POLITECNICO DI TORINO

Master Degree in Mechatronic Engineering

Master's thesis

Fiber Optic Channel Design for Dynamic Reconfiguration in SRAM-Based FPGA Satellite Payloads

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Chapter 1

Introduction

Fiber optic technology has become an integral component of modern communication systems due to its unparalleled advantages in high-speed data transmission, bandwidth capacity and immunity to electromagnetic interference. Over the past few decades, fiber optics have undergone rapid advancements, evolving from a innovative research concept to a key component of global telecommunications, networking and high-performance computing. Today, their application extends beyond terrestrial networks to critical domains such as satellite payloads, where robust and efficient communication channels are essential for mission success.

The transition to optical communication channels in space systems, particularly in satellite payloads, is driven by the need to overcome intrinsic limitations in traditional electronic communication systems. Optical fibers offer significantly higher data rates, reduced weight and the ability to transmit over longer distances without significant signal degradation. These features make fiber optics an attractive choice for the dynamic and resource-constrained environment of satellite systems. For satellite payloads, such as those implemented on SRAM-based Field-Programmable Gate Arrays (FPGAs), optical channels support dynamic reconfiguration, enabling adaptability and efficient use of resources to meet the varying demands of space missions.

However, as with any transmission medium, optical channels are not immune to errors. In the space environment, factors such as radiation, temperature extremes and mechanical stress can affect the integrity of transmitted signals. Errors during transmission can lead to corrupted data, degraded performance or even mission failure. This makes error mitigation a critical design consideration.

Ensuring the safety and reliability of optical communication in satellite payloads requires robust error detection and correction mechanisms. These mechanisms not only enhance data integrity but also improve the resilience of the system to harsh environmental conditions. By mitigating transmission errors, designers can reduce the risk of system failures, enhance mission longevity and ensure the continuous operation of critical satellite functions.

1.1 Motivation

This thesis explores the design of fiber optic channels for dynamic reconfiguration in SRAM-based FPGA satellite payloads, with a focus on optimizing performance while addressing error mitigation. The research aims to contribute to the development of more reliable and efficient optical communication systems, paving the way for advanced space technologies that meet the growing demands of modern satellite missions. Specifically, this work aims to identify a simpler solution to mitigate errors, focusing on enhancing system performance while minimizing complexity. The motivation behind this research stems from the increasing need for robust communication systems in space, where traditional methods often fall short due to harsh environmental conditions and the dynamic nature of satellite operations. As satellite payloads become more complex and mission requirements evolve, there is a growing need for adaptable, efficient and error-resilient communication systems that can handle high data rates without compromising reliability. By simplifying error mitigation techniques, this work seeks to offer practical solutions that address these challenges, improving satellite system performance and contributing to the success of future space missions.

1.2 Contribution

This thesis builds upon the foundation of existing research and studies in the field of optical communication systems and their application in satellite payloads. The primary contributions of this work lie in the detailed analysis of communication processes in fiber optic channels and the identification of the effects of errors in these systems. It goes deep into the process of transmission of data through an optical channel, by introducing and simulating two different types of dispersion: Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD). This works contributes to giving new insights into error mitigation techniques, by experimenting a new and simpler method to do it, exploiting the Least Mean Square (LMS) filter. The outcomes of this research provide a foundation for designing more reliable and efficient satellite communication architectures.

1.3 State of the art

The issue of errors in optical communication systems, particularly in satellite applications, has been the subject of extensive research in recent years. Mitigation techniques are not unique, as they depend on the structure of the transducers used. However, they all share a common principle: incorporating additional information into the system to help identify and correct fluctuations caused by the measured variables.

Among the various approaches to mitigate these errors, one notable method, proposed into recent resource, combines the use of Dispersion Compensating Fibers (DCF) with Erbium-Doped Fiber Amplifiers (EDFA), Wavelength Division Multiplexing (WDM) and Fiber Bragg Gratings (FBG).

This integrated approach leverages the strengths of each component: DCF compensates for chromatic dispersion, EDFA enhances signal strength over long distances, WDM increases data throughput by allowing multiple wavelengths to transmit simultaneously and FBG provides precise filtering and dispersion management. Together, these technologies create a robust framework to address error-inducing factors in optical systems, ensuring better signal integrity and reliability, particularly in dynamically reconfigurable satellite payloads.

This thesis builds upon such state-of-the-art methodologies to further analyze and propose optimized solutions for error mitigation in fiber optic communication systems for satellites. In particular, the mitigation method suggested in this work concerns mainly the error at the exit of the transmitter side rather than the whole optical channel, that's why it was proposed a easier method compared to those typically found in the literature, which is based on the use of a Least Mean Square filter. Despite its simplicity, this mitigation method effectively achieves its objective by filtering out noise,obtaining the desired and reliable signal. Its efficiency lies in its ability to maintain signal integrity with minimal complexity, making it a practical solution for improving performance without introducing significant overhead.

1.4 General structure

Chapter 1 gives an introduction of this work about motivation, contribution, state of art of the optical world and the need for a method to mitigate errors during the transmission. Chapter 2 gives an overview on optical transmission, explaining what is the optical medium and how does it work. It, also, explore the components of a transmission systems and how do they operate. Chapter 3 is a look inside the OTDR and FPGA world, from the general structure to the specific system used in this thesis. Chapter 4 describes the used methodology to analyze the system and the transmission. In chapter 5 there is an analysis primarily done on the transmitter side to understand how it is affected by errors. Chapter 6 is devoted to experimental results. Finally, chapter 7 proposes a mitigation methodology to overcome errors.

Chapter 2

Technical background

2.1 Optical transmission

2.1.1 Transmission systems

A transmission system is the technological mechanism that allows the passage of information from a source called transmitter to a destination called receiver. This transfer occurs through a transmission medium that can be electric (cables), wireless (radio waves), fiber (light) and air (light, li-fi). Transmission media can be divided into 2 large categories: physical carriers and radio carriers. The former are classified as such when a continuous connection is established between the transmitting and receiving ends or between various components of the devices involved in the transmission. Copper cables and optical fibers fall under this category. Radio carriers, on the other hand, encompass all the equipment within both transmission and reception centers, as the medium consists of open space. This category includes terrestrial and satellite radio links and in the future, li-fi links will also be included.

In general, transmission media attenuate signals based on both the distance traveled and the signal's frequency and transmit signals at speeds that are proportional to their frequencies. As a result, for any transmission medium, the bandwidth decreases as the length of the medium increases.

The selection of the transmission medium is crucial and must align with the type of transmission system in use, ensuring the transfer of signals within a specific frequency range. Transmission media for analog signals must preserve the original waveforms over time, while those used for digital transmissions must enable accurate recognition of the value $x(t)$ at any given moment to ensure proper signal reconstruction.

Optical fiber stands out as the transmission system with the greatest potential for future advancements. It offers a combination of low cost, exceptionally high transmission capacity and light weight for the same bandwidth (two fibers outperform 1,000 twisted pairs, 100 kg/km versus 8,000 kg/km). Additionally, optical fiber is completely immune to electromagnetic interference and highly resistant to unauthorized eavesdropping.

2.1.2 Optical concepts

Optics is a branch of physical science that deals with the propagation and behavior of light and its interaction with materials. In a general sense, light is that part of the electromagnetic spectrum that extends from X-rays ($\approx 0.1\, \text{nm}$) to millimeter waves

($\approx$ 1 mm). The visible spectrum, which produces the sensation of vision, ranges from approximately 400 nm to 750 nm.

Light can range from white light to lasers, exhibiting characteristics such as collimation, coherence and Lambertian distribution. It encompasses a variety of colors, shapes and distributions. One definition of light is "the electromagnetic radiation that can be perceived by the human eye." Another perspective describes light as radiant energy that interacts with the retina to enable vision. The human eye is remarkable in its ability to perceive color and adjust to a brightness range spanning more than six orders of magnitude automatically.

Humans can only detect light from a limited portion of the optical spectrum, specifically the visible spectrum. The remainder falls into the ultraviolet (UV) and infrared (IR) regions. Many animals utilize their ability to detect infrared light for hunting, while insects rely on UV reflection to locate sources of pollen.

Light is primarily characterized by its wavelength, which is typically measured in nanometers (nm). Each wavelength corresponds to a specific frequency, calculated by dividing the speed of light by the wavelength. The human eye is most sensitive to light at a wavelength of 555 nm, equivalent to approximately 5.4×10^{14} Hz. This high frequency, along with its inherent bandwidth, makes light an excellent information carrier in optical fibers.

Although these near-visible wavelengths are invisible to us, advancements in technology over the past few centuries have enabled the development of electro-optical sensors for their detection and measurement, new light sources for their production and optical fibers for their transmission.

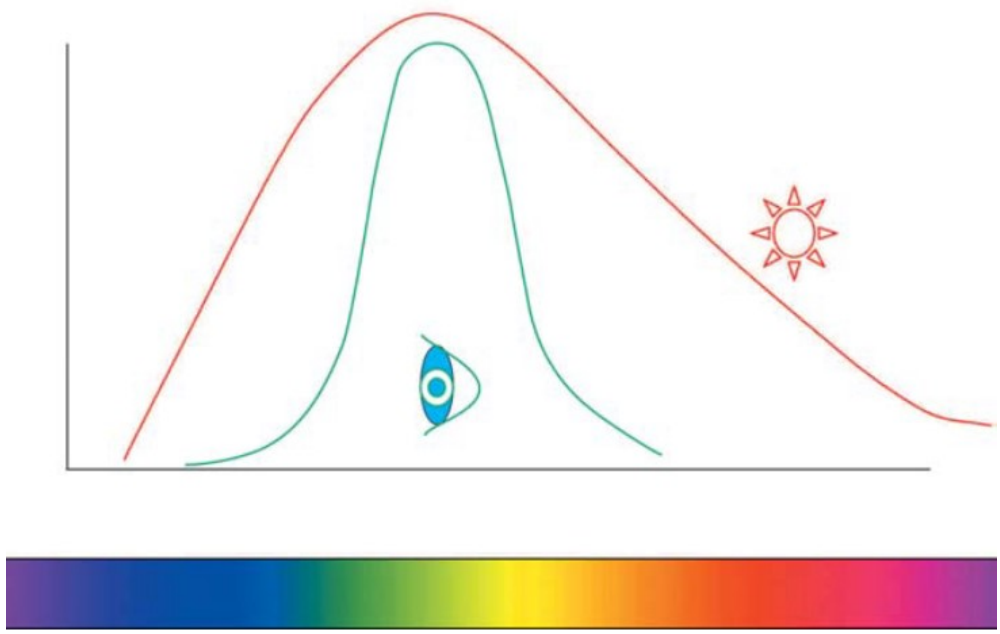

Figure 2.1: Light and Nature

Two additional properties of light that are important in many areas of optics are the spatial distribution of the light and the coherence of the lightwaves. The spatial distribution describes the direction(s) that the light is traveling. If it appears uniform in all directions, that is it has uniform brightness from any viewing angle, it is called Lambertian. The other extreme is collimated light, which essentially travels in only one direction such as a laser. The coherence of light refers to the way the light waves are ordered or phased with each other. Common incandescent lamps are incoherent (random phase) while lasers are coherent (in-phase). [**1**]

2.1.3 The optical medium

At the beginning, the development of optical fiber was initially hindered by the existence of the glass that was initially thought to be the perfect conductor for light signals but then dismissed due to excessive losses observed during disappointing experiments in the 1950s in which a glass cylinder immersed in air was considered as the transmission medium. The major unknowns that prevented the advancement of optical transmission were twofold: weak light sources and high losses in the transmission medium. The breakthrough came in 1960 when Theodore H. Maiman developed and patented the first laser, using a ruby wrapped in a glass spiral and enclosed in a hollow aluminum cylinder. This discovery breathed new life into the quest for a transmission medium that could fully exploit the power of lasers. The solution arrived in 1966 when Kao and Hockman proposed placing the glass cylinder inside another cylinder with a much lower reflective index. This marked the birth of the predecessor to modern optical fiber. Despite these advancements, signal losses remained significant, around 1000 dB/km. To understand how the transmission medium (glass) was improved, it's necessary to have a look at the chemical and physical properties of the material itself.

Glass has an amorphous, non-crystalline structure and, at dimensions of just a few nanometers, its structure becomes entirely random. Common glass, produced from silica (quartz powder), sodium or calcium carbonates and lead oxides, is poorly transparent. In the early 1970s, a technique known as Chemical Vapor Deposition (CVD) was developed. The initial technical improvements to the transmission medium reduced signal losses to around 20 dB/km. This was a significant starting point, though still far from today's values of 0.2–0.22 dB/km for commercial fibers and 0.18 dB/km for "cutting-edge" fibers.

The current structure of an optical fiber consists of a central core designed to carry light signals. Surrounding the core there is the cladding, a thin layer that aids in guiding the light through the fiber. Over the cladding, a protective coating is applied to safeguard the core. To prevent damage, especially during installation, a strength member typically made of steel, fiberglass or aramid yarn is included to reinforce the fiber core. The outermost layer, known as the cable jacket, protects the cable from environmental damage as shown in Figure 2.2. Additionally, the outer jacket is often color-coded to indicate the type of fiber optic cable. While this describes the basic structure of a fiber optic cable, variations in design exist depending on the specific type of cable. [**1**] [**2**] [**3**]

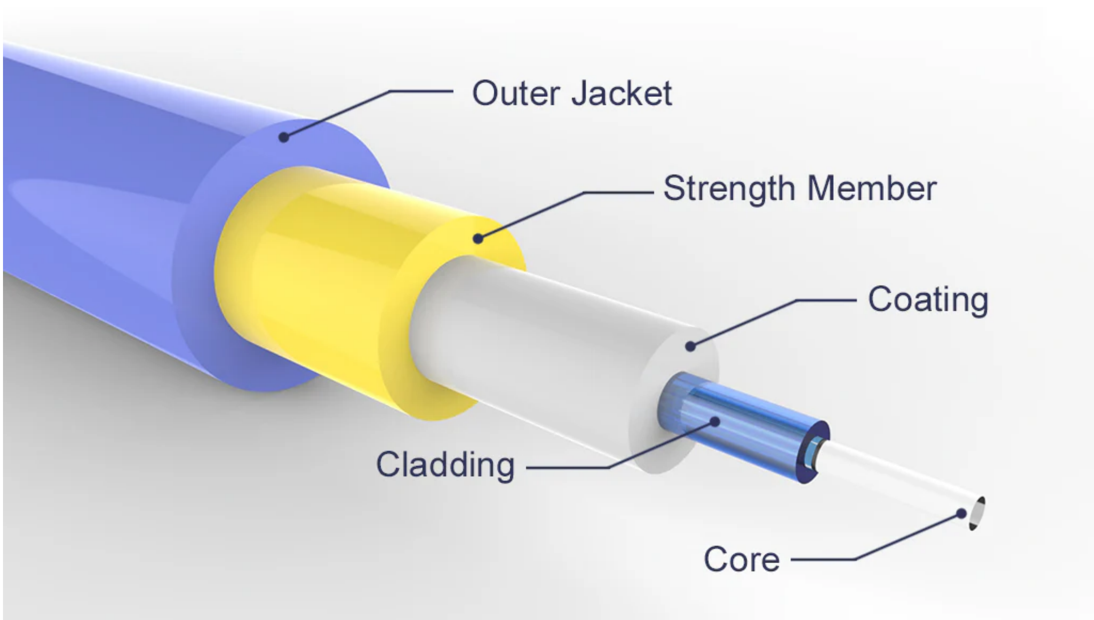

Figure 2.2: Optical fiber's structure

As with all data transmission systems, the construction of the material is the first step in determining communication performance. The two key factors that significantly impact transmission performance are signal losses and dispersion induced by the source. Given that the optical signal operates at a carrier frequency of around 100 THz and considering that the usable bandwidth is approximately 1–2% of the carrier frequency, it becomes clear that it is theoretically possible to develop communication systems with an available bandwidth exceeding 1 THz.

Advances in fiber manufacturing processes have significantly improved transmission performance within a relatively short time. This progress can be summarized in five generations:

First generation: Developed in the late 1970s, with a bit rate of 45 Mb/s and a wavelength of 0.8 m, the repeater distance was approximately 10 km.

Second generation: Early 1980s, operating at a wavelength of 1.3 m. Initially, multimode fibers were used but they faced limitations due to modal dispersion. Later, with single-mode fibers, bit rates of 1.7 Gb/s were achieved, with transmission distances between repeaters of approximately 50 km.

Third generation: Introduced in 1990, these systems operated at wavelengths of 1.55 m with losses of less than 0.2 dB/km. They achieved bit rates exceeding 4 Gb/s and repeater distances over 100 km. These systems used photodetectors to regenerate the optical signal by first converting it into an electrical signal and then retransmitting it in optical form.

Fourth generation or the generation of optical amplifiers: These systems employed wavelength division multiplexing (WDM) techniques. In the 1990s, they reached bit rates of 5 Gb/s over distances of 14,300 km.

Fifth generation: Soliton systems that enabled single-channel capacities of 20 Gb/s over transoceanic distances.

2.1.4 Optical transmission operation

The science of fiber optics deals with the transmission or guidance of light along transparent fibers of glass, plastic, or a similar medium (through the core surrounded by the cladding layer). The phenomenon responsible for the optical fiber or light-pipe performance is the law of Total Internal Reflection (TIR). Total internal reflection occurs when light traveling from a medium of higher refractive index to a lower refractive index hits the boundary at an angle greater than the critical angle (θ_c), this mechanism allows the light to travel long distances with minimal loss. The refractive indices of the core (n_1) and cladding (n_2) determine how light is guided through the fiber. The critical angle can be computed through Snell's law:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \tag{2.1}$$

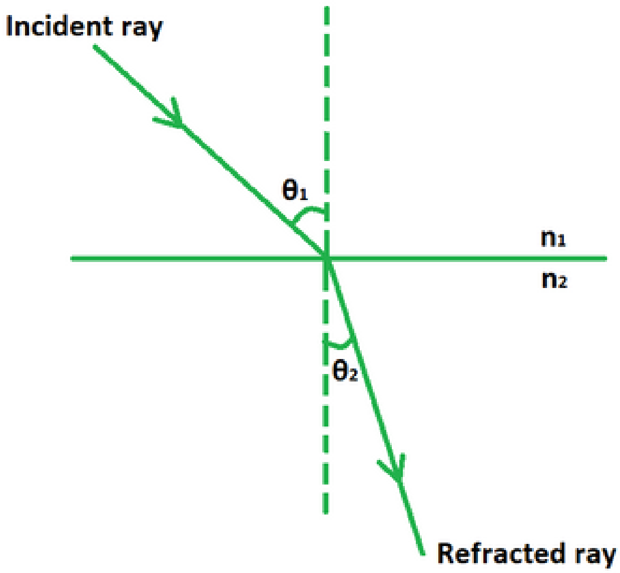

Figure 2.3: Snell's principle

In this way it results:

$$\theta_c = \arcsin\left(\frac{n_2}{n_1}\right) \tag{2.2}$$

having that $\theta_2 = 90°$. [**4**]

As it can be seen in Figure 2.4, the behavior of optical signals in fiber optics is significantly influenced by the fiber's cross-sectional geometry and the mode of propagation.In fiber optics, the term "mode" refers to a stable propagation state of light down the fiber. Fibers can have any number of stable propagation states (modes), giving rise to two basic types of optical fibers, multi-mode and single-mode. Multi-mode fibers can be further broken down into two subcategories, step-index and graded-index.

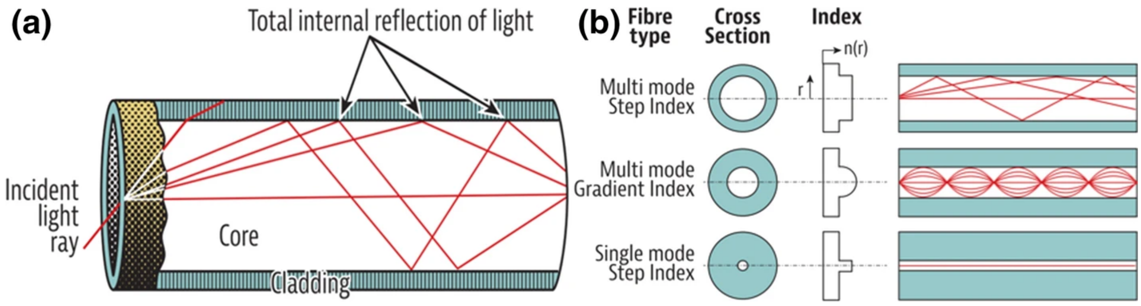

Figure 2.4: Optical fiber working principle

Single-mode fibers have a small core diameter, typically around 5-10 μm. This design allows only one mode of light to propagate through the fiber. This mode essentially travels straight through the fiber and thus is not subject to the pulse spreading seen in multi-mode fiber due to different path lengths. The advantages of single-mode fibers include:

- Reduced Dispersion: Because only one mode is allowed, modal dispersion is eliminated, leading to higher signal integrity and bandwidth over long distances.
- Higher Bandwidth: Single-mode fibers can support higher bandwidths because they are less susceptible to signal degradation.
- Longer Transmission Distances: The reduced losses and lack of modal dispersion enable longer distances between repeaters.

Multi-mode fibers have, on the other hand, a larger core diameter, typically ranging from 50 to $>$ 2000 μm, allowing multiple modes of light to propagate simultaneously. While this design facilitates higher light-carrying capacity, it also introduces some limitations: as one pulse spreads, it eventually interferes with neighboring pulses, distorting the transmission signal, which can limit the effective bandwidth. The longer the fiber length the more severe this pulse spreading will become. The advantages of multi-mode fibers include:

- Shorter Transmission Distances: Due to increased losses and dispersion, multi-mode fibers are generally used for shorter distances (up to a few kilometers) compared to single-mode fibers.
- Lower Cost: Multi-mode fibers and associated components tend to be less expensive than their single-mode counterparts, making them suitable for many local area networks (LANs).

The light signals used in optical fibers are typically generated by lasers or light-emitting diodes (LEDs) that are super small, allowing them to be easily coupled to the tiny cores of optical fibers. Moreover, their small emitting area matches well with the small diameter fiber cores. This maximizes light injection into the fiber. The power of the transmitted optical signal (P_{out}) can be expressed as:

$$P_{\text{out}} = P_{\text{in}} \cdot \eta \tag{2.3}$$

where P_{in} is the input power and η is the efficiency of the optical source.

2.1.5 Factors that influence the optical fiber

Two critical factors influencing the performance of optical fiber transmission are attenuation and dispersion.

Signal Attenuation

Attenuation of optical signals limits the distance in which the signal can travel through optical fiber and can be expressed in decibels per kilometer (dB/km). The attenuation coefficient (α) represents the fraction of power lost per unit length and can be calculated as:

$$\alpha = -10 \cdot \frac{\log_{10}(P_{\text{out}}/P_{\text{in}})}{L} \tag{2.4}$$

where L is the length of the fiber.

