping and quantization in the ADC, the CP extraction, the FFT, the zero padding extraction, and the BER/EVM calculation.

The ADC performance takes the signal after the normalization process and quantizes the received signal, depending on the resolution of the ADC and clips it according to the rails of the ADC. This stage is explained in section 4.2.2.3.

After the digitalization process, the next stage is the extraction of the CP. A deep analysis of the simulation of synchronization issues in VPI involving the choice of the reference frequency in the fiber and the CD behaviour, gave as a result that the correct extraction of CP is to have it centred in the border of OFDM frames so that it is distributed between the end of one frame and the beginning as it is shown in Figure 4.20. [9]
In our simulator given the matrix structure and the periodicity of the *TimeWindow*, that means taking half the symbols of CP at each side of the OFDM frame row, as shown in the Figure 4.21.

When the CP is removed, the next step is to apply the Fast Fourier Transform, FFT, to the information matrix. Extraction of the zero padding due to the hermitian symmetry and the additional zero padding added by the user then follows.

Now the most important stage is the equalization, since it permits to recover the signal that has been affected by a dispersive channel. The Monte-Carlo training method is the technique to estimate the coefficients of the channel.

Firstly, to choose equalization, the user has to enable the *Equalization* parameter in the decoder OFDM parameters. When the *Equalization* is in *On* mode, the user can choose *Training* mode. Then the user must specify how many symbols (*N_training*) wants to be taken into account to derive the channel coefficients. If a user selects the parameter *N_training* in *All* mode, it means that the estimation of the channel has been calculated with all the number of symbols in the simulation.
When the equalization process is finished, the next step is to calculate the EVM and BER to evaluate the transmission.

4.2.2.3 DAC/ADC

In the simulator, errors in the ADC/DAC sampling time are very difficult to take into account. In this thesis as it also the case for the VPI built-in demo, only the effect of quantization and limited dynamic margin (clipping) due to the DAC/ADC conversion have been considered.

![DAC/ADC Diagram](image_url)

**Figure 4.22** DAC/ADC device
The purpose of this function will be incorporate into the new coder and decoder modules the same feature provided by the VPI modules. The parameters for the DAC and ADC are: DAC or ADC, *Highest Level* and *Nbits*.

<table>
<thead>
<tr>
<th>DAC or ADC</th>
<th>On</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>highest Level</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Nbits</strong></td>
<td>10</td>
</tr>
</tbody>
</table>

```

Decoder ADC
```

<table>
<thead>
<tr>
<th>ADC</th>
<th>On</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Highest Level</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Nbits</strong></td>
<td>10</td>
</tr>
</tbody>
</table>

**Figure 4.23** DAC/ADC parameters

- **DAC or ADC** permits to enable the quantization function implemented in Matlab.
- **Highest Level** is the maximum input values that can quantize. If an input value exceed from this value, this input value will be saturated with the highest level parameter. The lowest level value will be the same value as highest level but with a negative sign.
- **Nbits**: defines the resolution in bits of the DAC/ADC device.

The design of DAC/ADC permits to perform two new stages: **Clipping** and **Quantization**.
4.2.2.3.1 Clipping Stage

The Clipping stage limits the signal between the maximum and minimum voltages rails of the device, these edge values are established by the parameter Highest Level, which defines the upper limit with the positive value and the lower limit with the negative value, Figure 4.24.

![Clipping Stage Diagram]

To implement this function in Matlab a vector strategy has been programmed.

The strategy consists of detecting, which values of the input vector are inside the dynamic range of the DAC/ADC. Thus, if these values exceed from the highest voltage and lowest voltage, then the input value will be fixed as the limit value.

In the next example the performance of the Clipping process is described:

For example, an input data vector \( x = 1 \ 3 \ 5 \ 6 \ 8 \ 7 \ 9 \) Volts with limit voltages \( V_{\text{max}} = 7V \) and \( V_{\text{min}} = 3V \):

Firstly, it detects the upper exceeded values from the input vector, such as:

\[
xx1 = x > V_{\text{max}} ; \rightarrow xx1 = [0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 1]
\]  
(4.1)

Secondly, the rest of values lower than the maximum voltage are detected:

\[
xx2 = x < V_{\text{max}} ; \rightarrow xx2 = [1 \ 1 \ 1 \ 1 \ 0 \ 1 \ 0]
\]  
(4.2)

By applying the next expression, the upper clipped vector \( x1 \) is:

\[
x1 = x \cdot xx2 + xx1 \cdot V_{\text{max}}; \rightarrow x1 = [1 \ 3 \ 5 \ 6 \ 7 \ 7 \ 7]
\]  
(4.3)
Now, by using this upper clipped vector $X1$, the same technique is applied with the minimum clipping value, resulting in:

$$\begin{align*}
xx3 &= X1 \leq V_{min} \Rightarrow xx3 = [1 \ 1 \ 0 \ 0 \ 0 \ 0] \\
xx4 &= X1 > V_{min} \Rightarrow xx4 = [0 \ 0 \ 1 \ 1 \ 1 \ 1]
\end{align*}$$

$$X2 = X1 \cdot xx4 + xx3 \cdot V_{min}$$

$$X2 = [3 \ 3 \ 5 \ 6 \ 7 \ 7]$$

Then the output signal from the Clipping stage of the DAC/ADC, will be the following:

$$X2 = [3 \ 3 \ 5 \ 6 \ 7 \ 7]$$

### 4.2.2.3.2 Quantization Stage

The next step is the quantization stage, Figure 4.25, where the input signal is adjusted to the resolution values of the DAC/ADC.

![Quantization stage](image)

**Figure 4.25** Quantization stage

Firstly, the Dynamic Range ($DR$) and the quantization level parameters ($V_{level}$) are defined as follows.

$$DR = V_{max} - V_{min} ; \#levels = 2^N ; V_{level} = \frac{DR}{2^N}$$

Now the next step is the assignation of the levels to the input vector values, $X_2$, following the sequence:

- Calculate the number of quantization levels for every vector element

$$M = \text{round} \left( \frac{X_2 - V_{min}}{V_{level}} \right)$$
where $M$ is a vector which contains the number of levels per each position of the input vector $X_2$.

- Calculate the output signal which the M level assigned:

$$y = M \cdot V_{level} + (V_{min})$$

where $y$ is the final output vector after the quantization stage.

### 4.2.3 Results of IM/DD RF demo

The results of our customized Long-Haul system are the received signal, the constellation, EVM and BER. In the next figures the optical received spectrum and constellation are shown:

![Optical Spectrum RF](image1)
![Constellation](image2)

**Figure 4.26** Received OFDM signal with IM/DD RF demo  
**Figure 4.27** Received Constellation with IM/DD RF demo

With the parameters expressed below, the results obtained with this new IM/DD RF demo are: an EVM of 0.12472928, and a BER of zero:

- Fiber Length=1000 Km.
- Fiber Attenuation=0.2dB/Km
- Bit Rate= 10 Gbps.
- Sample Rate= 40 Gbps.
- Time Window=6.5536 $\mu$s.
- Modulation: 4-QAM.
- Number of FFT carriers=64.
- Cyclic Prefix = 20%
- Carrier Frequency (RF) = 7.5GHz.
- Roll-Off=0.2.
- Equalization=On.

The EVM value obtained with our setup is lower as compared with that in the VPI demo because of the optimized CP extraction, which completely eliminates ISI from the received signal.
4.3 Hermitian Symmetry Demo

In the design of OFDM coding and decoding modules the flexibility to use them in a variety of simulations has been a primary concern. For example, an option to apply the Hermitian symmetry has been incorporated so that the output signal is completely real. This is equivalent to the DMT option in the VPI modules.

The next Figure 4.28 shows the new scenario of an HS OFDM system, where it can be appreciated that RF up/down conversion stage is not present. On one hand, the imaginary part of the Matlab OFDM coder is grounded because it is a null output, as it was explained in section 3.2. On the other hand, in the receiver only one pulse shaping is required to reconstruct the OFDM signal.