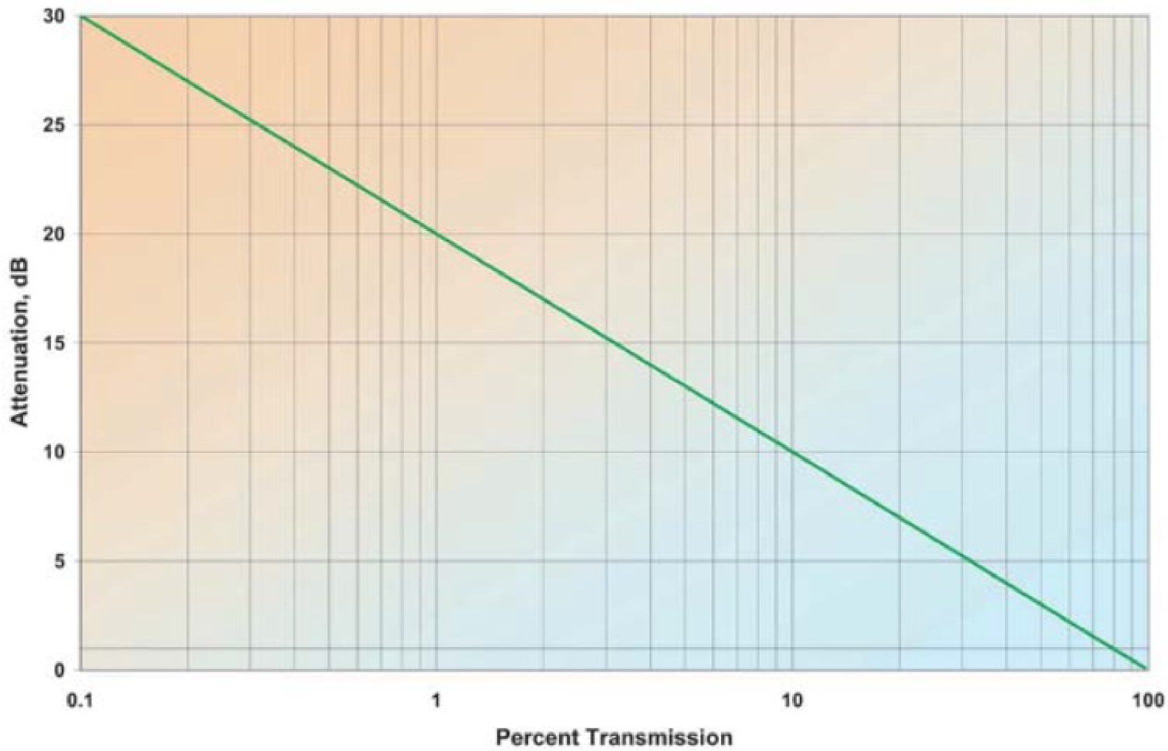

Figure 2.5: Attentuation versus Transmission

Optical loss in fibers, a key limiting factor in optical communication, reduces the average optical power reaching the receiver. It is composed of three main components: intrinsic loss, microbending loss and splicing loss.

Intrinsic loss, primarily due to OH absorption and Rayleigh scattering, follows a λ^{-6} dependency, decreasing with longer wavelengths and depending on the transparency of the optical material. For silica fibers, intrinsic loss is minimal over the 0.8–1.8 μm range, with three communication windows: around 810 nm (20 nm bandwidth), 1300 nm (80 nm bandwidth) and 1550 nm (40 nm bandwidth). Losses at 1300 and 1550 nm are approximately 0.15 and 0.3 dB/km, respectively, making these optimal for current optical communication systems. For "power-hungry" systems, optical or extra-long systems should operate at 1550 nm.

The absorption loss in silica glass primarily consists of ultraviolet (UV) and infrared (IR) absorption tails of pure silica. The IR absorption, resulting from the vibration of the silica tetrahedron structure, causes strong resonances around 8–13 μm, with losses up to 10^{10} dB/km, as shown in the IR curve of Figure 2.6. Overtones and combinations of these vibrations create additional absorption peaks in the lower wavelength range, visible in the UV curve. Impurities, including transition metal ions and OH ions (from water), can also cause spurious absorption within the 1.2–1.6 μm range. However, these impurity-related losses have been significantly reduced in recent years.

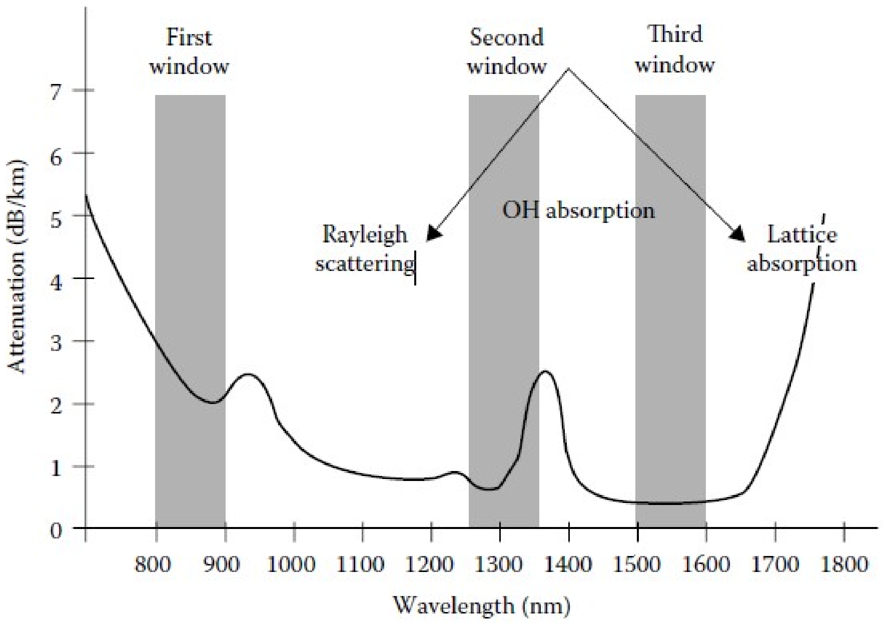

Figure 2.6: Attenuation of silica as a function of wavelength

Microbending loss occurs due to power coupling from the fiber's guided fundamental mode to radiation modes when the fiber axis experiences random, high-frequency bends as it is shown in Figure 2.7. This can arise during the cabling process.

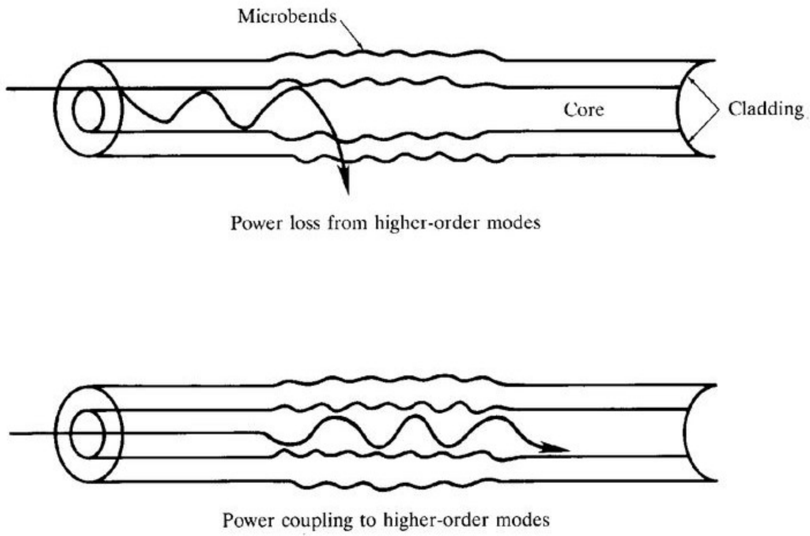

Figure 2.7: Microbending losses

In single-mode (SM) fibers, microbending loss depends on the fundamental mode spot size, r_0: fibers with larger spot sizes are more susceptible to bending losses. Thus, minimizing the spot size is essential for reducing microbending loss.

To form the final transmission link, fibers must be spliced together, here is were the **splice loss** occurs. This loss is due to miss alignment and other splicing process parameters as shown in Figure 2.8. For fiber cables with an average loss of 0.4–0.6 dB/km, splice losses exceeding 0.2 dB/splice significantly reduce the achievable unrepeated distance.Minimizing splice loss is thus crucial in fiber design, as splice loss primarily results from axial misalignment of the fiber core. [**5**] [**6**]

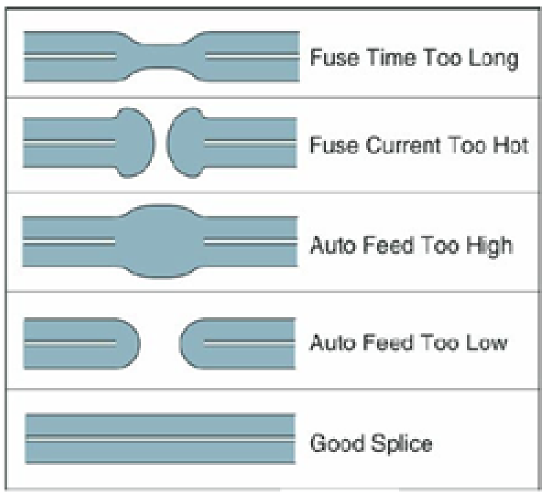

Figure 3

Figure 2.8: Splice losses

Signal Distortion

Dispersion, instead, leads to pulse broadening, which can degrade the quality of the transmitted signal. There are three primary types of dispersion in optical fibers: Chromatic Dispersion, Polarization Mode Dispersion and Waveguide Dispersion.

Chromatic dispersion(CD) occurs because different wavelengths of light travel at different speeds through the optical fiber. This variation in speed causes different spectral components of a pulse to spread out over time, leading to pulse broadening. There are two primary components of chromatic dispersion: material dispersion, which arises from the wavelength-dependent refractive index of the fiber materialand waveguide dispersion, which results from the fiber's core structure and geometry. [7]

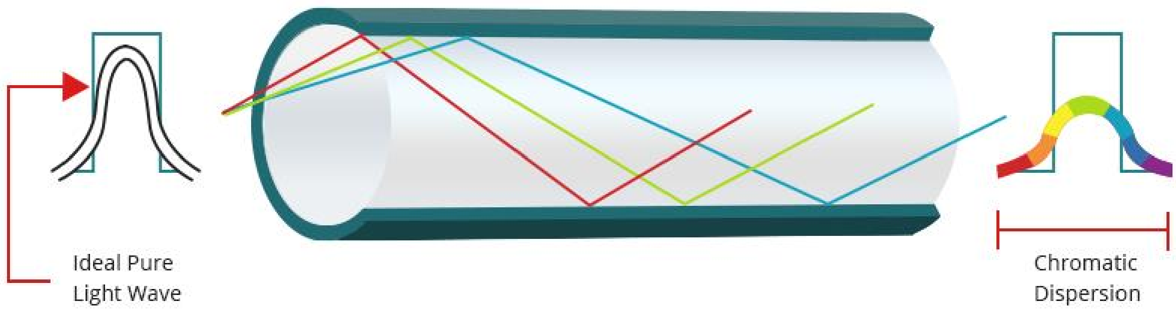

Figure 2.9: Chromatic Dispersion

Polarization mode dispersion (PMD), on the other hand, is caused by random fluctuations in the fiber's birefringence, which leads to different polarization modes propagating at different speeds. This effect introduces variations in the polarization state of light, causing additional pulse spreading and signal degradation. Both types of dispersion need to be carefully managed to ensure high-performance and reliable optical communication systems. [8]

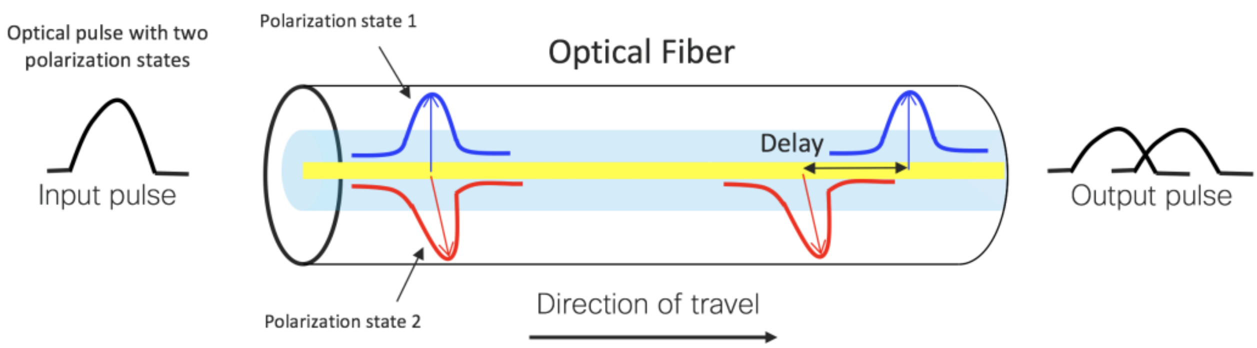

Figure 2.10: Polarization Mode Dispersion

The total dispersion (D) can be computed using:

$$D = D_{\mathrm{c}} + D_{\mathrm{m}} \tag{2.5}$$

where D_{c} is chromatic dispersion and D_{m} is polarization mode dispersion.

Waveguide Dispersion is due to the geometry of the fiber and results in different velocities of the various modes for different wavelengths and, more specifically, to the change in specific group delay of a signal with wavelength in digital communication systems, leading to temporal broadening of the pulse as different spectral components propagate through the fiber at varying speeds. It is the least important of the causes of dispersion and that's why is not taken into account in this thesis. [**1**]

Kerr Effect

The nonlinearity effects in the optical fiber are due to an electro-optic effect, referred to as the Kerr effect, which arises from the dependence of the optical fiber refractive index on the transmit signal power. This characteristic makes the optical fiber channel different from other transmission media used for information transfer. In a linear transmission medium, the information signals are usually perturbed by additive noise, which generally results in channel capacities that monotonically increase with transmit power and a corresponding increase in the signal-to-noise ratio (SNR). However, the detrimental effects of Kerr-induced signal nonlinear distortions grow at a faster rate than the SNR capacity gain at higher launch powers. This, in turn, causes the channel capacity to become a nonmonotonic function of the transmit launch power, with a maximum value at a particular launch power, termed the *optimum launch power*. The achievable transmission rate decreases rapidly beyond this optimal power point as the launch power increases due to the corresponding increase in the Kerr-induced signal nonlinear distortion. The transmission performance of single-channel optical communication systems is primarily limited by the intra-channel Kerr nonlinearity effect. [**9**]

The intra-channel nonlinear interactions can be categorized into three types:

- **Self-phase modulation (SPM)**: the refractive index is modulated by the intensity of the electric field. In amplitude-modulated signals, the phase of the optical signal is also modulated, causing spectral broadening.

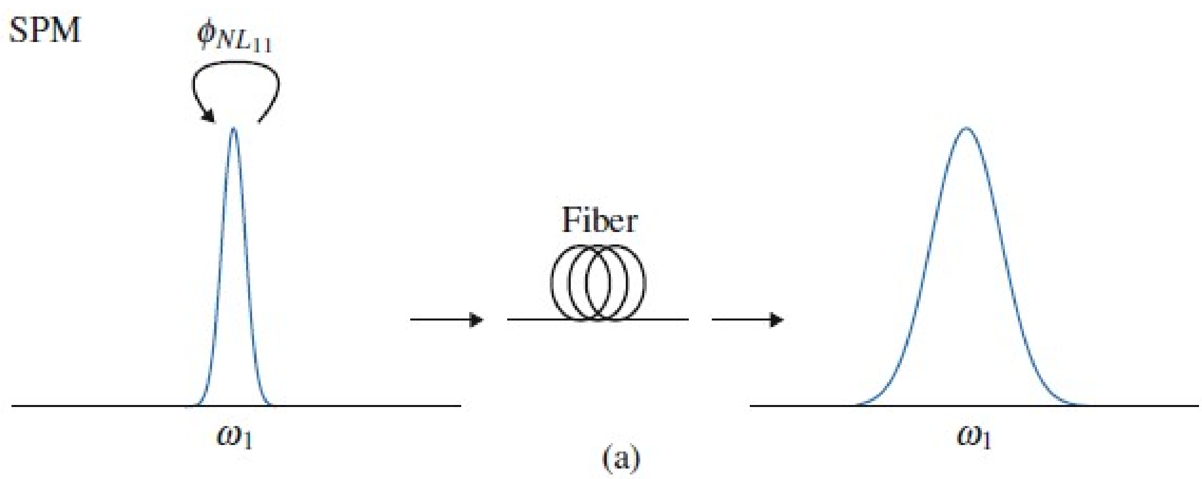

Figure 2.11: Intra-Channel SPM

[**9**]

- **Intra-channel cross-phase modulation (XPM)**: Amplitude variation of a signal at frequency ω_1 generates a pattern-dependent nonlinear phase shift (Φ_{NL12} or Φ_{NL21}) on a second signal at frequency ω_2, causing spectral broadening and impairing transmission.

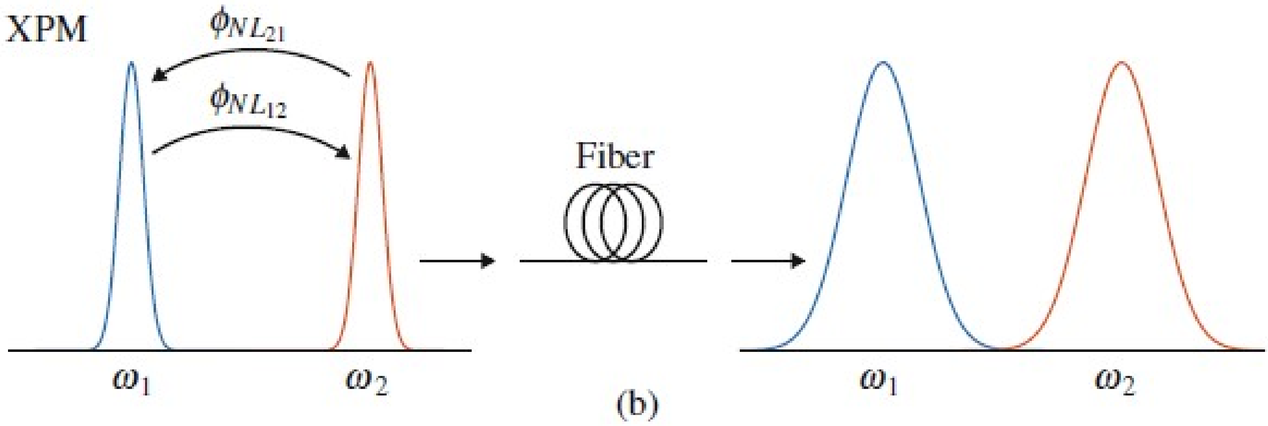

Figure 2.12: Intra-Channel XPM

[**9**]

- **Intra-channel four-wave mixing (FWM)**: Three signals at frequencies ω_i, $\omega_j$and ω_k generate a fourth signal at frequency ω_{ijk} such that $\omega_{ijk} = \omega_i + \omega_j - \omega_k$. If $k \neq i, j$ and $i = j$, the products are referred to as *degenerate*; if $i \neq j$, they are considered *non-degenerate.*

In the recent history of optical fiber communications, the Kerr effect has been studied in various settings, with outcomes identified as self-phase modulation (SPM), cross-phase modulation (XPM), or four-wave mixing (FWM), depending on the number of mixing frequencies involved. The study of these effects has facilitated the design and dimensioning of several generations of optical fiber systems based on on-off keying (OOK) modulation and dispersion management.

However, modern communication systems employing Nyquist pulse shaping and electronic dispersion compensation exhibit properties that favor alternative approaches to studying nonlinearities. These approaches are based on the observation that, in long-distance dispersion-uncompensated systems, nonlinear interference can be effectively modeled as additive white Gaussian noise (AWGN) for system modeling purposes.

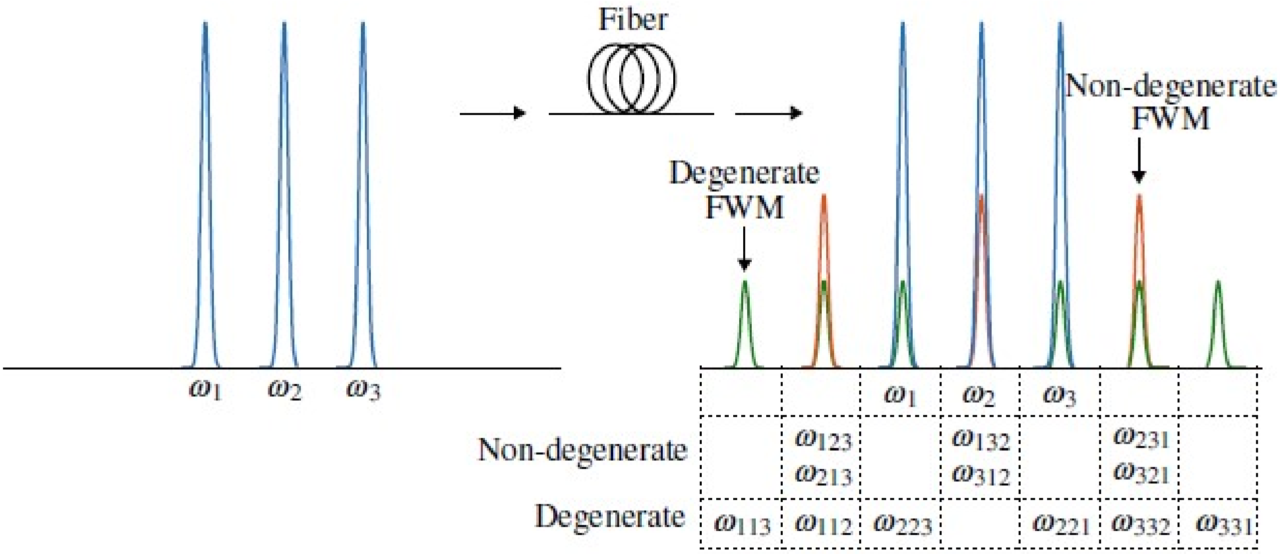

Figure 2.13: Intra-Channel FWM

[9]

It is important to mention that self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM) can be effectively compensated using digital nonlinearity compensation (NLC) techniques known as coherent detection. Coherent detection also facilitates the implementation of advanced forward error correction (FEC) coding techniques and adaptive digital signal processing (DSP) algorithms to counteract time-varying transmission impairments.

2.1.6 Vertical and Horizontal polarization

Another important feature to take into account when talking about light, which is strongly connected to CD and PMD, is the polarization. Light, as an electromagnetic wave, can be polarized in various orientations, with vertical and horizontal polarization being the most common. In optical fibers, polarization affects how light propagates, interacts with the fiber material and ultimately impacts the dispersion of signals.

Polarization refers to the orientation of the electric field vector of a light wave as it propagates through space. In optical fiber systems, the polarization of light can vary and it is generally classified as:

- **Vertical Polarization:** The electric field oscillates in a plane that is perpendicular (vertical) to the horizontal axis of propagation.

- **Horizontal Polarization:** The electric field oscillates in a plane parallel to the horizontal axis of propagation.