![Figure 4.28: OFDM system with HS](image)

Firstly, it is important to know that the parameter $HS$ in the Matlab OFDM coder and decoder must be enable to have a good performance.

Next Figure 4.29 represents the global parameters of the whole HS scenario. These parameters have been designed following the same conditions than in the IM/DD RF demo to accomplish a user-friendly interface and to solve the problem of the limited bits per symbol. Due to the principles of hermitian symmetry, the RF up/down stage is removed, this implies that in the general parameters of the HS demo the $RF$ parameters will be change by $Filtering$ parameters which contains the important features of the filters in the demo. Hence, the global parameters are divided in different groups depending on their functionalities: $Coding$ Parameters, $Filtering$ and $Global$.
### 4.3.1 Matlab OFDM coder and decoder in HS mode

The Matlab OFDM coder and decoder for the HS simulation are the same used in the IM/DD RF mode, but now two new parameters are enabled and visible: the ZP_Guardband and the N_zeros.

#### Matlab OFDM coder in HS mode

![Figure 4.30 Matlab OFDM coder in HS mode](image)

#### Matlab OFDM decoder in HS mode

![Figure 4.31 Matlab OFDM decoder in HS mode](image)

#### Table: HS System parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BpS</td>
<td>2</td>
</tr>
<tr>
<td>CP</td>
<td>0</td>
</tr>
<tr>
<td>N_FFT</td>
<td>64</td>
</tr>
<tr>
<td>ZP_Guardband</td>
<td></td>
</tr>
<tr>
<td>CarrierFrequency</td>
<td>1.5*(BitRateDefault/BpS)</td>
</tr>
<tr>
<td>RotOll</td>
<td>0.2</td>
</tr>
<tr>
<td>TimeWindow</td>
<td>(2^15)*(BpS/BitRateDefault)</td>
</tr>
<tr>
<td>GreatestPrimeFactorLimit</td>
<td>2</td>
</tr>
<tr>
<td>BandNoiseBins</td>
<td>OFF</td>
</tr>
<tr>
<td>BoundaryConditions</td>
<td>Periodic</td>
</tr>
<tr>
<td>LogicalInformation</td>
<td>ON</td>
</tr>
<tr>
<td>SampleModeBandwidth</td>
<td>1230e9</td>
</tr>
<tr>
<td>SampleModeCenterFrequency</td>
<td>193.1e12</td>
</tr>
<tr>
<td>SampleRateDefault</td>
<td>(2^3)*(BitRateDefault/BpS)</td>
</tr>
<tr>
<td>BitRateDefault</td>
<td>10e9</td>
</tr>
</tbody>
</table>

Figure 4.29 HS System parameters
- When HS is in On mode, a new parameter is visible, ZP_Guardband. This parameter selects the possibility of using a zero padding to emulate the RF up/down conversion. Once ZP_Guardband is enabled, the number of zeros ($N_{zeros}$) is visible, and it permits to define the number of zeros between the optical carrier and the OFDM sideband signal. If set to $N_{FFT}/2$ the required guard band for avoiding CD nonlinear distortion is allocated.

In this mode also additional zeros (for example for oversampling) can be inserted by means of the ZP_mask. In this case, these zeros are ordered taking into account the fact that due to HS only half of the total carriers are active carriers, and if in addition we have enabled the ZP_Guardband some subcarriers are already set to zero.

For example, in Figure 4.32 an OFDM system with Hermitian Symmetry, ZP_Guarband=Off, and a ZP_mask = [4 8 12 16 20 24] is represented.

![Figure 4.32 Hermitian symmetry signal with ZP_Mask but without ZP_Guardband](image)

The HS technique distributes the 64 carriers, as it shows in Figure 4.33, where the carrier 1 and 33 will be zero to have the symmetry required in the IFFT/FFT algorithm. Then, the ZP_Mask is added to the signal to null the carriers, knowing that the first sub-channel is zero, so the counter of subcarriers in the ZP_Mask array starts from the second subcarrier, as it shows in Figure 4.32.