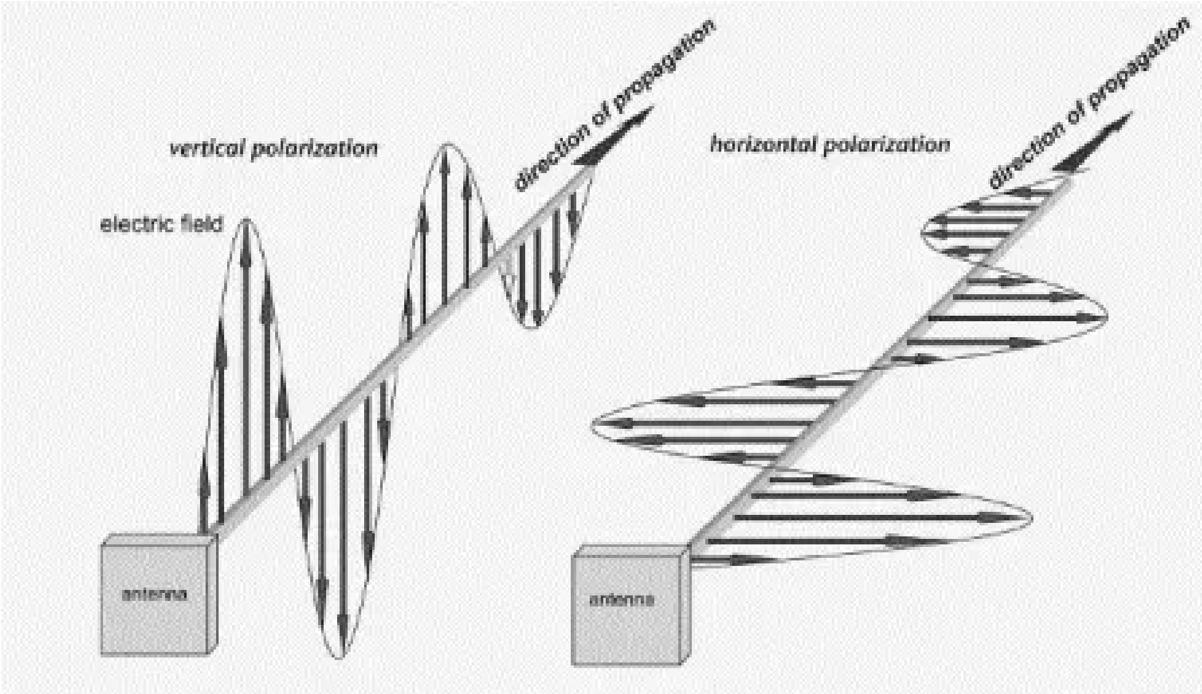

Figure 2.14: Vertical and Horizontal Polarization

In optical fibers, light is typically launched with a certain polarization state, but as it travels through the fiber, this polarization can change due to the interaction with the fiber's physical characteristics, including imperfections, stress and bending. [**10**]

Birefringence is a phenomenon that occurs in optical fibers due to slight asymmetries in the fiber's geometry or material properties. This asymmetry causes the fiber to support different refractive indices for light polarized in the vertical and horizontal directions. As a result, light polarized vertically and horizontally will travel at different speeds, which introduces polarization mode dispersion (PMD).

Polarization mode dispersion is directly related to the polarization states of light in an optical fiber. As vertically and horizontally polarized light travels at different speeds due to birefringence, the two polarization components become misaligned, causing signal distortion. The key aspect of PMD is the **Differential Group Delay (DGD)**, the time difference between the arrival of the two polarization components (vertical and horizontal) at the receiver. This delay introduces signal distortion, as the information carried by the two components arrives at different times. The DGD is mathematically expressed as:

$$\Delta\tau = \frac{L}{c}\left(n_v - n_h\right) \tag{2.6}$$

where:

- $\Delta\tau$ is the Differential Group Delay (DGD),
- L is the length of the optical fiber,
- c is the speed of light in vacuum,
- n_v and n_h are the refractive indices for vertically and horizontally polarized light, respectively.

As the DGD increases with distance, the overlap between the vertical and horizontal polarization states becomes more pronounced, leading to pulse broadening and signal degradation. In high-speed communication systems, PMD can be a significant limiting factor in achieving high data rates over long distances.

In the presence of chromatic dispersion, instead, light waves of different wavelengths experience different delays as they travel through the fiber. When light is polarized vertically and horizontally, these polarization components may also experience different propagation speeds due to birefringence in the fiber, leading to PMD. The interaction between chromatic dispersion and polarization can compound the effects of both, causing complex distortion in the optical signal.

2.2 Optical Signal propagation

In optical fiber communication, the fundamental components responsible for the transmission and reception of data are the transmitter and receiver. Together, they form a crucial link in the optical communication system, enabling the seamless flow of information across vast distances with minimal loss and interference.

2.2.1 The Optical Transmitter

The optical transmitter is the first crucial component in an optical communication system, converting electrical signals into optical signals for transmission through the fiber. The core of the optical transmitter is the **light source**, which generates the optical signal. Common types of light sources used include:

- Light-Emitting Diodes (LEDs): These are widely used for short-distance applications due to their cost-effectiveness and simplicity. LEDs emit incoherent light and are suitable for multimode fiber.
- Laser Diodes (LDs): For long-distance and high-speed applications, laser diodes are preferred. They emit coherent light, which allows for higher data rates and longer transmission distances due to their narrow wavelength.

Another important component of the transmitter is the **modulator**. It controls the light source to encode data onto the optical signal. Modulation techniques may include:

- On-Off Keying (OOK): The simplest form of modulation, where the presence or absence of light represents binary data (1s and 0s).
- Amplitude Shift Keying (ASK), Phase Shift Keying (PSK) and Frequency Shift Keying (FSK): More advanced modulation techniques that allow for greater data rates and increased capacity by varying the amplitude, phase, or frequency of the light signal.

The simplest modulation format is that of intensity modulation. In this format the information carrying current is injected into the optical source and consequence the intensity, that is the square of the field, is modulated. For analogue modulation the optical source is biased at a given point and the modulation current is superimposed on it. For digital modulation the device is based either around zero (LEDs) or at threshold (lasers). If lasers are biased at zero current then there is significant turn on delay, which impairs the performance at high bit rates. The typical high speed digital modulator is current mode logic otherwise known as the emitter coupled switch. The advantage of this configuration is the large bandwidth available and the ability to control the modulation current through the constant current source at the tail of the switch. In addition to the actual modulator an optical transmitter is required to maintain a constant output optical power. This is far more important for lasers which are very sensitive to temperature. A typical arrangement to maintain the output power constant is shown in Figure 2.15

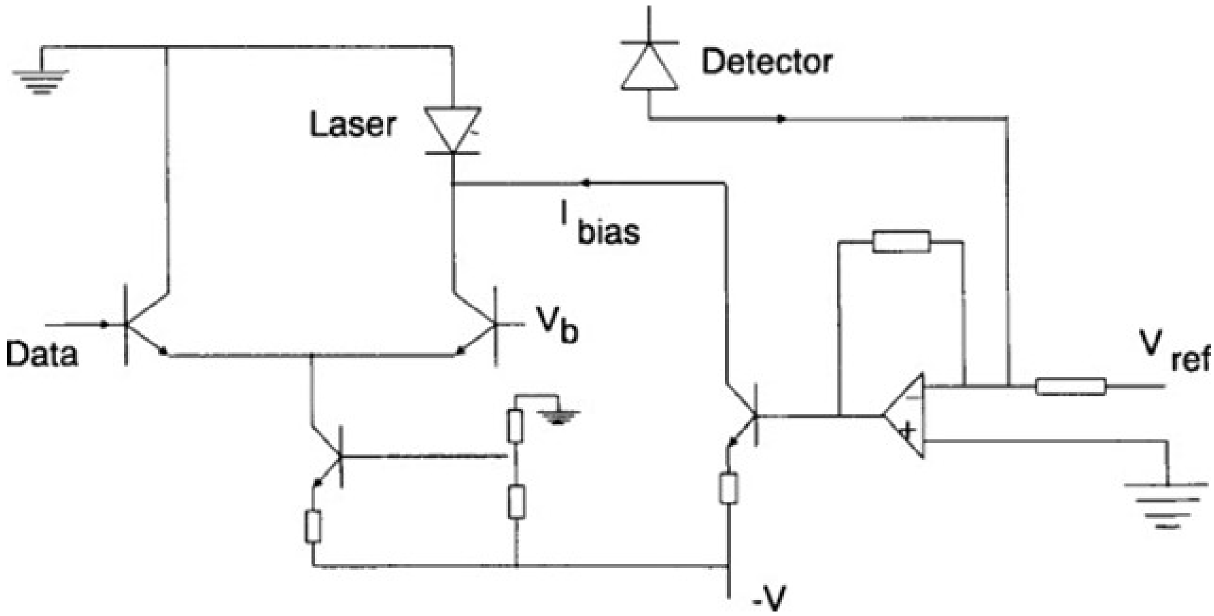

Figure 2.15: Transmitter's circuit

Then there is the **driver** circuit that amplifies the electrical signal and provides the necessary power to the light source, ensuring that the optical signal is strong enough to traverse the fiber without significant loss. To efficiently couple the generated light into the optical fiber a **lens or fiber coupler** is used. This component aligns the light beam with the core of the fiber, maximizing the amount of light transmitted. [**11**]

2.2.2 Criticality of the optical transmitter

The performance and reliability of the optical transmitter directly influence the efficiency, speed and integrity of the overall communication link. Several performance parameters determine the efficiency and reliability of an optical transmitter:

- Optical Power Output: The amount of optical power emitted by the transmitter influences how far the signal can travel without significant degradation. High optical power is essential for long-distance communication, especially in scenarios where signal amplification is limited or unavailable.

- Linearity: In intensity-modulated optical systems, the linearity of the optical transmitter is important to minimize distortion in the transmitted signal. Non-linearities in the transmitter can lead to signal degradation, introducing errors at the receiver end.

- Wavelength Accuracy and Stability: The wavelength at which the transmitter operates must be stable and precise, especially in WDM systems where multiple channels are carried over the same fiber. Any drift in the transmitter's wavelength can lead to crosstalk between channels, significantly degrading system performance.

- Signal-to-Noise Ratio (SNR): The optical transmitter should generate a signal with a high signal-to-noise ratio. Low SNR can lead to bit errors in the transmitted data, requiring retransmission and reducing the overall efficiency of the communication system.

- Modulation Bandwidth: The modulation bandwidth of the optical transmitter determines how fast data can be transmitted. A high modulation bandwidth is essential for achieving high data rates in modern optical communication systems. The transmitter's ability to handle fast modulation directly impacts the system's throughput.

2.2.3 Bit Error Rate (BER)

The *Bit Error Rate (BER)* is a fundamental performance metric in digital communication systems. It is one of the most critical parameter influencing the transmitter's operation. It represents the proportion of erroneous bits received to the total number of bits transmitted over a communication channel. Mathematically, BER is defined as:

$$\text{BER} = \frac{N_e}{N_t} \tag{2.7}$$

Where:

- N_e is the number of bit errors detected in the received signal

- N_t is the total number of bits transmitted

The BER provides insight into the reliability of the transmission system, as it directly relates to the quality of the received data. In practical communication systems, a lower BER implies better system performance, meaning fewer bit errors and higher data integrity.

Several factors influence BER, including the *Signal-to-Noise Ratio (SNR)*, modulation scheme, channel conditions and the presence of error-correcting codes. Communication channels typically introduce noise, interference, fading and other distortions that degrade the signal quality, resulting in errors during transmission. [**12**] [**13**]

BER in Modulation Schemes

Different modulation schemes exhibit distinct BER performance under identical channel conditions. For instance, in *Quadrature Amplitude Modulation (QAM)*, the BER increases with the modulation order. This is because higher-order QAM packs more bits into each symbol, making the system more susceptible to noise. Lower-order modulation schemes like *BPSK (Binary Phase Shift Keying)* and *QPSK (Quadrature Phase Shift Keying)* tend to have lower BER at the same SNR levels compared to higher-order schemes like *16-QAM*, *64-QAM*, or *256-QAM*.

Higher-order QAM offers improved spectral efficiency by transmitting more bits per symbol but suffers from increased BER in noisy environments. The key to design a good communication system is to find the best trade-off between data rate and BER.

For instance, Figure 2.16 shows the theoretical BER curves for various modulation schemes plotted against SNR. As shown, *BPSK* offers the best BER performance for a given SNR, while *16-QAM* and higher-order QAM schemes exhibit a steeper rise in BER as SNR decreases.

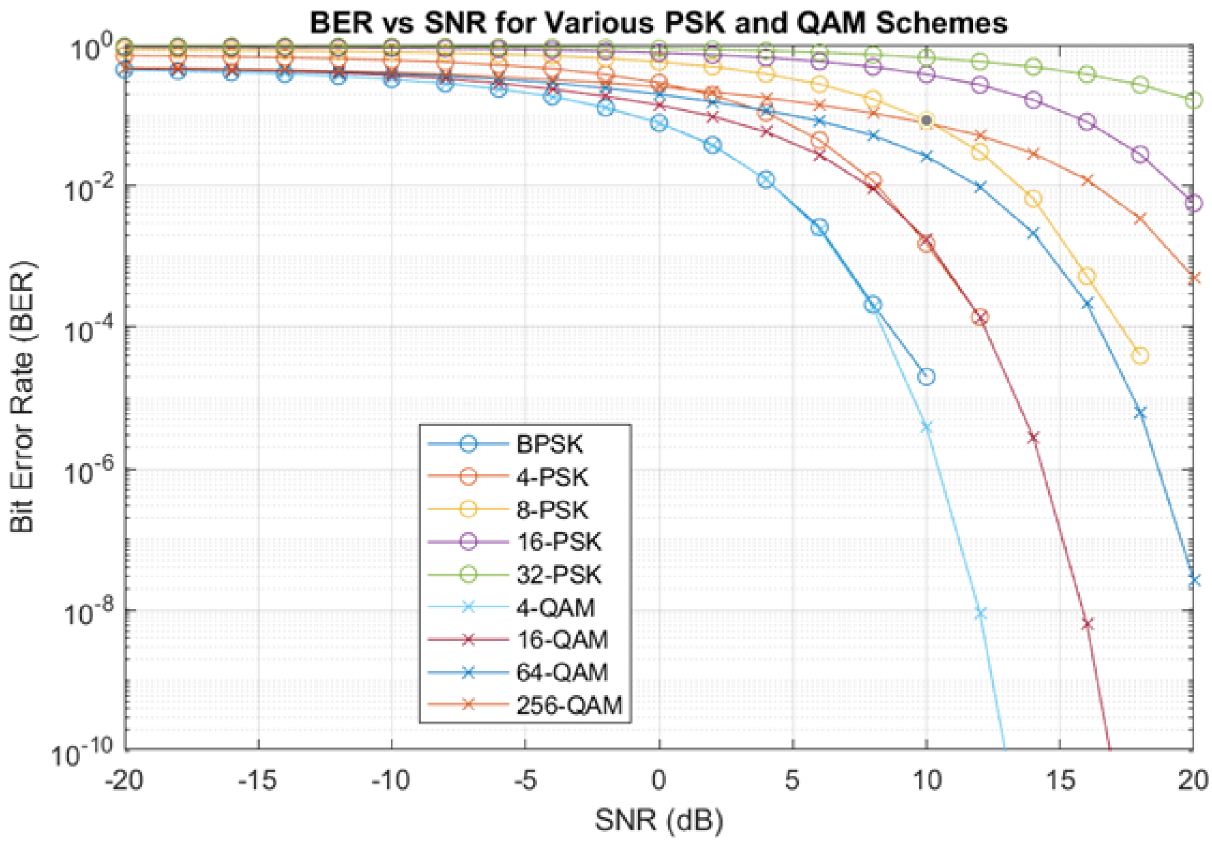

Figure 2.16: Theoretical BER vs. SNR for different modulation schemes

Generally, more complex modulation schemes have higher BER for the same SNR due to increased susceptibility to noise.

Factors Affecting BER

Several factors contribute to the BER observed in a communication system, including:

- **Signal-to-Noise Ratio (SNR)**: A higher SNR generally leads to a lower BER since the signal strength is more dominant over noise. BER is inversely proportional to SNR in most systems.

- **Modulation Scheme**: The choice of modulation scheme directly impacts BER. Lower-order modulation schemes, such as BPSK, tend to have lower BER, while higher-order schemes like 64-QAM exhibit higher BER due to increased susceptibility to noise.

- **Channel Conditions**: In real-world communication, channels may experience fading, interference, or multi-path propagation, which degrade signal quality and increase BER. Techniques like channel coding and diversity can mitigate these effects.

- **Error Correction Mechanisms**: The use of error-correcting codes, such as *Convolutional Codes*, *Turbo Codes*, or *LDPC Codes*, can significantly reduce the effective BER by detecting and correcting bit errors before the data is decoded.

2.2.4 The Optical Receiver

The optical receiver is responsible for converting the incoming optical signal back into an electrical signal for further processing. Its main components include:

The **photodetector** is the heart of the optical receiver, where the optical signal is converted into an electrical signal. Common types of photodetectors include:

- PIN Photodiodes: These are widely used due to their sensitivity and speed, making them suitable for various applications.

- Avalanche Photodiodes (APDs): Known for their high sensitivity and ability to amplify weak signals, APDs are used in long-distance communications and environments with low signal levels.

Once the optical signal is converted to an electrical signal, it may be weak and require amplification. This is where the **amplifier** comes in, boosting the signal strength to facilitate further processing.

The **demodulator** extracts the original data from the amplified electrical signal by reversing the modulation process applied at the transmitter. This step is essential for recovering the transmitted information accurately.

After demodulation, the **signal processing unit** may include error correction, data formatting and any other necessary processing to prepare the data for use or transmission to other devices.

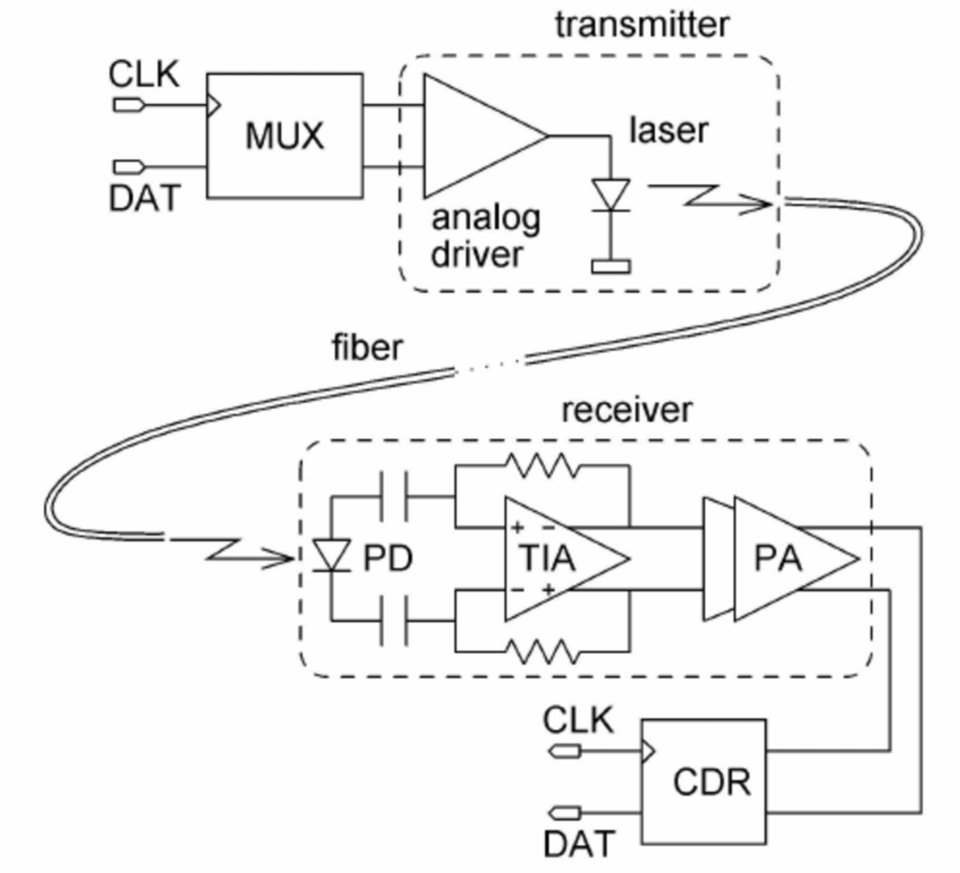

Figure 2.17: Transmitter and Receiver circuits

Where:

- **TIA** is the most widely used optical receiver preamplifier because of its wide dynamic range. The value of the feedback resistor influences the the bandwidth, sensitivity and overload.
- **CDR** stands for Clock and Data Recovery.

The most relevant parameters for an optical receiver are:

- **Sensitivity**: the minimum optical input power to the receiver for which it will deliver an acceptable Bit Error Rate (BER).
- **Overload**: the maximum optical input power to the receiver for which it will deliver an acceptable BER. Overload can also be defined by an acceptable limit on jitter.
- **Dynamic Range**: the range of optical input powers for which the receiver will deliver acceptable performance.

An important factor to be taken into account in transmission and, even more, in reception is the noise. Shot noises and thermal noises are the two most significant noises in optical detection systems. Shot noises are generated by either quantum process or electronic biasing. The noises are specified in noise spectral density that is the square of the noise current per unit frequency (in Hz). Thus, the noise spectral density is to be integrated over the total amplifier bandwidth to obtain the equivalent noise currents. [**5**] [**14**]

2.2.5 The Optical Channel

The optical channel is a fundamental component of modern optical communication systems, facilitating the transmission of information over long distances through optical fibers. The optical channel is located between the transmitter and the receiver.

Key factors influencing the optical channel include attenuation, which reduces signal power due to absorption and scattering and dispersion effects, which can cause signal distortion and intersymbol interference, as it was seen above. These effects necessitate the use of advanced signal processing techniques and optical amplification to maintain signal integrity over extended distances. Additionally, nonlinear phenomena, such as self-phase modulation (SPM) and cross-phase modulation (XPM), introduce further complexities that impact system performance, especially in densely populated wavelength division multiplexing (WDM) systems.

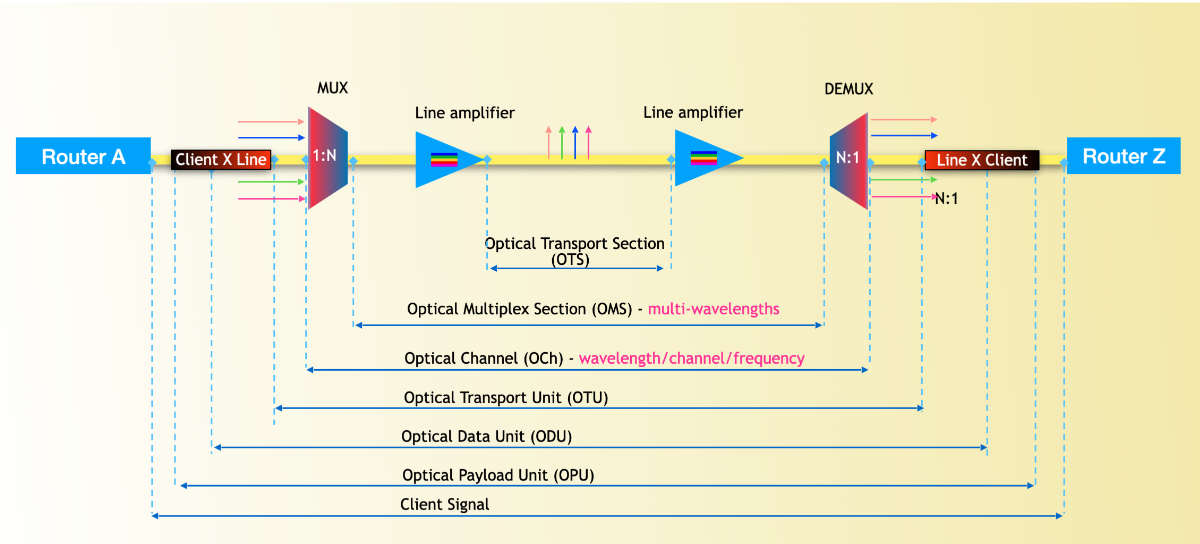

Figure 2.18: Optical Channel

The fundamental effect is attenuation, which reduces signal power along the link due to absorption and scattering, necessitating periodic amplification. In-line amplifiers, however, introduce noise, impacting system reach. Linear effects like polarization mode dispersion (PMD) and chromatic dispersion (CD) spread symbols over time, causing intersymbol interference. These are typically compensated at the receiver with digital signal processing (DSP) techniques, though CD requires long static equalizers and PMD requires adaptive equalization.

The simplest approach to mitigating attenuation is to increase the launch power of optical signals into the fiber. However, indiscriminate power increases can amplify nonlinear fiber effects, which degrade system performance. Consequently, long-distance optical systems typically employ periodic insertion of optical amplifiers along the link. Among the available solutions, the erbium-doped fiber amplifier (EDFA) is the most widely used. [5]

2.2.6 The Transceiver

A transceiver combines the functions of both a transmitter and a receiver into a single unit, streamlining the optical communication system. By combining both functions, transceivers reduce the overall size and complexity of the system, making them ideal for applications where space is limited. Transceivers can be more economical than separate transmitter and receiver units, reducing manufacturing and installation costs. With a single device handling both transmission and reception, installation becomes more straightforward, requiring fewer connections and less wiring. Transceivers can be designed to support various communication protocols and standards, allowing for flexibility in different network configurations. Many of them support bidirectional communication, enabling simultaneous sending and receiving of data over a single optical fiber, further enhancing the efficiency of the system.

The transmitter and receiver can be linked to the same antenna with the help of an electric switch. This keeps the emitter's signal from hurting the receiver. The transceiver generates a signal, which could be electrical optical, or radiofrequency, depending on the medium of communication. The signal is then subjected to modulation. The modulated signal is then sent out through an antenna or through a cable. At the receiving end, another transceiver is waiting to capture the incoming signal. Then finally the signal gets subjected to demodulation and transmitted data gets recovered and the data gets provided to system for further processing or display.

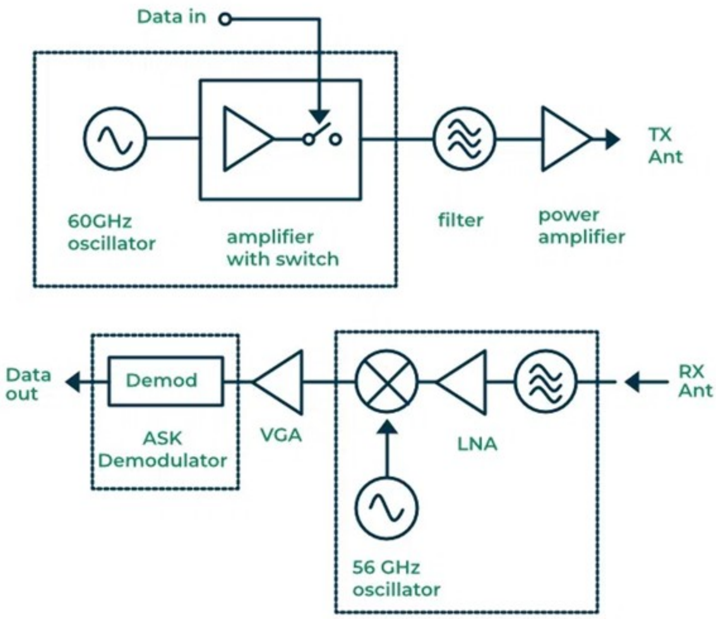

Figure 2.19: Transceiver circuit

In a transceiver with half-duplex capabilities, it is not possible to receive signals while the device is transmitting. However, certain transceivers, known as full-duplex, are designed to receive signals even during transmission. In these systems, the transmitter and receiver operate on different frequencies, preventing the transmitted signal from interfering with the received signal.

The main parameters of the optical an transceiver are:

- **Data Rate**: the number of bits transmitted per second.
- **Transmission Distance**: the maximum distance over which optical signals can transmit. Optical signals sent from different types of sources can be transmitted

over different distances due to the effects of optical fibers, such as dispersion and attenuation. When connecting optical interfaces, optical modules and fibers should be selected based on the maximum signal transmission distance.

- **Central Wavelength**: the central wavelength represents the waveband for optical signal transmission. Currently, standard fiber transceiver modules operate primarily at three central wavelengths: 850 nm, 1310 nm and 1550 nm, corresponding to three different wavebands.
- **Optical Transmit Power**: the output optical power of an optical transceiver when it is functioning correctly. When two optical transceivers are connected, the transmit optical power of one end must be within the received optical power range of the other end.
- **Receiving Sensitivity**: the minimum power at which the receiver of a fiber optic transceiver can detect optical signals while maintaining an acceptable Bit Error Rate (BER = 10^{-12}), measured in dBm.
- **Fiber Mode**: The mode of optical fibers is defined based on core diameter and fiber characteristics. Fibers are classified as single-mode (SMF) or multi-mode (MMF). Multi-mode fibers have large core diameters and can carry light in multiple modes, but they experience greater inter-mode dispersion, making them suitable for short-distance transmission. Single-mode fibers (SMF) have small core diameters and support only one mode of light, resulting in lower dispersion and suitability for long-distance communication.
- **Connector Type**: the type of interface on an optical transceiver to connect a fiber. Common connector types include the LC connector (used with QSFP, SFP, SFP+, SFF and XFP transceivers), SC connector (for BIDI SFP, GBIC, X2, XENPAK and 1×9 transceivers) and MPO connector (used with QSFP+, SR4 and CXP modules).
- **Extinction Ratio**: the minimum ratio of the average optical power when signals are transmitted to the average optical power when no signals are transmitted in complete modulation mode. The extinction ratio reflects the capability of an optical module to distinguish between signal 0 and signal 1, serving as a quality indicator for fiber optic transceivers.
- **Eye Diagram**: an oscilloscope display in which a digital signal from a receiver is repeatedly sampled and displayed vertically, while the data rate is used to trigger the horizontal sweep.

[**15**]

2.2.7 Cluster and Large scale application

The optical fiber is prone to be used in different applications. In this section they will be taken into account the cluster and the large-scale application.

In general, the term *cluster* refers to a group of elements, often very similar to each other or connected by a shared feature. In computing a cluster is composed of a series of interconnected machines that work together in parallel. Using a cluster system allows for the execution of highly complex operations by distributing the processing load across all the nodes within the cluster. The main advantage is a significant reduction in computational time. Cluster systems for servers and storage are widely used solutions for disaster recovery and operational continuity. In the event that the primary server or storage unit (often called the active node) experiences a malfunction, the data can be managed by a passive node in the cluster. This configuration ensures seamless data access, completely transparent to the user.

Clusters in optical fiber systems enable efficient data processing, load balancing and fault tolerance, making them ideal for meeting the demands of modern, high-speed telecommunications networks

In cluster settings, optical fibers enable high-speed connectivity within local area networks, data centers and medical devices, thereby enhancing efficiency across various domains. Fiber port clusters are compact opto-mechanical units that split the radiation from one or more polarization-maintaining (PM) fibers into multiple output polarization-maintaining fiber cables with high efficiency and variable splitting ratio. The beam delivery system consists of compact, modular opto-mechanic units. The modularity ensures that almost any desired system can be assembled that is compact and sealed. Because of the polarization sensitive properties of the optical components within the fiber port cluster, PM fibers are used to transport the light to the cluster with defined linear polarization. An example of fiber port cluster is shown Figure 2.20.

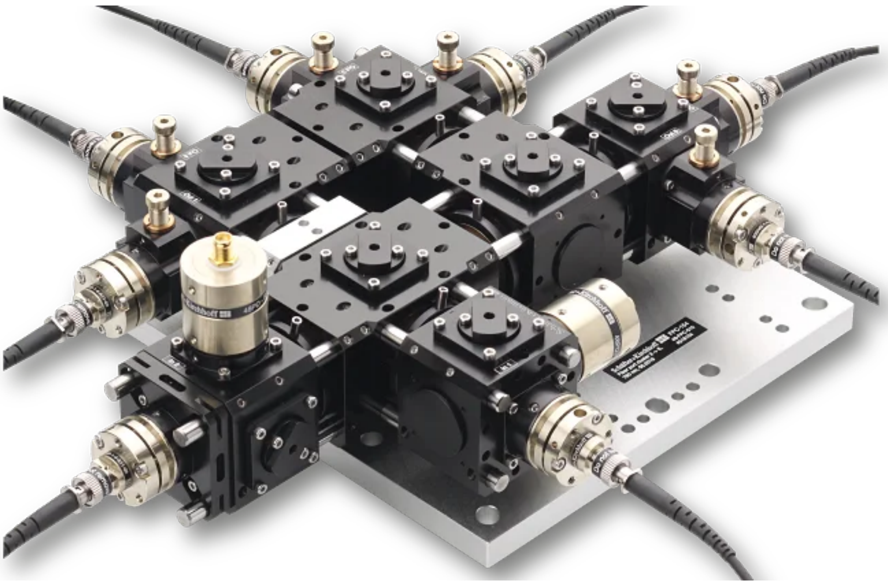

Figure 2.20: Fiber port cluster

The stability of any fiber port cluster is dependent on the stability of the laser beam couplers used for collimation at the input and for coupling the radiation into the output PM fibers.

On a larger scale, they serve as the backbone of global telecommunications, driving internet infrastructure, facilitating smart city projects and ensuring high-quality broadcasting. With the ever-increasing demand for faster and more reliable communication, the role of optical fibers in both localized and large-scale applications continues to be of paramount importance. [**16**] [**17**]

Chapter 3

Optical Time-Domain Reflectometer systems

Optical Time-Domain Reflectometer (OTDR) systems are essential tools used in optical communication networks to monitor, diagnose and mitigate errors in transmission systems, including those originating from optical transmitters. OTDR operates by sending short pulses of light into an optical fiber and analyzing the backscattered and reflected signals to detect imperfections, such as losses, faults, or fiber breaks. By evaluating these deviations, the specific trouble spot can usually be accurately identified. In the context of mitigating transmitter errors, OTDR systems provide real-time insights into signal quality, detecting issues like power fluctuations, signal degradation due to dispersion, or non-linearities introduced during transmission. By identifying and locating the source of these impairments, OTDR systems help maintain the integrity of the transmitted optical signal, ensuring efficient and reliable communication over long distances. As optical networks grow in complexity, OTDR technology becomes increasingly vital for minimizing downtime, optimizing performance and improving the overall resilience of communication systems.

3.1 Operation of OTDR Systems

An OTDR combines a laser source and a detector to provide an inside view of the fiber link. The laser source sends a signal into the fiber where the detector receives the light reflected from the different elements of the link. This produces a trace on a graph made in accordance with the signal received and a post-analysis event table that contains complete information on each network component is then generated. The signal sent is a short pulse that carries a certain amount of energy. A clock then precisely calculates the time of flight of the pulse and time is converted into distance knowing the properties of this fiber. As the pulse travels along the fiber, a small portion of the pulse's energy returns to the detector due to the reflection of the connections and the fiber itself. When the pulse has entirely returned to the detector, another pulse is sent until the acquisition time is complete. Therefore, many acquisitions will be performed and averaged in a second to provide a clear picture of the link's components. After the acquisition has been completed, signal processing is performed to calculate the distance, loss and reflection of each event, in addition to calculating the total link length, total link loss, ORL and fiber attenuation. The main advantage of using an OTDR is the single-ended test,requiring only one operator and instrument to qualify the link or find a fault in a network.

In few words, the OTDR provides a view of the link by reading the level of light that returns from the pulse which was sent. There are two types of light levels: a constant low level created by the fiber called "Rayleigh backscattering" and a high-reflection peak at the connection points called "Fresnel reflection". Rayleigh backscattering is used to calculate the level of attenuation in the fiber as a function of distance (expressed in dB/km), which is shown by a straight slope in an OTDR trace. This phenomenon comes from the natural reflection and absorption of impurities inside optical fiber. When hit, some particles redirect the light in different directions, creating both signal attenuation and backscattering. Higher wavelengths are less attenuated than shorter ones and, therefore, require less power to travel over the same distance in a standard fiber.

The second type of reflection used by an OTDR, Fresnel reflection, detects physical events along the link. When the light hits an abrupt change in index of refraction higher amount of light is reflected back, creating Fresnel reflection, which can be thousands of times bigger than the Rayleigh backscattering. Fresnel reflection is identifiable by the spikes in an OTDR trace.

Summing up it can be said that the OTDR operates indirectly. While source and meter measurements directly reflect the actual system loss, OTDR relies on a distinctive property of the fiber to infer loss. The primary contributor to loss in optical fibers is scattering, a process similar to billiard balls colliding, but occurring on a microscopic scale between photons and atoms or molecules. This phenomenon leads to a reduction in light intensity at the receiving end of the fiber. Figure 3.1 depicts how light scattering occurs within a fiber optic cable due to air bubbles, impurities and microbends.

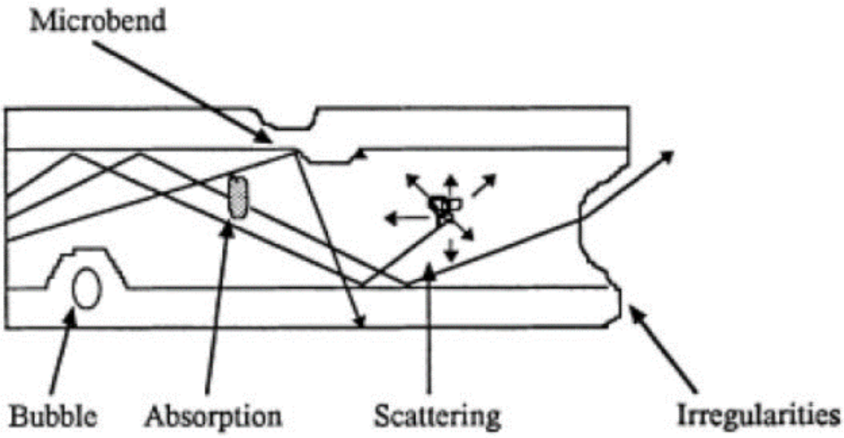

Figure 3.1: Scattering of the OTDR system

OTDRs are capable of detecting faults, breaks, bends and splices in fiber optic cables. Thanks to that is possible to measure the amount of light loss and pinpoint the exact location where the loss is occurring where a fiber-optic cable is bent to 180 degrees. Light loss in fiber cables is a significant concern, as it can impair or completely halt data transmission. With many communication networks relying on fiber optic cabling for data transfer, the ability to quickly diagnose issues is crucial, enabling faster repairs and reducing network downtime. [**18**] [**19**]

3.2 Components of OTDR systems

An OTDR contains a laser diode source, a photodiode detector and a highly accurate timing circuit (or time base). The laser emits a pulse of light at a specific wavelength, this pulse of light travels along the fiber being tested, as the pulse moves down the fiber portions of the transmitted light are reflected/refracted or scattered back down the fiber to the photo detector in the OTDR. The intensity of this returning light and the time taken for it to arrive back at the detector tells us the loss value (insertion and reflection), type and location of an event in the fiber link.

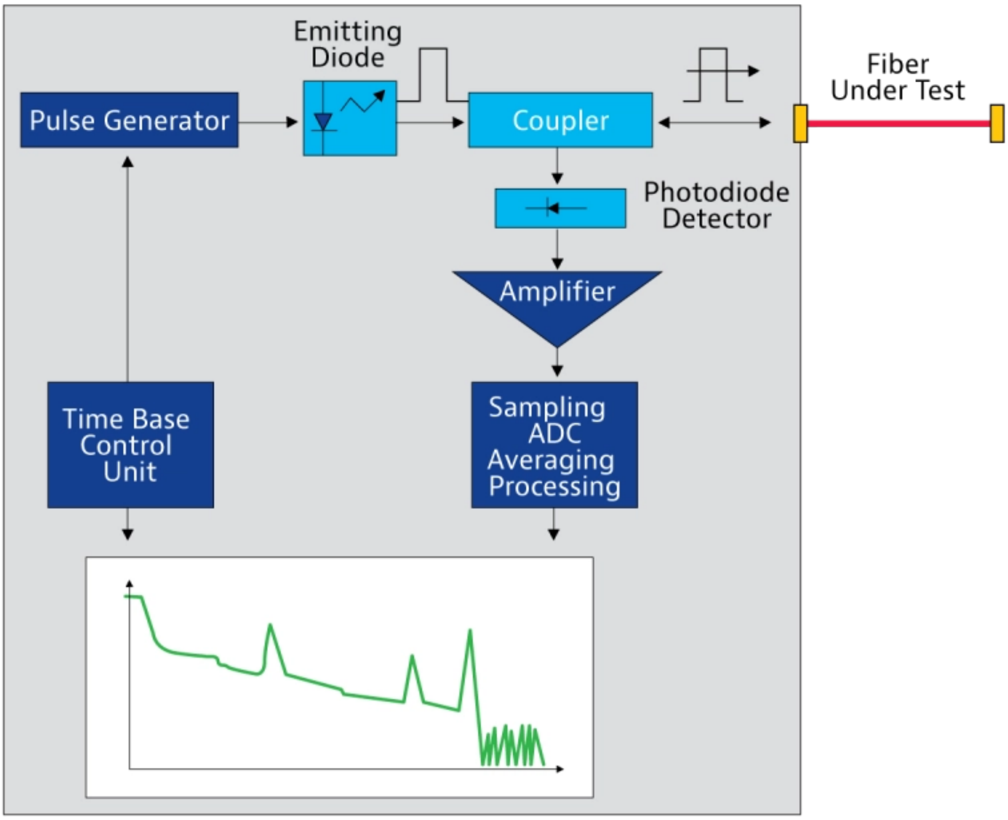

Figure 3.2: Componets of an OTDR system

3.3 Field-Programmable Gate Array (FPGA)

An important component of OTDR systems is the Field-Programmable Gate Array (FPGA). It offers numerous advantages in terms of performance, flexibility and processing capabilities. FPGAs are part of a class of devices known as programmable logic or programmable hardware. Unlike traditional hardware, an FPGA does not perform any specific function until it is configured. However, once programmed, it can be tailored to implement virtually any digital circuit. This flexibility arises without any physical modifications to the device. A configuration is simply loaded into the FPGA, enabling it to function as the desired circuit. There is no need for soldering or hardware rewiring. Additionally, FPGAs can be reprogrammed to emulate different circuits repeatedly, as their configuration is stored in volatile memory (RAM), allowing for unlimited reconfigurations. FPGAs can offer significantly greater efficiency in terms of processing time, owing to their ability to execute operations in parallel, unlike traditional processors that operate sequentially. Additionally, FPGAs provide precise control over timing, enabling designers to implement circuits with extremely tight timing constraints, which is essential for high-performance, real-time applications. This makes FPGAs particularly well-suited for tasks requiring low-latency and deterministic processing, such as signal processing, data encryption and other high-speed computing tasks. A con of FPGAs use is thate they tend to be expensive, the larger ones easily go for tens of thousands of dollars per chip.

3.3.1 FPGA's structure

Every FPGA chip is made up of a finite number of predefined resources with programmable interconnects to implement a reconfigurable digital circuit and I/O blocks to allow the circuit to access the outside world. FPGA resource specifications often include the number of configurable logic blocks, number of fixed function logic blocks such as multipliers and size of memory resources like embedded block RAM. Of the many FPGA specifications, these are typically the most important when selecting and comparing FPGAs for a particular application. The configurable logic blocks (CLBs) are the basic logic unit of an FPGA. Sometimes referred to as slices or logic cells, CLBs are made up of two basic components: flip-flops and lookup tables (LUTs). Various FPGA families differ in the way flip-flops and LUTs are packaged together, so it is important to understand flip-flops and LUTs.

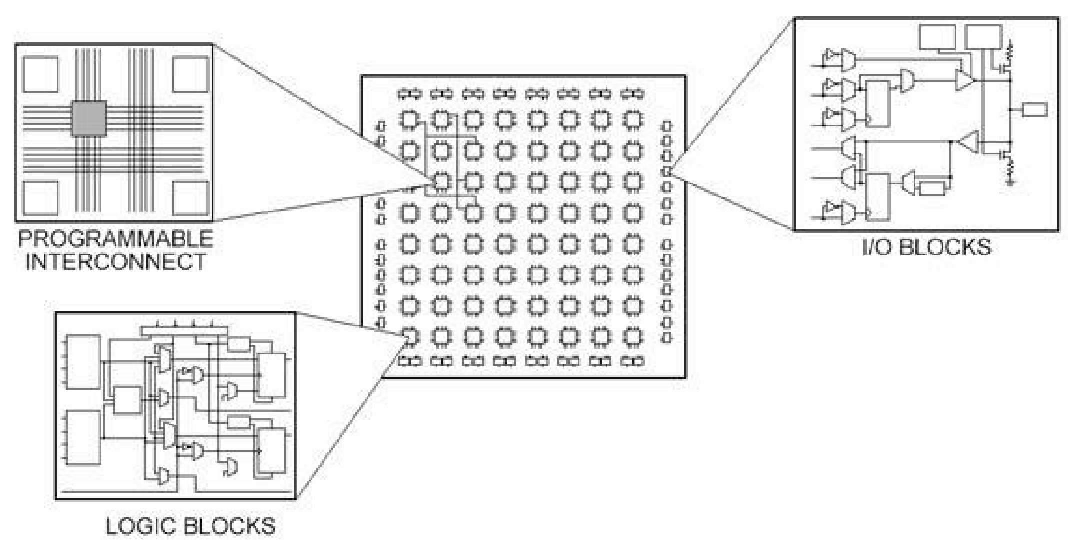

Figure 3.3: FPGA components

Flip-flops are binary shift registers used to synchronize logic and save logical states between clock cycles within an FPGA circuit. On every clock edge, a flip-flop latches the 1 or 0 (TRUE or FALSE) value on its input and holds that value constant until the next clock edge.

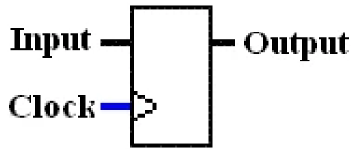

Figure 3.4: Flip-Flop Symbol

Flip-flops are binary shift registers used to synchronize logic and save logical states between clock cycles within an FPGA circuit. On every clock edge, a flip-flop latches the 1 or 0 (TRUE or FALSE) value on its input and holds that value constant until the next clock edge.