Now if a user needs to add the guard band stage and cancel some subcarriers inside the information bandwidth, just enabling the ZP_Guardband parameter and a ZP_Mask will be enough. When the ZP_Guardband is enabled automatically the quarter part of the total number of carrier will be zero. For this reason, the ZP_Mask array must be start at least in the $1 + \frac{1}{4} N_{FFT}$ carrier. In Figure 4.33 an example is shown:
4.3.2 Results of Hermitian Symmetry simulation

The results of our Hermitian Symmetry demo are shown through the representation of the received signal and the constellation, and through the calculation of the EVM and the BER. The following figure shows the constellation obtained:

The EVM of this Hermitian Symmetry demo is 0.09982, and the BER is zero with the parameters:

- Fiber Length=50 Km.
- Fiber Attenuation=0.2dB/Km
- Bit Rate= 10 Gbps.
- Sample Rate= 40 Gbps.
- Time Window=6.5536 µs.
- Modulation: 4-QAM.
- Number of FFT carriers=64.
- Cyclic Prefix = 20%
- ZP_Guardband = On with \( N_{\text{zeros}} = \frac{N_{\text{FFT}}}{4} - 1 \).
- Roll-Off=0.2.
- Equalization=On.

These results obtained in this kind of simulations can’t be compared with the IM/DD RF demo because HS demo send a quarter of the information due to the symmetry among subcarriers and zero padding for the guard band. If we want to have same bit rate efficiency, the parameter BitRateDefault will be 4 times higher to transmit the same load information.
CHAPTER 5. Optimization Algorithms

In the simulation scenarios which were the main focus of previous chapters, the quality of an OFDM link was quantified in terms of EVM and SER in the VPI demo, and also in terms of BER in the case of the Matlab demos. In an optical access network the goal is set in optimizing the user base served for given reach and bit rate while maintaining quality above a given threshold. In the context of fiber access networks $BER = 10^{-3}$ is considered a target BER since after application of Forward Error correction (FEC) codes it leads to the required $10^{-9}$ quality threshold.

To simulate that in VPI takes the try and error of different attenuations until the $BER = 10^{-3}$ is obtained. This process can be carried out by VPI automatically through script programs. The language accepted by VPI for such programming is Tcl/Tk.

In this section, the design of scripts programs to automate the calculation of power-budget curves in optical fiber networks is described.

In the next figure the relationship between the Simulation Script and the GUI Script is shown.

![Figure 5.1 Simulation Script and the GUI Script in VPI](image)

The Tool Command Language ($Tcl$) is a powerful programming language, suitable for a wide range of uses as web and desktop applications. $Tcl$ is a mature yet evolving language that is truly cross platform, easily deployed and
highly extensible. On the other hand, Tk is a graphical user interface toolkit that takes developing desktop applications to a higher level than conventional approaches. [13]

To execute a script in VPI the user must select in the Toolbar the option Tools, and then choose the Run function. After that, a new window called Submit Simulation Job is opened. Then the user must select the Edit Script button and the Script Editor is opened to write the script.

![Figure 5.2 Script Editor in VPI](image)

When a user opens the Script Editor, the run command is shown, which is the most important command because it permits to execute the schematic system a given number of times, just one in the example in the figure. The script editor window (Figure 5.2) is the graphic interface where the Tcl instructions have to be inserted. They may be directly typed by the users or loaded from a text file.

On the other hand, a user can automate far more complex processes with Simulation Scripts, to save time and to allow simulations to run without supervision. For example:

- Simulations can run until a goal is reached.
- Data from simulations can be sent to a list of files.
- Data for simulations can be extracted from files.
- Parameters can be swept in almost any way.
- Custom optimization routines can be placed around a simulation.
In this thesis several script programs have been written to study the behaviour of the IM/DD RF and the Hermitian Symmetry schemes. In the next sub-section, the results of optimization scripts are given.

5.2 Results of Scripts

In the next section, the results of a power budget curve against fiber length using scripts of the IM/DD RF demo and a Hermitian Symmetry scenario are shown.

After the insertion of the BER vs FiberLength.txt script, Annex C.1, in VPI and running the simulation, a new window appears asking for the minimum length, maximum length and the length resolution to start the sweep mode, see Figure 5.3. When the sweep is finished the result of the simulation is plotted in a graphic.