RAM which stands for Random Access Memory is the temporary storage in your computer that gives applications a place to store and access data on a short-term basis. Having more RAM means that more data can be accessed and read almost instantly. Key roles of RAM in OTDR systems include:

- **Data Buffering:** RAM is used to temporarily store the backscattered signal data as it is collected. This ensures that the system can handle large volumes of data quickly and prevents data loss during processing.

- **Signal Processing:** OTDR systems rely on sophisticated algorithms to analyze the backscattered light and detect faults, losses and other imperfections in the fiber. RAM provides the necessary fast-access memory for these real-time calculations and analyses.

- **Storage of System Configuration and Results:** RAM may also be used to store system parameters, configurations and interim measurement results, which can then be further processed or transferred to non-volatile storage.

ZBT RAM (Zero Bus Turnaround Random Access Memory) is a type of synchronous static random-access memory (SRAM) that offers fast access times with zero bus turnaround cycles. In traditional SRAMs, there is a delay between when the address is set and when valid data appears on the output pins. During this delay, the memory cannot respond to any other commands. This delay is known as the bus turnaround time. ZBT SRAMs eliminate this delay by allowing the output data to appear immediately after the address is set, without waiting for any turnaround cycles. This means that the memory can respond to commands and provide data on the same clock cycle.

More than single FPGA, usually in OTDR systems are employed **SoC FPGAs**. They combine programmable logic (the FPGA) with a hard processor system (typically ARM cores) on a single chip. By keeping processing close to the data acquisition logic, SoC FPGAs can minimize latency, leading to faster data processing and response times. [**20**] [**21**] [**22**]

3.4 MUX/DEMUX

Fiber optic mux/demux (multiplexer/demultiplexer) is an optical device used to multiplex and separate multiplexed signals in fiber optic communication systems. It can combine multiple optical signals into one optical fiber for transmission, or separate multiple signals on a single optical fiber to different receiving ends. Optical fiber multiplexing technology is a technology that realizes the simultaneous transmission of multiple signals by rationally utilizing the optical fiber transmission bandwidth. It uses equipment such as fiber optic mux demux to multiplex multiple signals, thereby improving the efficiency and capacity of the optical fiber transmission system.

The basic principle of optical fiber multiplexing technology is to use different optical wavelengths or time slots to distinguish and multiplex multiple signals. This allows multiple signals to be transmitted on the same optical fiber without interfering with each other.

The main fiber multiplexing technologies include:

- **Wavelength Division Multiplexing (WDM)**: WDM uses different optical wavelengths to multiplex multiple signals into optical fibers. It includes two types: dense wavelength division multiplexing (DWDM) and coarse wavelength division multiplexing (CWDM). DWDM uses very tight wavelength intervals in the optical fiber, which can achieve high-density signal multiplexing; CWDM uses wider wavelength intervals and is suitable for shorter distance transmission.

- **Time Division Multiplexing (TDM)**: TDM divides multiple signals into different time slots according to time and transmits them alternately on the optical fiber. The receiving device synchronizes the signals and separates them into their original form.

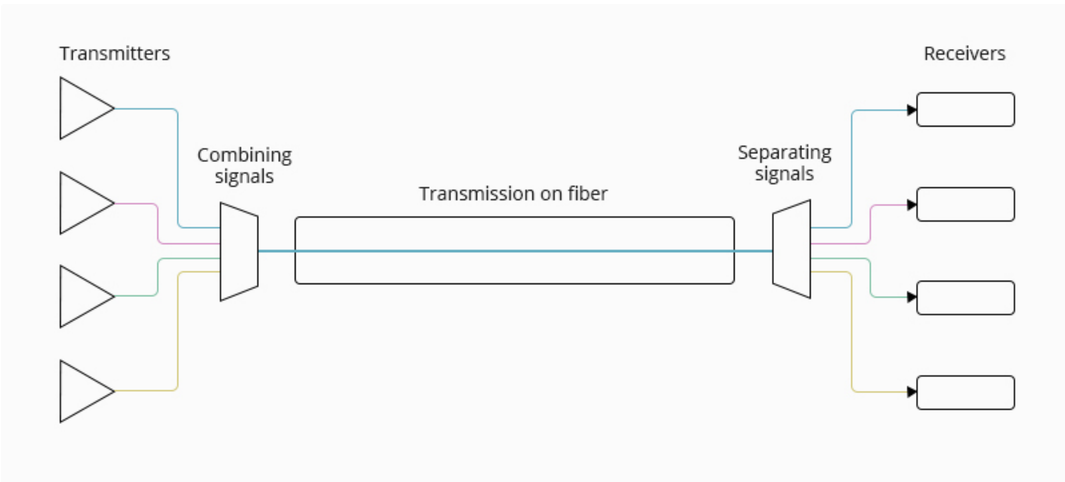

Figure 3.5: Operation of DWDM Mux and Demux

For instance, talking about DWDM, according to its working principle, the structure of a DWDM network begins with a transponder or transceiver that receives data inputs from various traffic types and protocols. This device maps the input data to individual DWDM wavelengths. Each wavelength is then fed into a optical Mux, which filters and combines multiple wavelengths into a single output port for transmission through the main DWDM fiber. At the receiving end, a Demux separates the transmitted wavelengths. Each channel is isolated and routed to the appropriate client output through an additional wavelength-matching transponder or transceiver. This process ensures that data is accurately transmitted and received across the DWDM network. [**23**] [**24**]

3.5 OTDR system exploited in this thesis

The OTDR system analyzed in this thesis' project consists of various components, as illustrated in Figure 3.6, such as the pulse generator, the delay system, the registers, the PLL (Phase-Locked Loop) and the ZBT RAM memory.

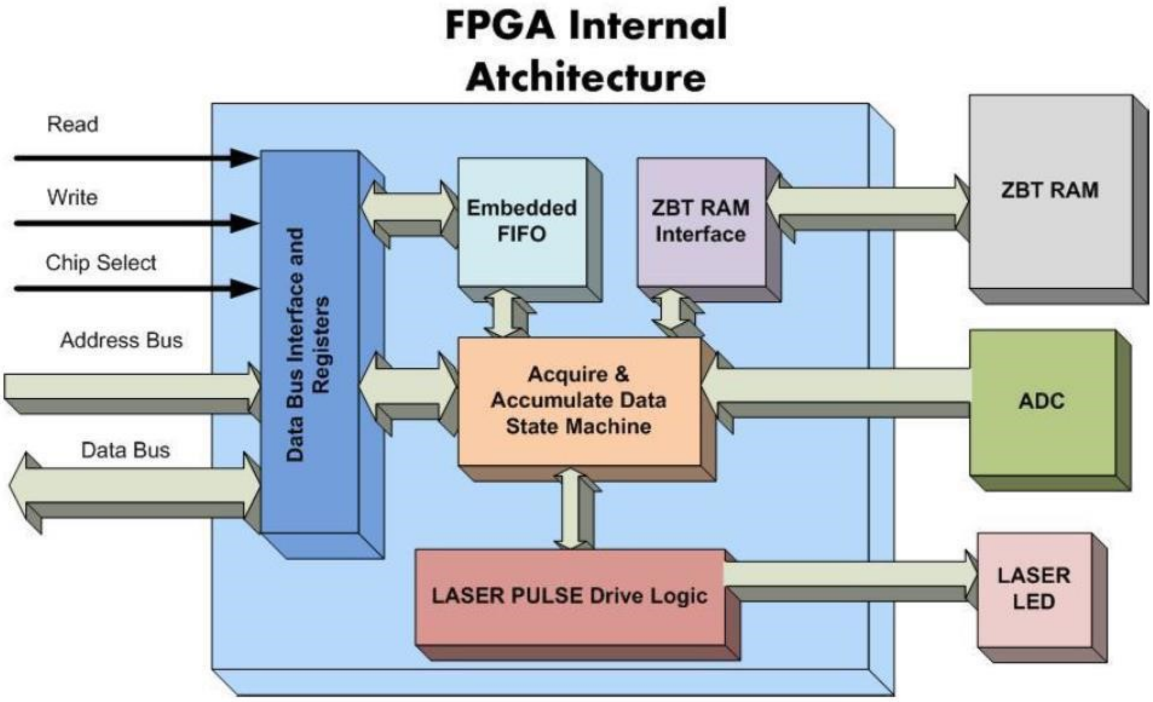

Figure 3.6: FPGA internal architecture

- **FPGA:**
  - This is the central processing unit of the system.
  - It contains the Acquisition State Machine that controls the operation of the OTDR, including data acquisition and processing.
- **ZBT RAM:**
  - This is used for temporary storage of data.
  - The FPGA writes the acquired data to the ZBT RAM for fast access and processing.
- **Laser LED Driver:**
  - Controlled by the FPGA, it generates and sends laser pulses into the optical fiber.
  - The driver ensures that the laser pulses are of the correct intensity and duration for effective measurement.
- **Optical MUX/DEMUX (Multiplexer/Demultiplexer):**

- Directs the laser pulses into the optical fiber and routes the returning signals (backscattered and reflected light) to the ADC.
- MUX/DEMUX helps in separating the input signal and the backscattered signal to ensure accurate measurement.

- **ADC (Analog-to-Digital Converter):**
  - Converts the analog signals (reflected light intensity) received from the optical fiber into digital data that can be processed by the FPGA.
  - The signals received correspond to various points along the fiber where reflections and backscatter occur.

- **Fiber-Optic Cable:**
  - The optical fiber being tested. The laser pulses travel down this fiber and are partially reflected back due to imperfections, splices, or the fiber end.
  - The reflected light is analyzed to determine the characteristics of the fiber.

The primary objective of this project was to verify and optimize the functionality of these components within the OTDR system, with particular focus on the logic for generating laser pulses and the interface with the ZBT RAM memory. In order to do that a VHDL project was exploited. With that it was possible to verify the correct working of the laser pulse and delay generator. These pulses will go through the optical fiber channel and analyzed at the output to understand if they change and how they do that.

Chapter 4

Proposed methodology

The experimental methodology used in this project to work with optical components is illustrated in the following sections. It is based on the use of two different languages: VHDL to work with the OTDR system and MATLAB to simulate and work with the optical fiber's channel.

4.1 VHDL operational process

What the VHDL project basically does can be divided into three steps:

1. **Generation and Injection of the Laser Pulse**: The FPGA sends a control signal to the laser LED driver, generating a laser pulse with a variable duration, ranging from 10 ns to 10 µs. This pulse is then injected into the fiber optic cable through an optical MUX/DEMUX.

2. **Propagation and Backscattering of the Signal**: As the laser pulse travels through the optical fiber, a portion of the light is backscattered and reflected due to imperfections or changes in the refractive index along the cable. This backscattered signal returns through the fiber and is directed by the optical MUX/DEMUX to an ADC (Analog-to-Digital Converter), which converts it into a digital signal.

3. **Processing and Storage of the Signal**: The converted digital signal is processed by the FPGA and then stored in the ZBT RAM for further analysis. Correct synchronization and management of the pulses within the system are crucial to ensure that the collected data is accurate and usable for cable diagnosis.

For the purposes of the thesis only the first two steps have been analyzed.

4.1.1 Verification of system functionality

Once the program has been run it is possible to select the desired output to be shown. The signals of interest are the clock (`clk`) and the `pulse_out` signal that allow to understand the correct working of the program. The analysis of the outputs of the VHDL program, represented in Figure 4.1, shows that the generated pulses occur approximately every 1 µs, reaching a maximum of about 10 µs. This result confirms the correct operation of the pulse generator.

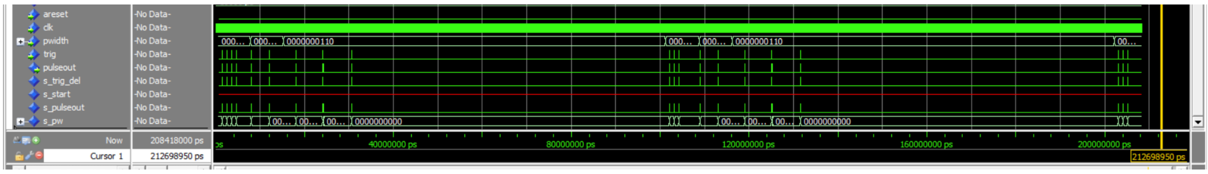

Figure 4.1: Output pulses generated by the VHDL program.

After that, the delay system was examined. The generated pulse should activate a LED for the set duration. Through `pulse_delay`, the program should generate a delay for this pulse in increments of ±1.25 µs. The delay is referenced to the start of data acquisition from the ADC. After the master unit, which can be a microprocessor, sets the pulse width and pulse delay step, the Acquisition State Machine (OTDR Core) will turn the Laser LED on for the set parameters. The laser pulse traveling in the optical fiber cable generates backscattered radiation that will vary as the light encounters splices and junctions throughout the length of the fiber cable. The ADC will sample the voltage generated by the high-performance photodiode installed at the same end of the fiber cable as the laser diode.

For this purpose, the following components are used:

- **Clocks:**
  - `clk_400_000`: A 400 MHz clock, phase 0.
  - `clk_400_180`: A 400 MHz clock, phase 1.
  - `clk_400`: Another clock with the same frequency (400 MHz), but with a phase that can be adjusted in order to have more or less delay.
- **Shift Register:**
  - A sequence of flip-flops used to store and shift the input pulse over time.

What the delay process code does is reported down below:

- The incoming pulse is initially registered (stored in a flip-flop) using `clk_400_000`. This means the pulse is synchronized with `clk_400_000`.
- The registered pulse is then fed into a shift register that is clocked by `clk_400_000`. This shift register shifts the pulse through its stages at each rising edge of `clk_400_000`.
- The pulse is injected into a selected stage of the shift register. This stage selection allows control over the number of shifts the pulse undergoes, effectively creating a variable length shift register.
- The output of the shift register is further registered (stored in another flip-flop) using `clk_400`, which is a multiplexed clock with an adjustable phase.
- By changing the phase of `clk_400`, the output delay changes. Specifically, the phase adjustment of `clk_400` allows the delay to be fine-tuned by increments of ±1.25 µs. This fine-tuning is due to the relationship between the phase shift and the clock period (since 1 cycle of a 400 MHz clock is 2.5 µs, a 180-degree phase shift equals 1.25 µs).

By looking the output of the simulation, in particular the signals shown in Figure 4.2, at the considered instant, the delay happens every 5 µs, then 7.5 µs and so on (multiples of 1.25 µs). Going on in the simulation, the delay increases by 1.25 µs steps, reaching a maximum of 10 µs. This result complies with the design specifications.

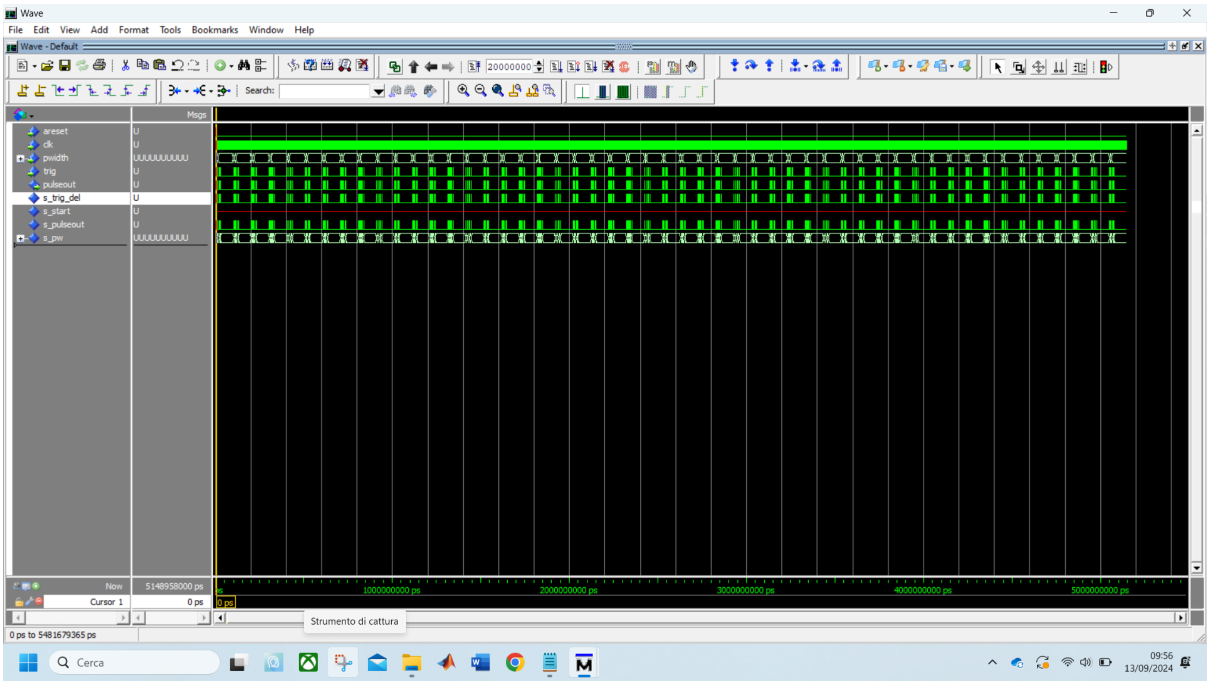

Figure 4.2: Output pulses from Modelsim.

In the next chapter it will be analyzed the optic fiber channel model on MATLAB. It was decided to analyze a time interval of 5000000 ns since the clock signal changes its value every 5000 ps and they wanted to be considered 1 megabit values. In order to do that it was generated a code to recreate the pulses coming from the VHDL project. In particular the pulses' value (0 or 1) and the time instants they occurred were exported into .txt file and on a 5000000 ns time interval the pulses at the corresponding instant value have been reported. As it can be seen on in Figure 4.3 and more precisely in the zoomed in Figure 4.4, the MATLAB code precisely recreated the sequence of pulses as the one showed in Figure 4.2 from the VHDL project.

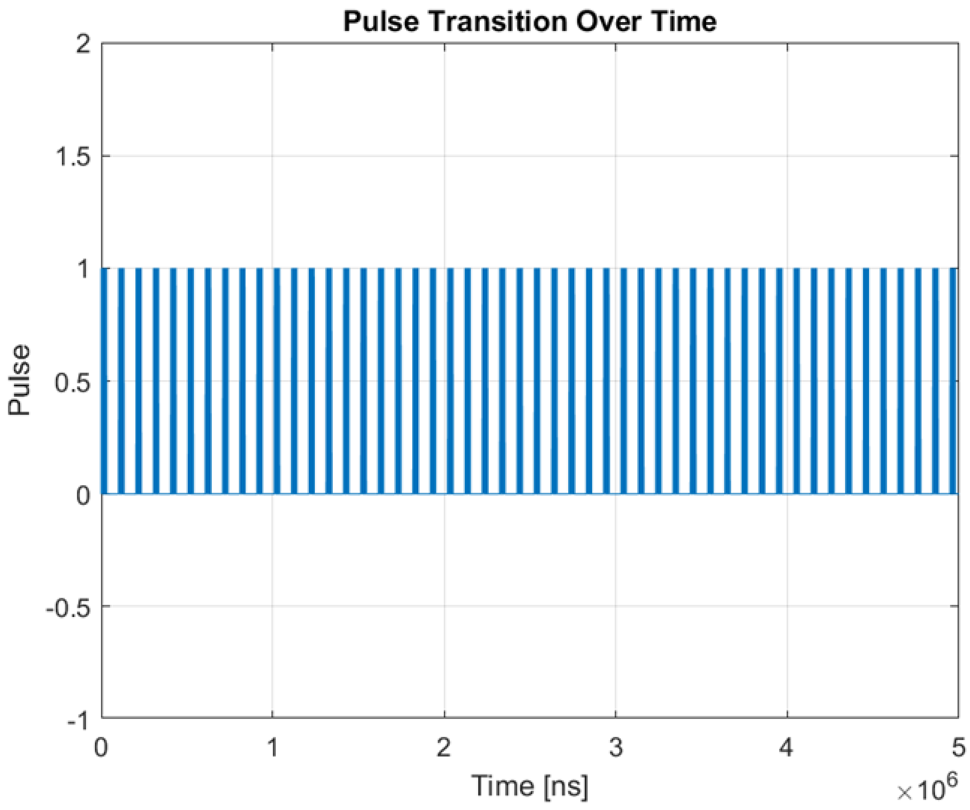

Figure 4.3: Pulses over time

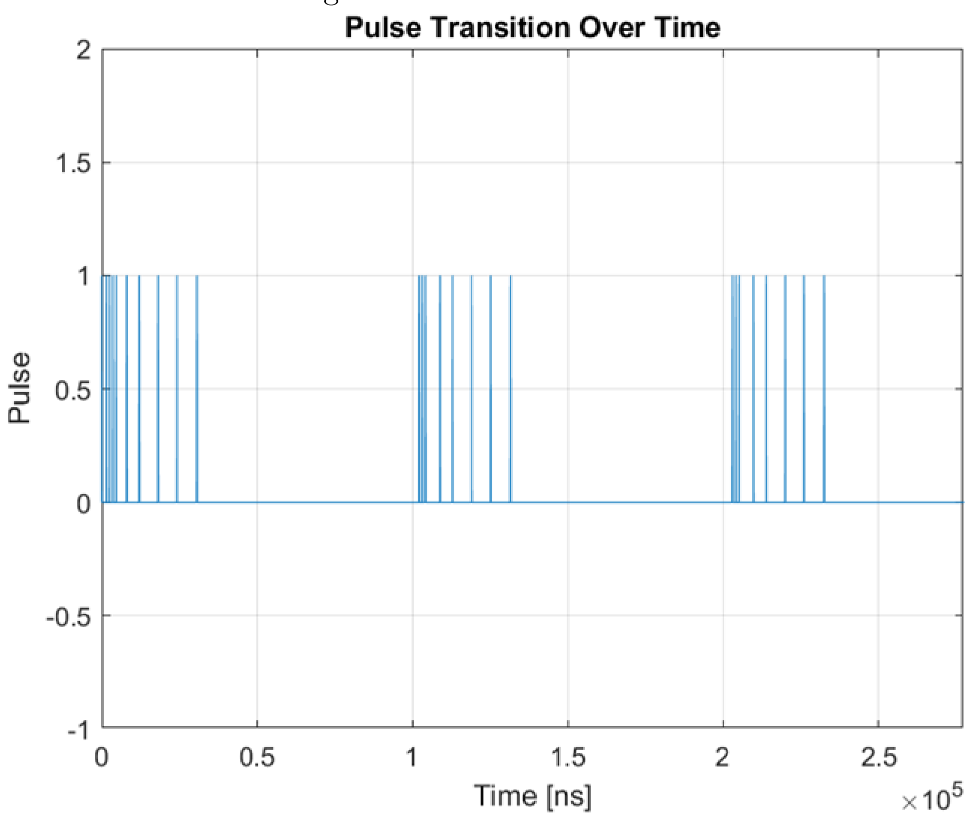

Figure 4.4: Zoom pulses over time

4.2 MATLAB model of the optical channel

After verifying the correct operation of the OTDR system, the focus is shifted to simulating the fiber optic channel using MATLAB. This simulation is crucial for understanding how imperfections within the cable can affect the optical signal, particularly considering two main phenomena: chromatic dispersion (CD) and polarization mode dispersion (PMD).

To simulate the optical fiber channel, two functions were implemented in the MATLAB environment to introduce these two types of dispersion into the channel. Subsequently, to ensure that the channel's input signal, coming from the VHDL program, was consistent with the code, digital modulation was performed. Specifically, QPSK (Quadrature Phase Shift Keying) modulation was chosen. This allows to convert the digital signal into a sinusoidal signal with 4 symbols that are phase-shifted by 90 degrees from each other. Both for simulating chromatic and polarization mode dispersion will be considered 2 polarization modes (Npol), one vertical and one horizontal. In this case, the functions require as input a matrix with two columns, one for each polarization mode. The vector obtained from the modulation represents one of the two polarization modes, so one of the two columns of the complex matrix given as input in the channel. The second column will be generated using random complex numbers. As these are not physical signals, there is no need for the two columns to contain orthogonal numbers.

4.2.1 Implementation and simulation of the Chromatic Dispersion Model

To simulate chromatic dispersion a MATLAB function was developed that operates in the frequency domain. The function is shown down below and:

- Calculates the Fast Fourier Transform (FFT) of one of the two modes to switch from the time domain to the frequency domain.
- Shifts the zero-frequency component to the center of the spectrum for better visualization of what the function implements.
- Applies the "G" filter that simulates chromatic dispersion.
- Shifts it back to return to the original configuration.
- Calculates the Inverse Fast Fourier Transform (IFFT) to switch from the frequency domain back to the time domain.

```
function [AOutput] = CDInsertion(AInput, SpS, Rs, D, CLambda, L, NPol)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% CDInsertion [AOutput] = CDInsertion(AInput, SpS, Rs, D, CLambda, L, NPol)
% This function simulates the insertion of chromatic dispersion (CD) in
% the signal 'AInput'.
% Input:                                                      % AInput = Input Signal. For transmission in single pol. orientation
% 'AInput' must be a column vector. For transmission with pol.
% multiplexing, 'AInput' must be a matrix with two columns,
% where each column corresponds to the signal of a pol.
```

```
% orientation (V and H pol. orientations);
% SpS = Number of samples per symbol in the input signal 'AInput';
% Rs = Symbol rate in [symbols/s];
% D = Dispersion parameter in [ps/(nm x km)]
% CLambda = Central lambda in [m]
% L = Fiber length in [m]
% NPol = Number of polarizations used;
% N = length(AInput) / NPol; % Number of samples per polarization
%
% Output:
% AOutput = Output signal after CD insertion. 'AOutput' is arranged in
% columns in the same way as 'AInput';
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Constants:
c = 299792458; % speed of the light
% Dispersion:
D = D*1e-12/(1e-9*1e3);
% Frequency vector:
w = 2*pi*(-1/2:1/size(AInput,1):1/2-1/size(AInput,1)).'*SpS*Rs;
% Calculating the CD frequency response:
G = exp(1i*((D*CLambda^2)/(4*pi*c))*L*w.^2); %filter
% Inserting CD to the transmitted signal:
AOutput(:,1) = ifft(ifftshift(G.*fftshift(fft(AInput(:,1)))));

% In the case of pol-mux:
if NPol == 2
    % Inserting CD to the transmitted signal:
    AOutput(:,2) = ifft(ifftshift(G.*fftshift(fft(AInput(:,2)))));
end

end
```

[9] Going into details:

[AOutput] = CDInsertion(AInput,SpS,Rs,D,CLambda,L,NPol)

This function simulates the insertion of chromatic dispersion (CD) in the signal 'AInput'.

Input:

- **AInput**: Input signal.
  - For single polarization transmission: 'AInput' must be a column vector.
  - For polarization multiplexing transmission: 'AInput' must be a matrix with two columns, where each column corresponds to the signal of a polarization orientation (Vertical and Horizontal polarization orientations).
- **SpS**: Number of samples per symbol in the input signal 'AInput'.
- **Rs**: Symbol rate in [symbols/s].
- **D**: Dispersion parameter in [ps/(nm × km)].
- **CLambda**: Central wavelength in [m].
- **L**: Fiber length in [m].
- **NPol**: Number of polarizations used.

- **N**: length($AInput$)/$NPol$: Number of samples per polarization.

Output:

- **AOutput**: Output signal after CD insertion. 'AOutput' is arranged in columns in the same way as 'AInput'.

4.2.2 Implementation and simulation of the Polarization Mode Dispersion

The function shown down below simulates the phenomenon of polarization mode dispersion and:

- Calculates the standard deviation of the Maxwell distribution and the Differential Group Delay (DGD) for each section.
- Creates the frequency vector (w) for FFT processing.
- Creates random unitary matrices V and U to describe mode coupling using Singular Value Decomposition (SVD).
- Calculates the group delay by obtaining the transfer matrix H for specific frequencies, computing its eigenvalues.
- Converts the input signal into the frequency domain using FFT.
- For each section, rotates the signal according to the U and V matrices, applies the DGD (differential group delay) and rotates again.
- Converts the signal back to the time domain using the Inverse FFT (IFFT).

```
function [EOutput,varargout] = PMDInsertion(EInput,DGDSpec,L,N,Rs,SpS
    ,...
EvalGroupDelay)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% PMDINSERTION [EOutput,varargout] = PMDInsertion(EInput,DGDSpec,L,N,
    Rs,SpS,EvalGroupDelay)

% This function simulates the PMD insertion in pol. multiplexed
    signals
% ('EInput'). The PMD model considers a cascade of 'N' sections, a
    mean
% DGD of 'DGDSpec' and a fiber of length 'L'. This function also
% estimates the group delay of one realization of the 'PMD channel'
    when
% the flag 'EvalGroupDelay' is set to true.
% Input:
% EInput = Input signal. 'EInput' must be a matrix with two
% columns, where each column has the signal of a pol.
% orientation (V and H pol. orientations);
% DGDSpec = Mean DGD in [ps/(km)^(1/2)];
% N = Number of sections of the PMD model;
% L = Fiber length [m];
% Rs = Symbol rate in [symbols/s];
% SpS = Number of samples per symbol in the input signal
```

```
% 'EInput';
% EvalGroupDelay = Variable to enable (true) or disable (false) the
% group delay estimation of one realization of the 'PMD
% channel'. To estimate the distribution of the
% accumulated DGD, the group delay of several
% realizations of the 'PMD channel' must be done.
% *Note: If this function is only used to obtain empirically the
% distribution of the accumulated DGD, 'EInput', 'Rs' and 'SpS' can be
% defined as: 'EInput = [0 0]' ; 'Rs = 0' ; 'SpS = 0';
% *Note: When EvalGroupDelay = false, the function has only one output;
%
% Output:
% EOutput = Output signal after PMD insertion. 'EOutput' is arranged
% in columns in the same way as 'EInput';
% varargout = Group delay in [ps], when 'EvalGroupDelay = true';

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Standard deviation of the Maxwellian distribution:
SDTau = sqrt(3*pi/8)*DGDSpec;
% DGD per section (it is equal to the standard deviation per section):
Tau = (SDTau*sqrt(L*1e-3)/sqrt(N))*1e-12;
% Frequency vector:
w = 2*pi*fftshift(-1/2:1/size(EInput,1):1/2-1/size(EInput,1)).'*SpS*Rs;
% Random unitary matrices V and U that describes mode coupling:
for i = 1:N
    [V(:,:,i),~,U(:,:,i)] = svd(randn(2) + 1i*randn(2));
end
% Estimation of the group delay (GD operator):
if EvalGroupDelay
    % Frequencies to consider when evaluating the group delay:
    wGD = [1 1.1];
    % Obtaining the transfer matrix H:
    for k = 1:numel(wGD)
        % Auxiliary matrix:
        HAux = 1;
        % Delay matrix (Lambda):
        Lambda = [exp(1i*wGD(k)*Tau/2) 0; 0 exp(-1i*wGD(k)*Tau/2)];
        % Transfer function of the i-th section and matrix H:
        for i = 1:N
            Hi = V(:,:,i)*Lambda*U(:,:,i)' ; HAux = HAux*Hi;
        end
        % Matrix H for frequency indicated by k:
        H(:,:,k) = HAux;
    end
    % Obtaining the eigenvalues (num. differentiating H):
    HDiff = (H(:,:,2)-H(:,:,1))/(wGD(2)-wGD(1));
    Eigenvalues = eig(1i*HDiff/(H(:,:,2)));
    % Group delays in ps:
    GroupDelay = abs(real(2*Eigenvalues(1)*1e12));
    varargout{1} = GroupDelay;
end
% Signals in frequency domain:
Freq_E_V = fft(EInput(:,1)) ; Freq_E_H = fft(EInput(:,2));
for i = 1:N
    % Hermitian of matrix U:
    UHermitian = U(:,:,i)';
```

```
    % Rotating the signals according to U:
    E_1 = UHermitian(1,1)*Freq_E_V + UHermitian(1,2)*Freq_E_H;
    E_2 = UHermitian(2,1)*Freq_E_V + UHermitian(2,2)*Freq_E_H;
    % Applying DGD:
    E_1 = exp(1i*w*Tau/2).*E_1 ; E_2 = exp(-1i*w*Tau/2).*E_2;
    % Rotating the signals according to V:
    Freq_E_V = V(1,1,i)*E_1 + V(1,2,i)*E_2;
    Freq_E_H = V(2,1,i)*E_1 + V(2,2,i)*E_2;
end
% Signals in time domain:
EOutput(:,1) = ifft(Freq_E_V) ; EOutput(:,2) = ifft(Freq_E_H);
end
```

[**9**] Going into details:

[EOutput,varargout] = PMDInsertion(EInput,DGDSpec,L,N,Rs,SpS,EvalGroupDelay)

This function simulates the PMD insertion in polarization multiplexed signals ('EInput'). The PMD model considers a cascade of 'N' sections, a mean DGD of 'DGDSpec' and a fiber of length 'L'. This function also estimates the group delay of one realization of the 'PMD channel' when the flag 'EvalGroupDelay' is set to true.

Input:

- **EInput**: Input signal. 'EInput' must be a matrix with two columns, where each column has the signal of a polarization orientation (Vertical and Horizontal polarization orientations).
- **DGDSpec**: Mean DGD in [ps/(km)$^{1/2}$].
- **N**: Number of sections of the PMD model.
- **L**: Fiber length in [m].
- **Rs**: Symbol rate in [symbols/s].
- **SpS**: Number of samples per symbol in the input signal 'EInput'.
- **EvalGroupDelay**: Variable to enable (*true*) or disable (*false*) the group delay estimation of one realization of the 'PMD channel'. To estimate the distribution of the accumulated DGD, the group delay of several realizations of the 'PMD channel' must be performed.

Note:

- If this function is only used to empirically obtain the distribution of the accumulated DGD, 'EInput', 'Rs' and 'SpS' can be defined as:
  - `EInput = [0 0];`
  - `Rs = 0;`
  - `SpS = 0;`
- When `EvalGroupDelay = false`, the function has only one output.

Output:

- **EOutput**: Output signal after PMD insertion.’EOutput’ is arranged in columns in the same way as ’EInput’.
- **varargout**: Group delay in [ps], when `EvalGroupDelay = true`.

Chapter 5

Analyses on the transmitter

After giving a general view on the operation of the optical fiber's channel, this thesis focuses on the transmitter side. In particular it was examined how the transmitter deals with errors and how these errors propagate through the channel.

The analyses on the transmitter were done through a program that randomly simulates the presence of an error (seen as an amplitude glitch) in the communication line and assign it to a node multiple times, in a random way too.

5.1 Amplitude Glitch

The term glitch is used to refer to a brief and sudden spike (non-periodic) in a waveform, caused by an unpredictable error. Specifically an amplitude glitch refers to a sudden and unexpected change in the amplitude of a signal, typically observed in waveforms. They are unintended signal transitions that occur due to imbalanced path delays at a gate's inputs. The presence of glitches in a digital system increases the number of signal transitions, which in turn raises the dynamic power consumption of the system. Consequently, the overall power consumption—an essential design criterion in digital systems—also increases. Additionally, glitches have been identified as a source of side-channel leakage and can be exploited to improve the success rate of power analysis attacks on cryptographic applications, even in the presence of side-channel countermeasures. Therefore, eliminating glitches in digital systems implemented on hardware platforms, such as Field Programmable Gate Arrays (FPGAs), is critical for achieving low-power and secure designs. However, effective application of glitch elimination techniques requires accurate detection of potential glitches. While post place-and-route simulation can detect and display glitches, it does not account for FPGA process variations and depends solely on the simulation model's accuracy.

The main effects of an amplitude glitch are the following:

- **Signal Distortion:** Amplitude glitches can distort the intended waveform, leading to errors in data transmission or signal interpretation.
- **Bit Errors:** In digital communication systems, amplitude glitches can cause bit errors, resulting in data corruption.
- **Performance Degradation:** Continuous presence of glitches can degrade the overall performance of electronic devices and systems, impacting reliability and efficiency.

To better analyze the effects of the glitch, it was chosen to simulate three different values of its amplitude. In particular: 254 ps, 351 ps and 453 ps. The total number of simulated nodes is 837. After running the simulation, they were obtained reports describing the propagation of the glitch and the main features of the signal after the glitch (max amplitude, broadening and probability of occurrence of the error). Thanks to those reports it was possible to understand which was the probability of having an error in each node exploiting the following formula:

$$\text{error}_{\text{probability}} = \frac{\text{max}_{\text{ampl}}}{T} \times 100 \quad [\%] \tag{5.1}$$

where

- T= 5 ns is the period, f= 200 MHz is the frequency
- max_{ampl} is the maximum amplitude of the signal

5.2 Results

With the data collected in the reports it was possible to generate boxplot graphs to better understand the trend of the errors. The Figures 5.1, 5.2 and 5.3 show the three boxplots for each glitch amplitude. As it can be seen they are organized in ascending order of the 75th percentile's value. The '+' represent the outliers points and the red line in the middle is the median value of the range.

Figure 5.1: Box Plot for 254 ps

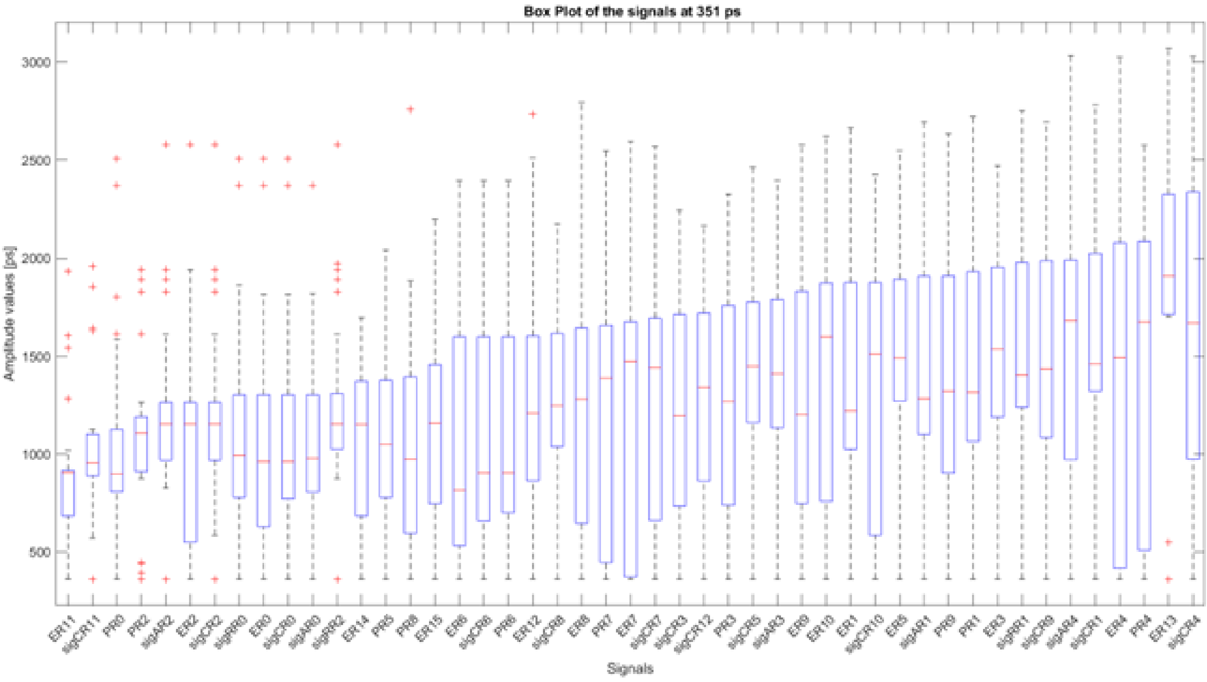

Figure 5.2: Box Plot for 351 ps

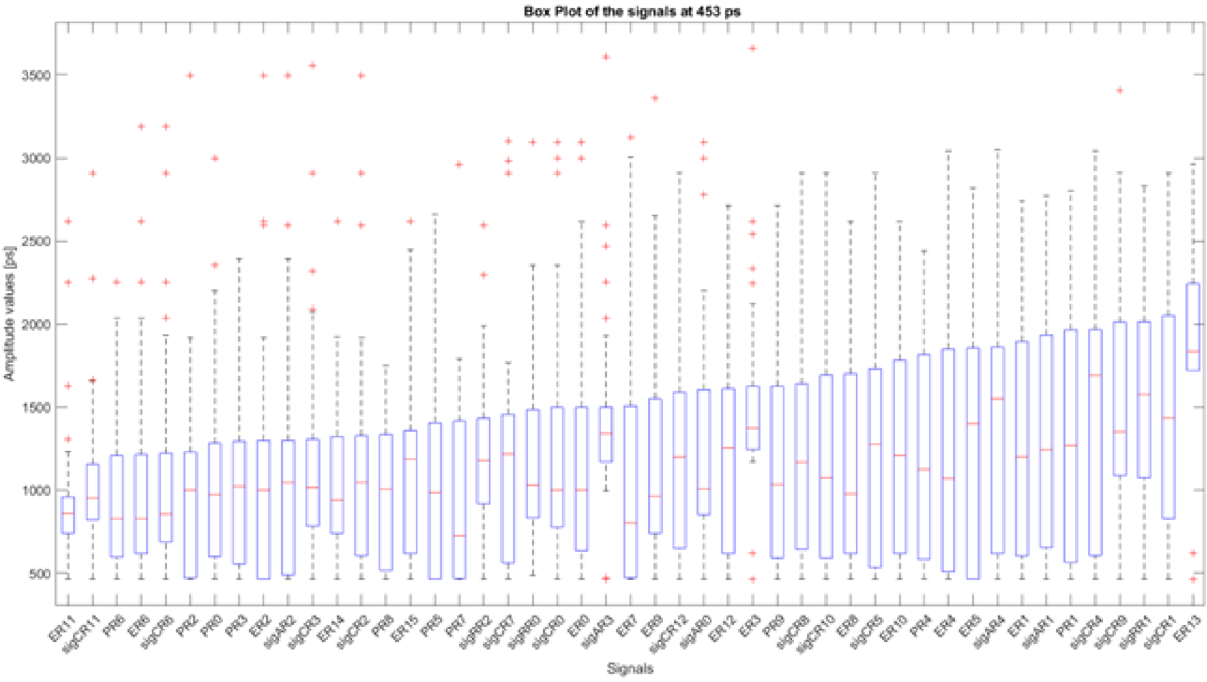

Figure 5.3: Box Plot for 453 ps

What is evident from the graphs is that the error affects each signal in a different and random way. Considering the boxplot in Figure 5.3, signals like ER11, sigCR6, sigCR3 and sigAR3, for instance, on the far right show a larger concentration of outliers, suggesting they may have significant variability or noise. In general ome boxes are more symmetrical, indicating a balanced distribution of values around the median, while others are skewed, with the median closer to one end of the box, showing an uneven distribution of values. The median amplitude values generally increase from left to right, suggesting a progressive increase in the central tendency of signal amplitude.

Through the propagation report it was possible to compute the sensitivity and vulnerability factor for each set of events existing for each glitch's amplitude, as reported in Figures 5.4 and 5.5. To do that it was implemented a MATLAB code that counts how many events exist and how many time a single event is repeated in the simulation.

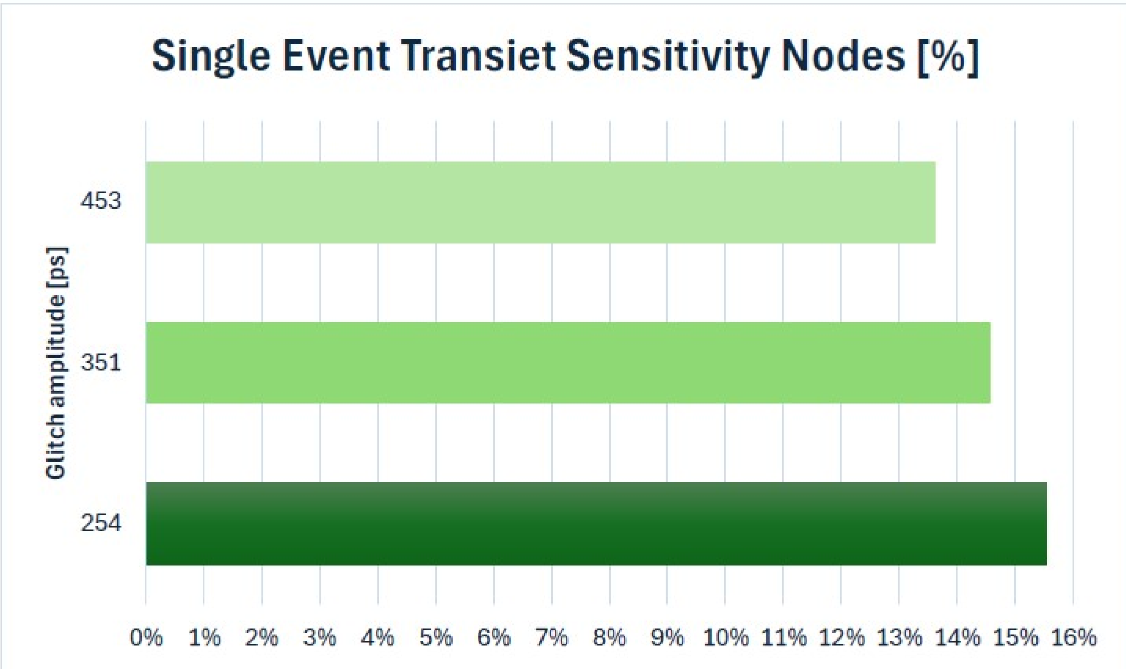

Figure 5.4: Single event transient sensitivity nodes

As it can be seen in the chart above, the error sensitivity is inversely proportional to the glitch's amplitude. In particular: for 245 ps of amplitude the sensitivity is about 15.5%, for 351 ps is about 14.6% and for 453 ps is about 13.6%.