![Figure 5.3 Menu window for typing the limit inputs lengths](image)

Firstly, a sweep simulation script is executed to represent a graphical view taking into account the fiber distance against the BER. This study will permit to know the maximum distance that the transmitter and the receiver can be separated to obtain a desired BER, and limit the next study, Attenuation versus Fiber Length.
On one hand, in Figure 5.4, the maximum distance obtained with a double side band signal (DSB) in order to send the information is 34.36 km. On the other hand, Figure 5.5, using a single side band (SSB) it reaches a distance equal to 72.88 km.
In Figure 5.6, the maximum distance which can achieve is 19.84 km using a DSB signal in HS demo. In Figure 5.7, a SSB signal arrives to a distance equal to 48.74 km.

Secondly, when the maximum distance is obtained, the next step is to execute the *Optimization Script.txt*, in Annex C.2, which will represent the power budget against fiber length. After loading the script and running the job, a new window appears, to set the parameters to be optimized such as the desired BER, the minimum length, the maximum length and the resolution to analyse.
Figure 5.8 Optimization window

Figure 5.9 Users Available Power vs Fiber Length to obtain $BER = 10^{-3}$ in IM/DD RF demo; DSB signal; CP=0; N_FFT=64 carriers; Roll-Off=0.2; $\alpha = 0.2 \text{ dB/Km}$; Bit Rate=10Gbps
Figure 5.10 Users Available Power vs Fiber Length in IM/DD RF demo; SSB signal; CP=0; N_FFT=64 carriers; Roll-Off=0.2, $\alpha = 0.2 \, DB/Km$; Max.Length at $BER = 10^{-3}$; Bit Rate=10Gbps

In Figure 5.9 and Figure 5.10, the attenuation against the fiber length between users in the IM/DD RF demo is represented, which determines the capacity of multiplexing users in each fiber distances.

Figure 5.11 Users Available Power vs Fiber Length HS demo to obtain $BER = 10^{-3}$; DSB signal; CP=0; N_FFT=256 carriers; Roll-Off=0.2, $\alpha = 0.2 \, DB/Km$; Bit Rate=40Gbps
The Attenuation value obtained in each graphic is a factor of 2, which defines the number of users that it is possible to multiplex in each scenario. Being the conversion:

\[ \sim 3.5 \text{dB} \implies \text{factor } 2 \text{ of users} \]  

For example, in Figure 5.11 at 10 km of distance the user available power is around 12 dB’s. If the previous approximation is fulfilled the total number of users for a HS simulation with 256 number of carriers, roll-off equal to 0.2 and transmitting over a fiber optic whose attenuation losses are $0.2 \text{dB/km}$ is:

\[ \frac{12}{3.5} \approx 3 \implies 2^3 = 8 \text{ users} \]  

Then the maximum number of users is 8,
CONCLUSIONS

This Master thesis has provided a study of the main concepts about optical OFDM systems based on IM/DD techniques using the VPI software as a tool to develop system simulations.

The chromatic dispersion has been identified as the main impairment for the OFDM signal transmission through the fiber. Three basic effects on the signal have been analysed: amplitude fadings, nonlinear distortion and phase noise, which have seen to be solved respectively by SSB filtering, guard-bands, and use of pilot tones, respectively.

Two strategies for transmission of OFDM signals have been described and studied: RF electrical IQ up and down conversion and the use of base band Hermitian Symmetry (DMT) kind of OFDM.

For the simulation of RF eIQ IM/DD optical OFDM systems, VPI features a built-in demo scenario. The use of this demo is very restrictive, because a procedure to calculate the equalizer coefficients is not available. On the other hand, only EVM and SER and not BER quality measures are provided, only power of two values of the QAM order are allowed, and the definition of galaxies and global parameters is not optimized to provide a user-friendly environment. Additionally, the coder and decoder modules are locked in VPI so that changes in code are not allowed.

A new eIQ IM/DD optical OFDM system simulation demo scenario has been designed. New OFDM coder and decoder modules have been programmed in Matlab exploiting the VPI Co-Simulation feature, and the user-friendliness of the demo has been improved by making use of the global variables VPI functionality.