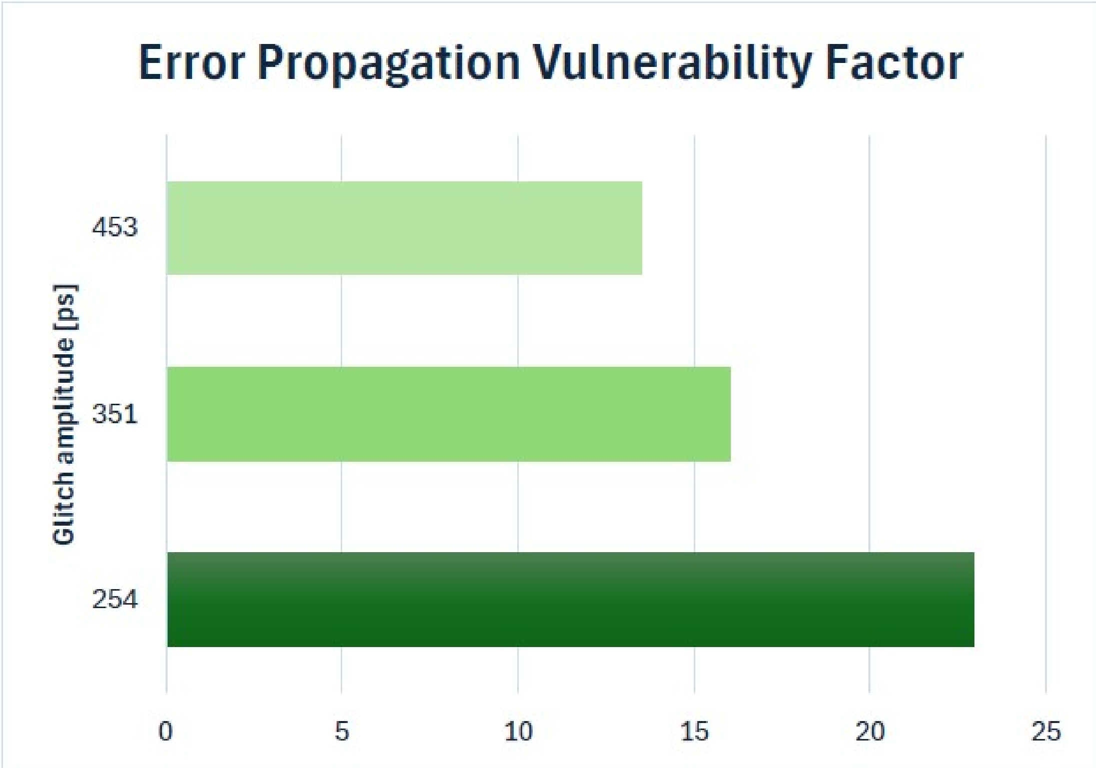

Figure 5.5: Error propagation vulnerability factor

Also for the vulnerability factor is evident the inverse proportionality between it and the glitch's amplitude. In particular: for 245 ps of amplitude the vulterability factor is about 23, for 351 ps is about 16 and for 453 ps is about 13.

This could indicate that systems are more vulnerable to errors and transients when the glitch amplitude is smaller. This might suggest that the system needs to be particularly robust against small glitches to prevent error propagation and maintain reliability.

Chapter 6

Experimental results

6.1 Optical fiber channel

The graphs in Figures 6.2 and 6.4 show the results obtained from the simulation. Specifically, vertical polarization represents the signal coming from the VHDL, while horizontal polarization represents the randomly generated signal. As it can be observed, both polarization modes are affected by the two types of dispersion applied.

Chromatic Dispersion (CD) causes frequency components to spread out over time, leading to intersymbol interference and signal degradation. This spreading can be quantified in terms of increased pulse duration. In addition to spreading, the shape of the signal can be distorted. The different spectral components not only separate temporally but can also change shape due to differing group velocities. This dispersion effect becomes more pronounced as the signal bandwidth increases, posing a significant challenge for high-speed optical communication systems.

Regarding Polarization Mode Dispersion (PMD), the temporal spreading of the signal due to PMD can lead to overlap between successive pulses, causing intersymbol interference. This phenomenon reduces the receiver's ability to clearly distinguish between different symbols, increasing the bit error rate (BER). Basically, the propagation of a pulse in a first order section induces a pulse splitting in two replicas as it can be seen in Figure 6.1. [**26**]

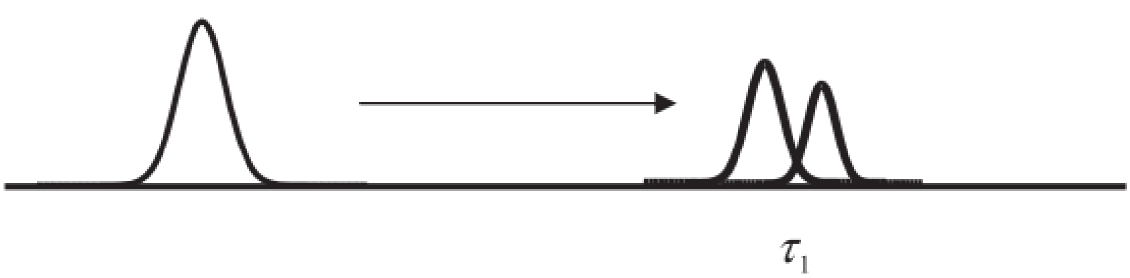

Figure 6.1: Pulse Splitting through PMD

More specifically, the Figure 6.2 and 6.3 represent the input and output signals of the vertical polarization once with respect to the number of bit and once with respect to the time interval. The blue line represents the input signal and the red line shows the output signal. A significant difference between them suggests that the signal has been distorted during transmission through the fiber channel and the distortions can be classified as follows:

- Amplitude Deviation: The most striking feature is the significant deviation between the input and output signals. The output signal exhibits increased amplitude fluctuations. These fluctuations are primarily a result of CD, which causes different frequency components to propagate at varying velocities, thus stretching the signal and causing phase distortions.

- Increased Oscillations: The output signal exhibits more rapid oscillations than the input. This can be attributed to the time-domain spreading caused by CD, which is evident from the higher frequency content in the output signal. Additionally, the V-polarized mode is more susceptible to PMD-induced delays, which contributes to the differential arrival of frequency components, thus further compounding the observed oscillations.

- Phase Shift: There is also a noticeable phase shift between the input and output signals, which is a direct consequence of PMD. Since PMD affects the polarization modes differently, it introduces a group delay between the components of the V-polarized signal. This delay causes a misalignment between the input and output signals, which is manifested as a phase shift.

Obviously, to show the results in more detail, the graphs have been zoomed in.

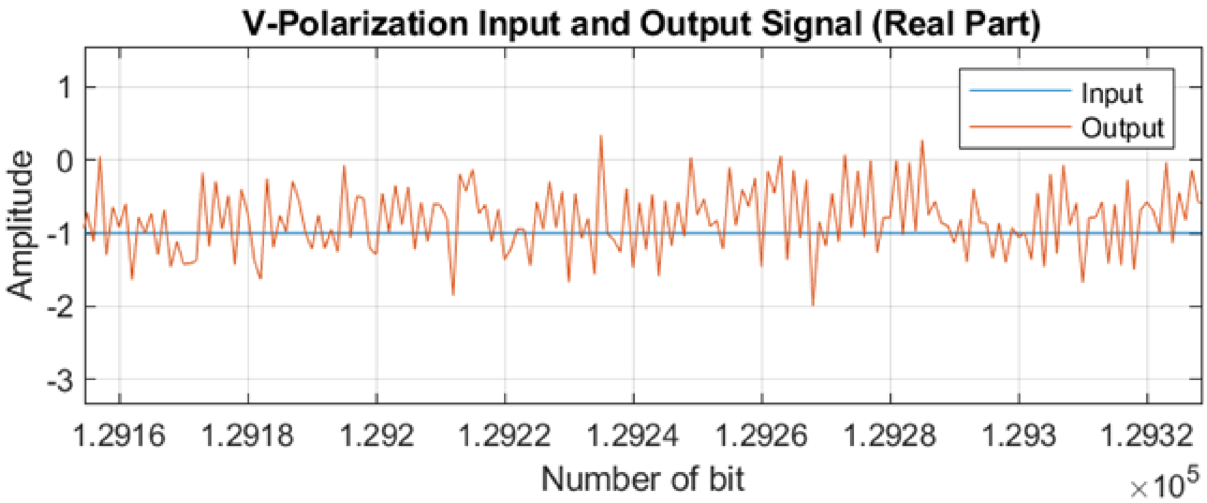

Figure 6.2: Vertical polarization amplitude vs number of bit

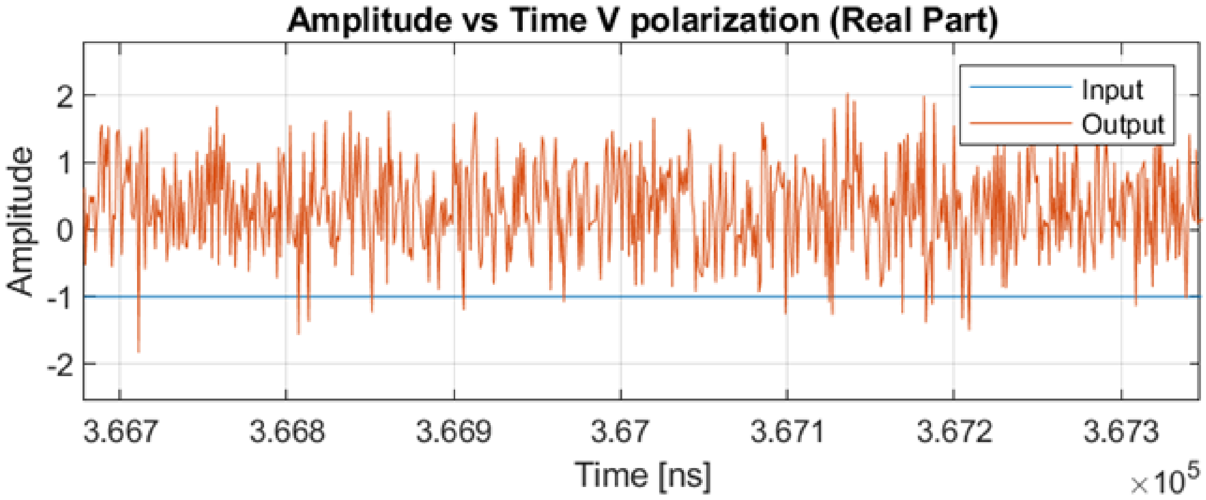

Figure 6.3: Vertical polarization amplitude vs time

Summing up, the impact of CD is clearly visible in the form of amplitude spreading and increased oscillations, while PMD contributes to phase distortions.

Like the vertical polarization graph, the Figures 6.4 and 6.5 show a comparison of the input and output signals. Also in this case there are three main distortions to focus on:

- Amplitude Correlation: In contrast to the V-polarization results, the H-polarization plot shows less severe amplitude deviations between the input and output signals. While there are still visible distortions, the output signal more closely follows the input signal, indicating that the H-polarized signal has experienced less degradation. This can be explained by the fact that PMD affects each polarization mode differently. In this case, the H-polarized signal has experienced a lower degree of differential delay.

- Reduced Oscillations: Unlike the V-polarized signal, the output signal in the H-polarization plot does not exhibit the same level of high-frequency oscillations. This suggests that the chromatic dispersion has had a lesser impact on the H-polarized signal, potentially due to different propagation characteristics of the polarization mode. The lower frequency content in the H-polarized output signal implies that the signal's integrity is less compromised compared to its V-polarized counterpart.

- Phase Alignment: The phase shift between the input and output signals is less pronounced in the H-polarized mode. This can be attributed to the smaller differential group delay introduced by PMD in the H-polarized component of the signal. Since PMD affects the two orthogonal polarization modes unequally, the H-polarized mode in this case is less delayed than the V-polarized mode, leading to improved phase alignment at the output.

Obviously, to show the results in more detail, the graphs have been zoomed in.

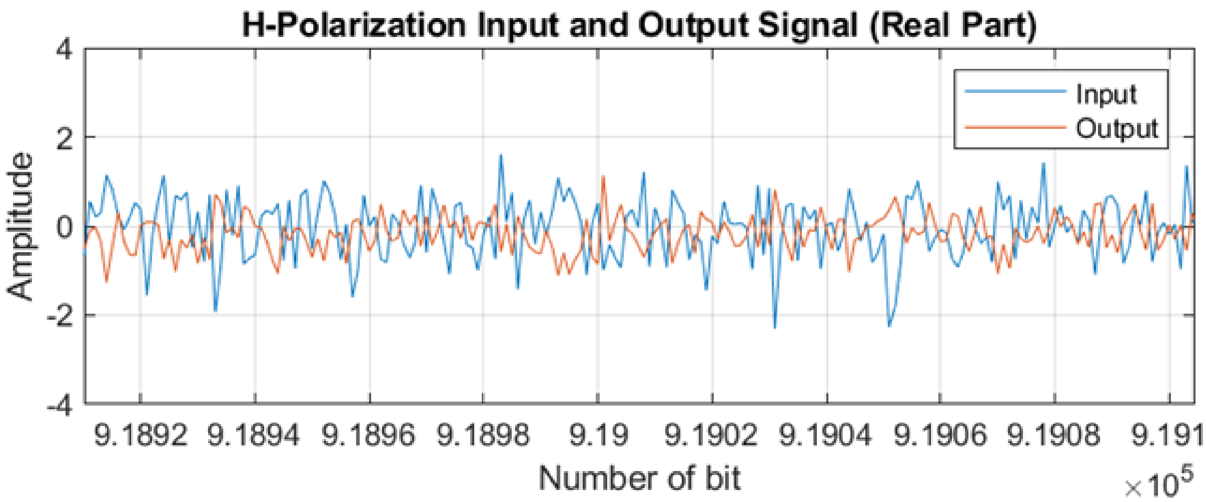

Figure 6.4: Horizontal polarization amplitude vs number of bit

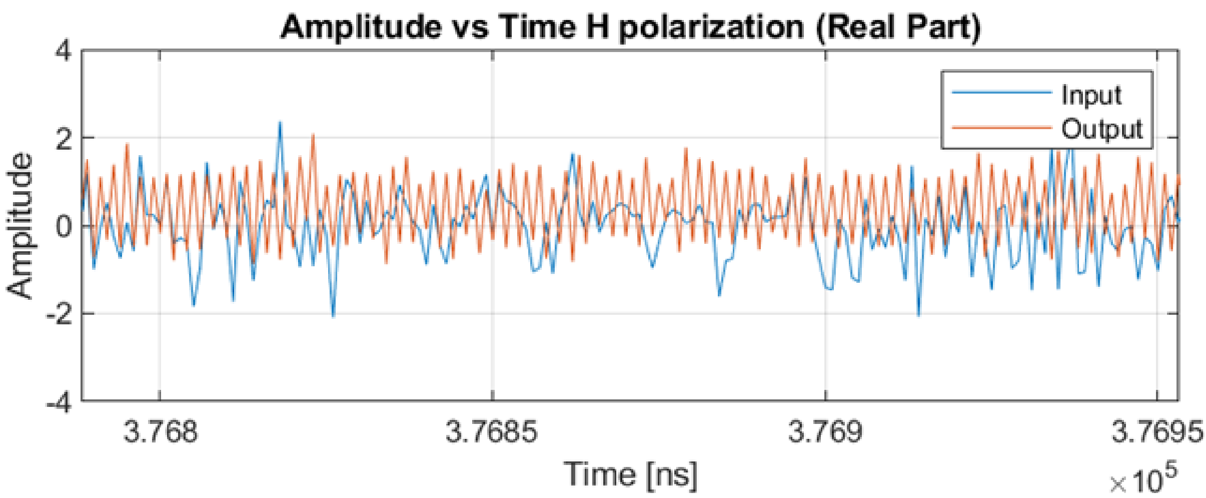

Figure 6.5: Horizontal polarization amplitude vs time

While both CD and PMD have introduced some degree of distortion to the H-polarized signal, the effects are noticeably less severe compared to the V-polarized mode. The reduced amplitude distortion and oscillations in the output suggest that the H-polarized mode has retained more of its original integrity, possibly due to its lesser susceptibility to birefringence effects or differential group delays introduced by the fiber.

Without compensation techniques, such as digital signal processing (DSP), the signal would likely suffer from significant errors in a real-world communication system.

6.1.1 Computation of Bit Error Rate (BER)

In simulations, the BER is typically calculated by comparing the transmitted bits with the received bits after passing through the channel model. A typical simulation workflow involves generating random bit sequences, modulating the data, passing the modulated signal through a noise model, demodulating the received signal and finally comparing the transmitted and received data to compute BER.

For what concerns this thesis' project the BER is computed in two different ways.

The first one is described as follows:

1. **Modulation**: The binary data is mapped to QAM symbols using MATLAB's `qammod` function.

2. **Channel**: The modulated symbols are transmitted over the optic fiber's channel, introducing noise proportional to the desired SNR.

3. **Demodulation**: The noisy received symbols are demodulated back to binary data using `qamdemod`.

4. **BER Calculation**: The original and received bits are compared to calculate the number of bit errors and the BER is computed through the MATLAB's `biterr` function which creates a two columns vector representing the number of differences between bits in comparison and the ratio of erroneous bits to the total number of transmitted bits.

For this project's simulation were considered a number of bits of 1000000 and what is obtained is a number of differences equal to 2460304 and a ratio of erroneous bit equal to 0.615076.

The second way goes more into details since it exploits the Q function that is essential for calculating the (BER) particularly in systems affected by Additive White Gaussian Noise (AWGN). The Q-function gives the probability that a Gaussian random variable with mean 0 and variance 1 exceeds a certain value. In the context of BER, it calculates the probability that noise will cause an error in detecting a transmitted bit. There are several ways to compute the BER through the Q function and they depend on the type of modulation used. In this simulation the QPSK modulation is applied in which two bits are modulated at once. This allows the signal to carry twice as much information as ordinary PSK using the same bandwidth. Considering that in a noisy channel the BER is also often expressed as a function of the normalized carrier-to-noise ratio measure denoted E_b/N_0, (energy per bit to noise power spectral density ratio in dB), for QPSK modulation it can be used the following formula:

$$\text{BER}_{\text{QPSK}} = Q\left(\sqrt{2 \cdot \frac{E_b}{N_0}}\right) \tag{6.1}$$

where:

- $Q(\cdot)$ is the Q-function, which gives the tail probability of the Gaussian distribution.

- E_b is the energy per bit.

- N_0 is the noise power spectral density.

In order to compute in MATLAB the theoretical value of BER through the formula above it is necessary to assume the value of the Signal to Noise Ratio (SNR), which is expressed in the formula through the ratio E_b/N_0. In particular:

$$\frac{E_b}{N_0} = \frac{\text{SNR}}{R_b/B} \tag{6.2}$$

where:

$$R_b = \frac{1}{5 \times 10^{-9}\,\mathrm{s}^{-1}} = 200\,\mathrm{Mbps} \tag{6.3}$$

$$B \approx \frac{R_b}{\log_2(M)} = \frac{200\,\mathrm{Mbps}}{2} = 100\,\mathrm{MHz} \tag{6.4}$$

knowing that M is the modulation order (for QPSK, $M = 4$) and $\log_2(M)$ is the number of bits per symbol (for QPSK, $\log_2(4) = 2$).

The BER vector is 21 numbers long because the code generates and evaluates BER for 21 different SNR values, ranging from 0 dB to 20 dB.

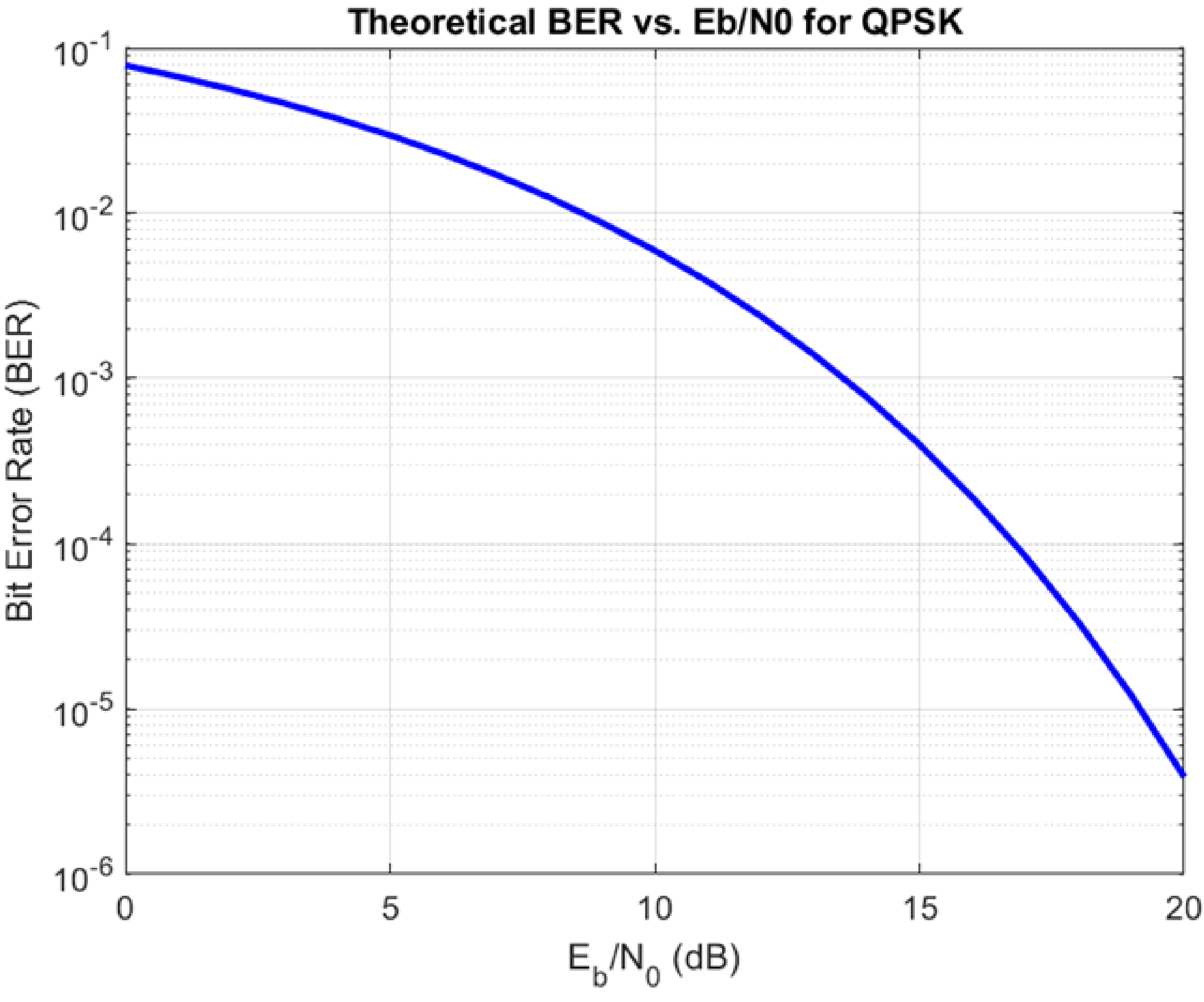

Figure 6.6: Theoretical BER

What is evident from the graph above is that the SNR and the BER are inversely proportional. This is because a higher SNR means the signal is stronger relative to the noise, leading to fewer errors in bit detection and at high SNR values, the BER approaches its theoretical minimum value. At low SNR values, the BER is high because the noise dominates, making it difficult to distinguish the signal from the noise. For practical purposes, the system is considered to perform well when the BER is very low.