The new Matlab OFDM coder and decoder are open modules which allow to follow and understand the operations performed over the signal and to make changes to the code. Besides the functionalities observed in the VPI modules they have included improvements, such as the display of BER results, a procedure for automatic calculation of the equalizer coefficients through training sequences, a flexible zero carrier insertion feature, and arrangement of global variables so that any value of $\text{BitsPerSymbol}$ is accepted.

The Matlab coder and decoder modules have also been used in an optical Hermitian Symmetry optical OFDM system simulation demo scenario, in which again the user-friendliness has been a priority.

Furthermore, since the interest in optical networks design is primarily on the power budget allowed for a fixed value of BER, the use of script program in $\text{Tcl/Tk}$ language has allowed to automate an otherwise tedious and long simulation procedure. The scripts are able to plot graphics with the results of the sweeping and optimization of different parameters in the scenario.
FUTURES LINES

The main results of this Thesis have been very efficient and user-friendly scenarios for the analysis of optical OFDM systems using IM/DD techniques. Similar studies that consider more advanced optical OFDM systems, based on optical IQ modulation and coherent detection, are found of interest for future works.

Phase noise correlation between the optical carrier and the sidebands makes IM/DD systems very robust against phase noise fluctuations and therefore pilot tones-based phase compensation has not been required in this work. It would be convenient to add this feature to the Matlab decoder to enable simulation of these techniques.

Presently the Matlab coder and decoder OFDM modules work with a fixed QAM modulation level which is the same for all subcarriers. In order to extend the coder and decoder capabilities, an option for independent selection of the QAM level of each subcarrier could be added.

On the other hand, only point to point systems have been considered in this work, extension to multiusers environments is also an interesting future line of research.
ACRONYMS

- **Accordance** - A Novel OFDMA-PON Paradigm for Ultra-High Capacity Converged Wireline-Wireless Access Networks
- **ADC** – Analogue to Digital Converter
- **ADSL** – Asymetric Digital Subscriber Line
- **BER** – Bit Error Rate
- **CD** – Chromatic Dispersion
- **CMOS** – Complementary Metal Oxide Semiconductor
- **CP** – Cyclic Prefix
- **DD** – Direct Detection
- **DFT** – Discrete Fourier Transform
- **DML** – Direct Modulated Laser
- **DMT** – Discrete Multi-Tone
- **DSB** – Double side Band
- **DVB** – TV Digital Video Broadcasting
- **eIQ** – Electrical In-phase Quadrature
- **E/O** – Electrical to Optical
- **EVM** – Error Vector Magnitude
- **FDM** – Frequency Division Multiplexing
- **FFT** – Fast Fourier Transform
- **HS** – Hermitian Symmetry
- **ICI** – InterCarrier Interference
- **IFFT** – Inverse Fast Fourier Transform
- **IM** – Intensity Modulation
- **IM/DD** – Intensity Modulation/Direct Detection
- **IQ** – In-phase and in-Quadrature
- **ISI** – InterSymbolic Interference
- **LTE** – Long Term Evolution
- **MZM** – Mach-Zehnder Modulator
- **O/E** – Optical to Electrical
- **OFDM** – Orthogonal Frequency Division Multiplexing
- **OFDMA** – Orthogonal Frequency Division Multiplexing Access
- **o-OFDM** – Optical OFDM
- **PON** – Passive Optical Network
- **PRBS** – Pseudo-Random Bit Sequence
- **QAM** – Quadrature Amplitude Modulation
- **QP** – Quadrature Point
- **RF** – Radio Frequency
- **SER** – Symbol Error Rate
- **SSB** – Single SideBand
- **SSMF** – Standard Single Mode Fiber
- **Tcl/Tk** – Tool Command Language/Tool Kit
- **TDMA** – Time Division Multiplexing Access
- **VPI** – Virtual Photonics Inc.
- **ZP** – Zero Padding
REFERENCES

[1] Neda Cvijetic, *OFDM for Next Generation Optical Access Networks*