Another significant aspect to analyze is the comparison between the theoretical and empirical BER that is reported in Figure 6.7.

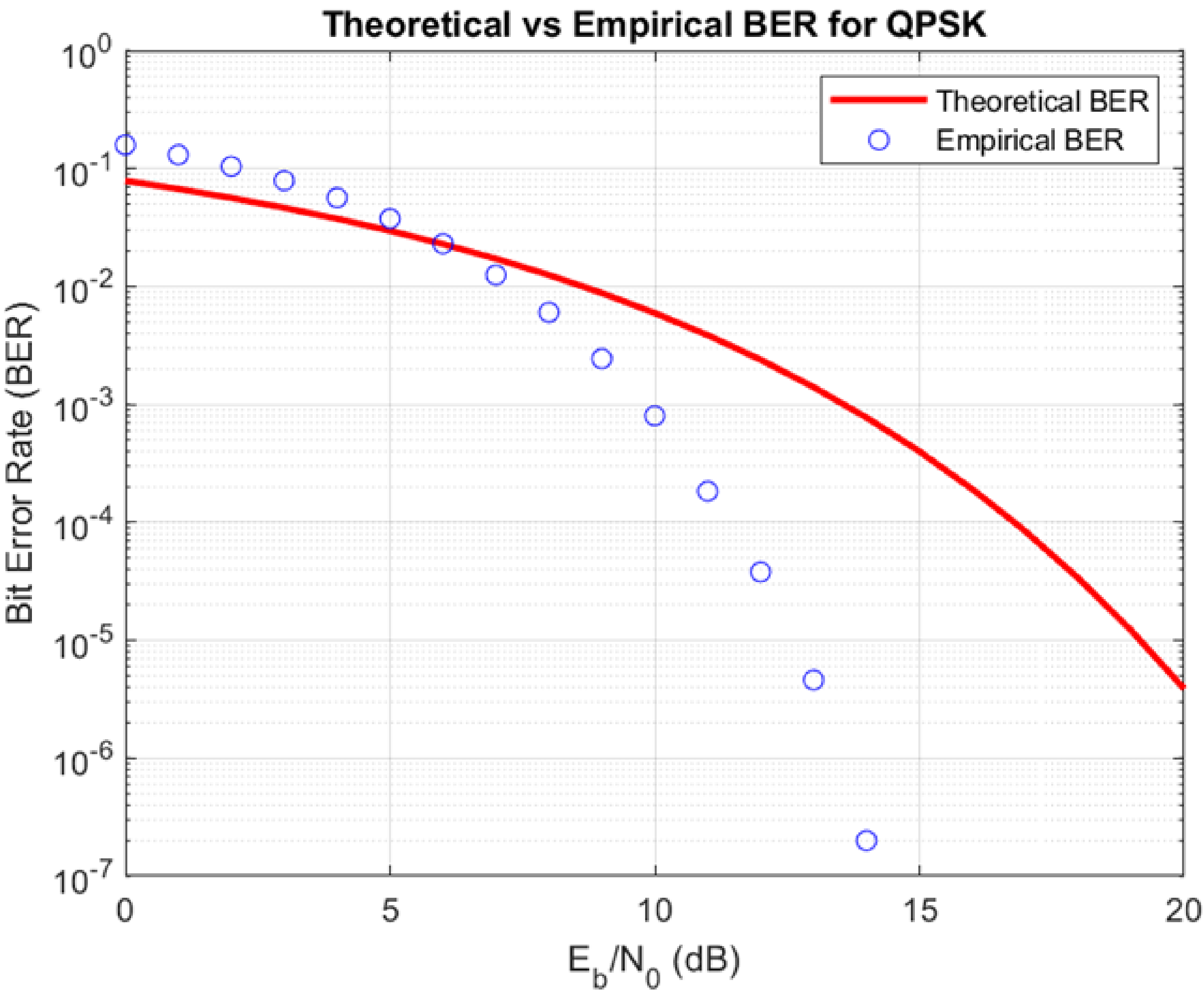

Figure 6.7: Theoretical BER vs Empirical BER

The graph shows that for low values of E_b/N_0 the empirical BER is higher than the theoretical one. That is because at low SNR the noise is stronger than the signal and the system is more prone to be affected by errors. As E_b/N_0 increases, the empirical BER decreases, closely matching the theoretical BER. The evident difference between the two BER may be attributed to the fact that the theoretical one is computed using the Q-function which gives back a probability computed for the worst case, so a higher number, instead the empirical one is computed as the ratio between the erroneous bits and the total number of transmitted bits, thus the actual value.

Chapter 7

Mitigation

As it has been showed, once signals enter the optical fiber channel they experience a distortion given by CD and PMD, increasing the BER. What is interesting to do is to understand how the signals arrive at the beginning of the channel, so right after the transmitter. This aspect is examined in chapter 5. There it can be seen that signals are already distorted before entering the optical channel. Once have learned that, it could be useful to think about the mitigation of those errors. A good solution to that can be LMS adaptive filter, that minimizes the error difference between the adaptive filter output and the desired signal that in this case is the input signal itself.

7.1 LMS adaptive filter

Least mean squares (LMS) algorithms are a class of adaptive filters used to mimic a desired filter by finding the filter coefficients that relate to producing the least mean square of the error signal (difference between the desired and the actual signal). It is a stochastic gradient descent method in that the filter is only adapted based on the error at the current time. An LMS filter consists of two components as shown below. The first component is a standard transversal or FIR (finite impulse response) filter. The second component is a coefficient update mechanism. The LMS filter has two input signals. The "input" feeds the FIR filter while the "reference input" corresponds to the desired output of the FIR filter. That is, the FIR filter coefficients are updated so that the output of the FIR filter matches the reference input. The filter coefficient update mechanism is based on the difference between the FIR filter output and the reference input. This "error signal" tends towards zero as the filter adapts. The LMS processing functions accept the input and reference input signals and generate the filter output and error signal.

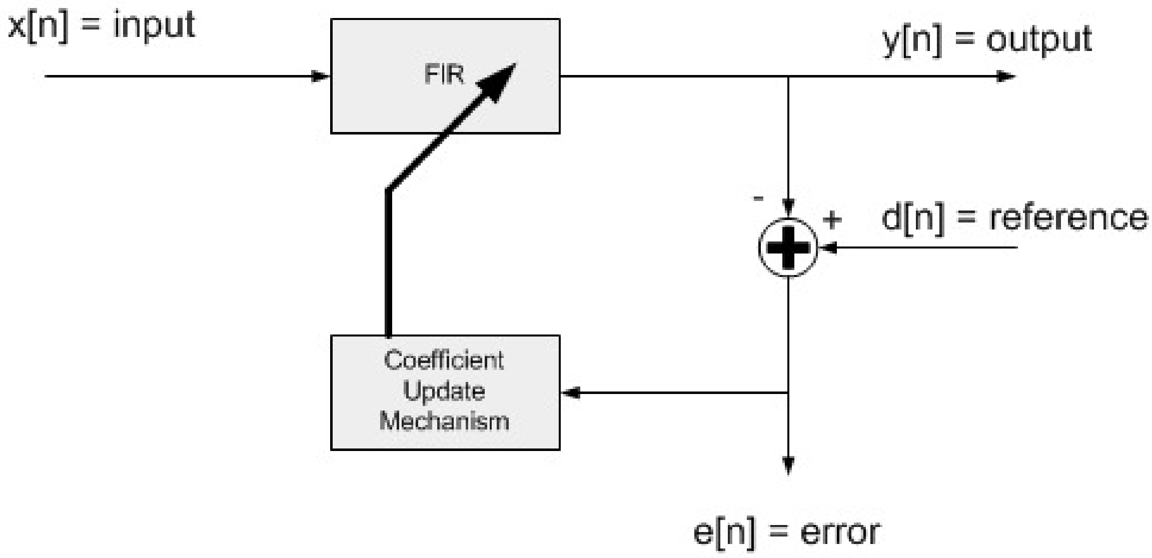

Figure 7.1: LMS filter

The functions operate on blocks of data and each call to the function processes block-Size samples through the filter points to input signal, points to reference signal, points to output signal and points to error signal. All arrays contain blockSize values.

The functions operate on a block-by-block basis. Internally, the filter coefficients b[n] are updated on a sample-by-sample basis. The convergence of the LMS filter is slower compared to the normalized LMS algorithm. [**27**]

7.1.1 LMS algorithm

The output signal $y[n]$ is computed by a standard FIR filter:

$$y[n] = b[0] \cdot x[n] + b[1] \cdot x[n-1] + b[2] \cdot x[n-2] + \ldots + b[\text{numTaps}-1] \cdot x[n-\text{numTaps}+1]$$

The error signal equals the difference between the reference signal $d[n]$ and the filter output:

$$e[n] = d[n] - y[n].$$

After each sample of the error signal is computed, the filter coefficients $b[k]$ are updated on a sample-by-sample basis:

$$b[k] = b[k] + e[n] \cdot \mu \cdot x[n-k], \quad \text{for } k = 0, 1, \ldots, \text{numTaps} - 1$$

where μ is the step size that controls the rate of coefficient convergence.

In the APIs, pCoeffs points to a coefficient array of size numTaps. Coefficients are stored in time-reversed order:

$$\{b[\text{numTaps}-1], b[\text{numTaps}-2], b[N-2], \ldots, b[1], b[0]\}$$

pState points to a state array of size numTaps + blockSize − 1. Samples in the state buffer are stored in the order:

$$\{x[n-\text{numTaps}+1], x[n-\text{numTaps}], x[n-\text{numTaps}-1],$$
$$x[n-\text{numTaps}-2], \ldots, x[0], x[1], \ldots, x[\text{blockSize}-1]\}$$

[**27**]

7.2 Implementation of LMS filter on MATLAB

The MATLAB function used in the algorithm to implement the LMS filter is `dsp.LMSFilter`.

The LMS algorithm iteratively adjusts filter coefficients based on the error signal, which is defined as the difference between the desired signal and the filter output. The filter operates on incoming signals by utilizing a FIR structure, where the output is computed as a weighted sum of the input samples, effectively capturing the characteristics of the signal over a specified number of taps. The filter's coefficients are updated in real time based on the computed error, using a predefined step size parameter that dictates the convergence rate of the filter. This adaptive approach allows the LMS filter to learn the optimal coefficients that minimize the mean square error between the desired output and the actual output, thereby enhancing signal fidelity. By processing the input signal in blocks, the LMS filter can efficiently handle large datasets while maintaining computational feasibility, making it particularly suitable for real-time applications in optical communication systems.

For all the graphs that will follow below, Channel 1 represents the vertical polarization and Channel 2 the horizontal polarization of the input signal.

7.2.1 Transmitter side

What is obtained applying the LMS algorithm is showed in Figures 7.2 and 7.3.

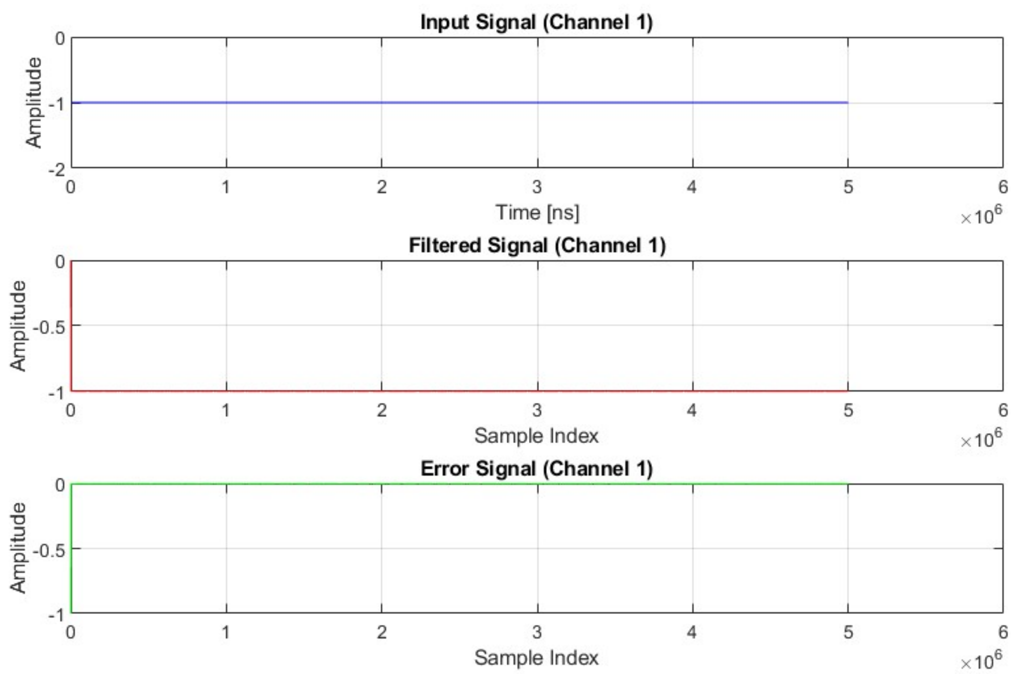

Figure 7.2: LMS filter on channel 1-transmitter side

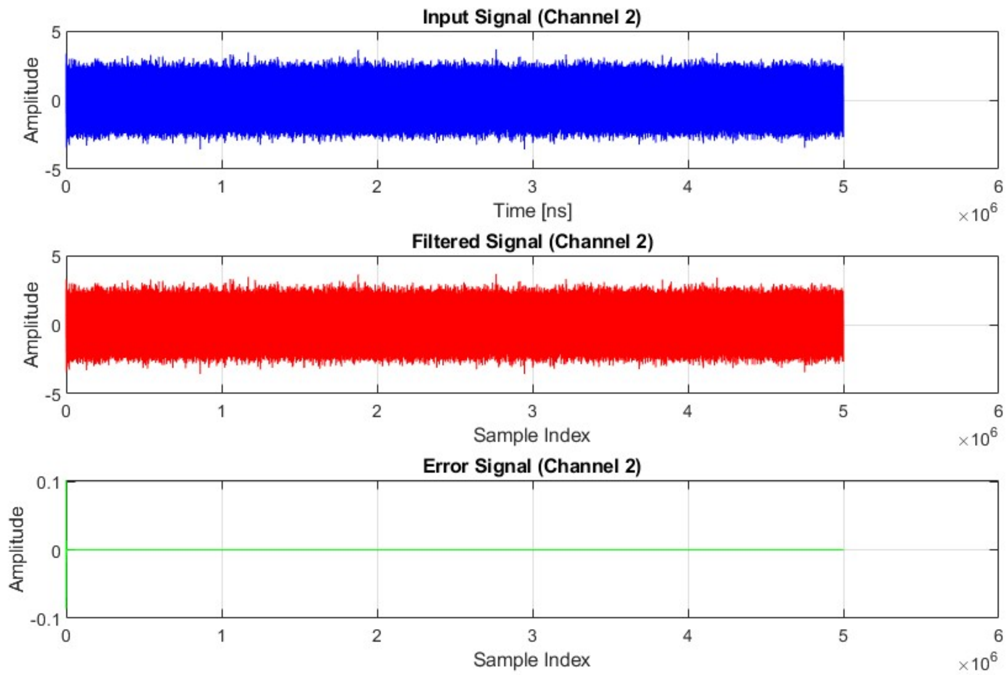

Figure 7.3: LMS filter on channel 2-transmitter side

The graphs, that shows only the real part of the signals, clearly illustrates that, once applied the LMS filter, the filtered signals maintain the same shape of the original one. That's because it was chosen to have the desired signal to be equal to the input and it was not delayed in any way. Moreover, to preserve the original shape it was imposed a number of blocks equal to the size of the original matrix. In this way, the algorithm divides the input signal into smaller segments (blocks) and applies the adaptive filtering algorithm to each of these segments sequentially.

For each block, the LMS filter applies its algorithm:

- It takes the current block of input samples
- It also takes the corresponding desired signal samples
- The LMS filter computes the filtered output and the error signal for that block
- The results for that block are then stored in the overall output arrays

What is clearly visible from the graph in Figure 7.2, so for the vertical polarization, is that the filtered signal appears to be a step signal at the beginning. This happens because when the LMS filter is applied, the filter coefficients are initialized to zero. This means that before any signal processing occurs, the output of the filter is also zero. Once the filter starts processing the input signal, it responds to the first sample (which is -1 in this case). This abrupt change from 0 to -1 can create a step-like appearance at the beginning of the filtered output. This might be solved by initializing the filter coefficients to small random values instead of zero. Anyway it could not be a big problem since, after the initial step, the filtered signal remains the same as the original signal and doesn't become distorted. Also for the second channel, so for the horizontal polarization, showed in Figure 7.3 the filter works correctly letting the signal not become distorted exiting the transmitter, therefore it suggests that the filter can perform well in scenarios with minimal pre-conditioning of the coefficients, making it versatile for practical applications.

7.2.2 Exit from the optical channel

The mitigation method proposed above operates on the errors happening on the signals coming from the transmitter side, right before entering the optical channel. This is because this thesis focuses mainly on the transmitter behavior without analyzing the receiver's one.

Without going deep into the receiver side it is possible to understand what happens right after the optical channel, before the signals enter the receiver, by applying the LMS filter to the output signals, as done for the transmitter side. What is obtained is showed in Figures 7.4 and 7.5

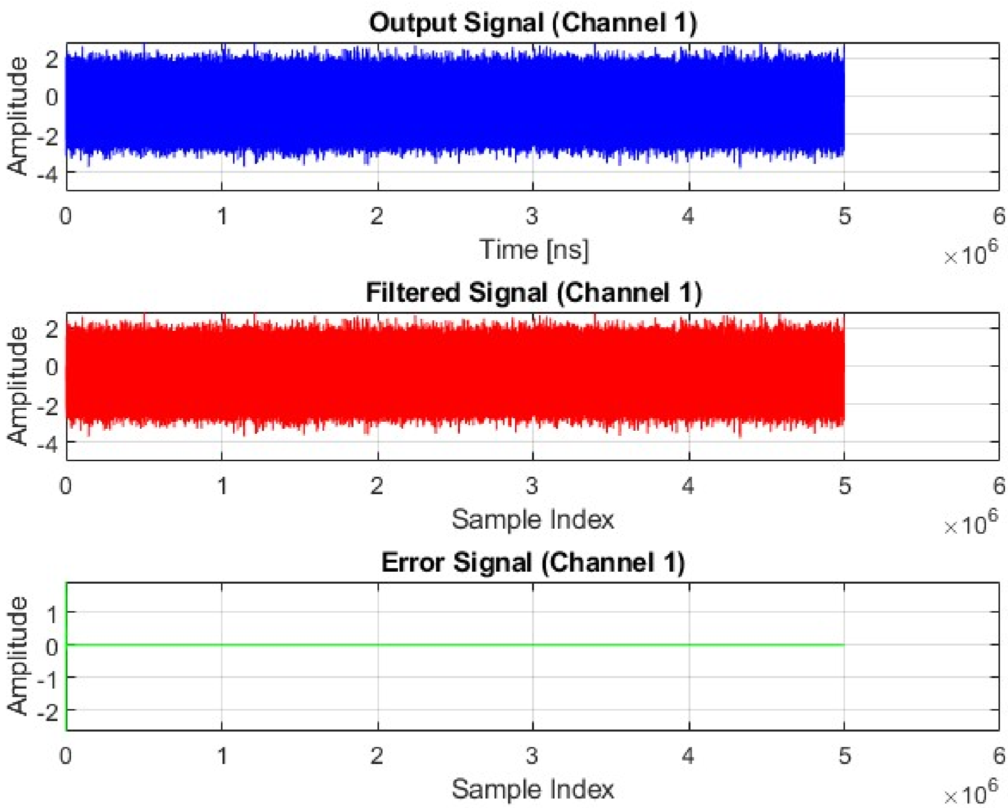

Figure 7.4: LMS filter on channel 1

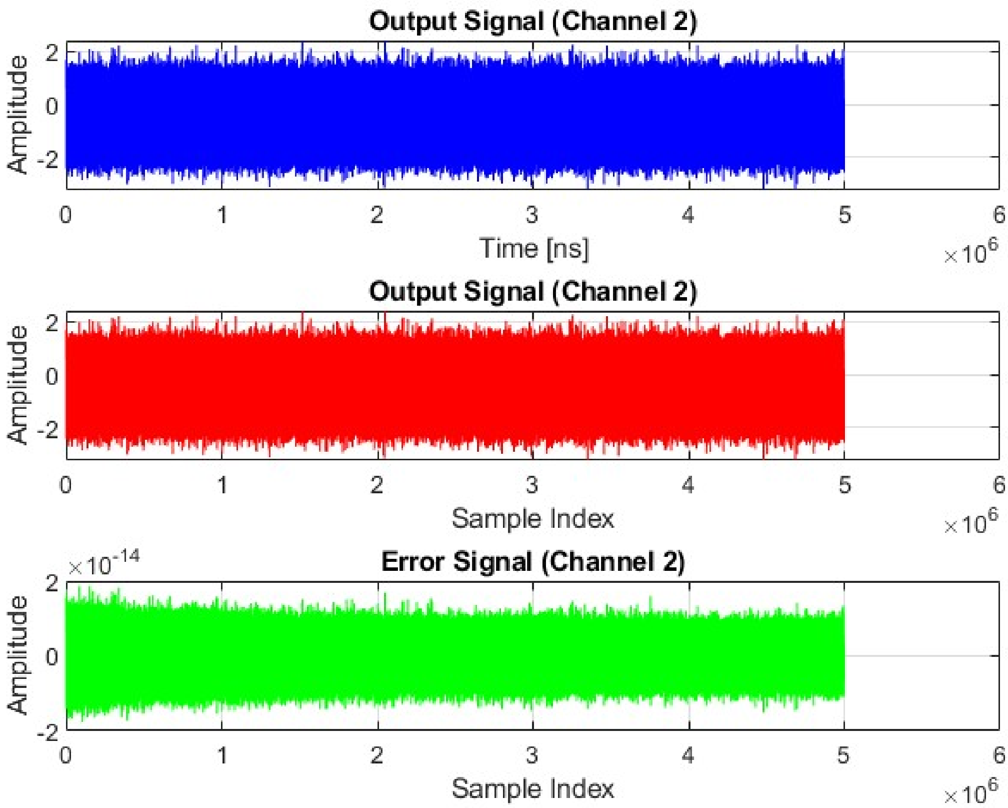

Figure 7.5: LMS filter on channel 2

What is evident from the graphs above is the optimal working of the LMS filter also in this case, since the filtered signals appear to follow the input behavior despite the complex shape.

7.3 Computation of the transmitter's BER

7.3.1 Transmitter side

As it was done for the BER computation of the optical channel, the BER for the transmitter was computed to assess the effectiveness of the mitigation techniques and the performance of the applied LMS filter. This recalculated BER was obtained in two distinct ways, following the methods outlined previously and using Equation 6.1.

The results show a total of 172 bit differences, leading to a BER of 8.6×10^{-6}. This value indicates a low error rate, suggesting that the filtering techniques are effective in maintaining signal integrity in the transmission process.

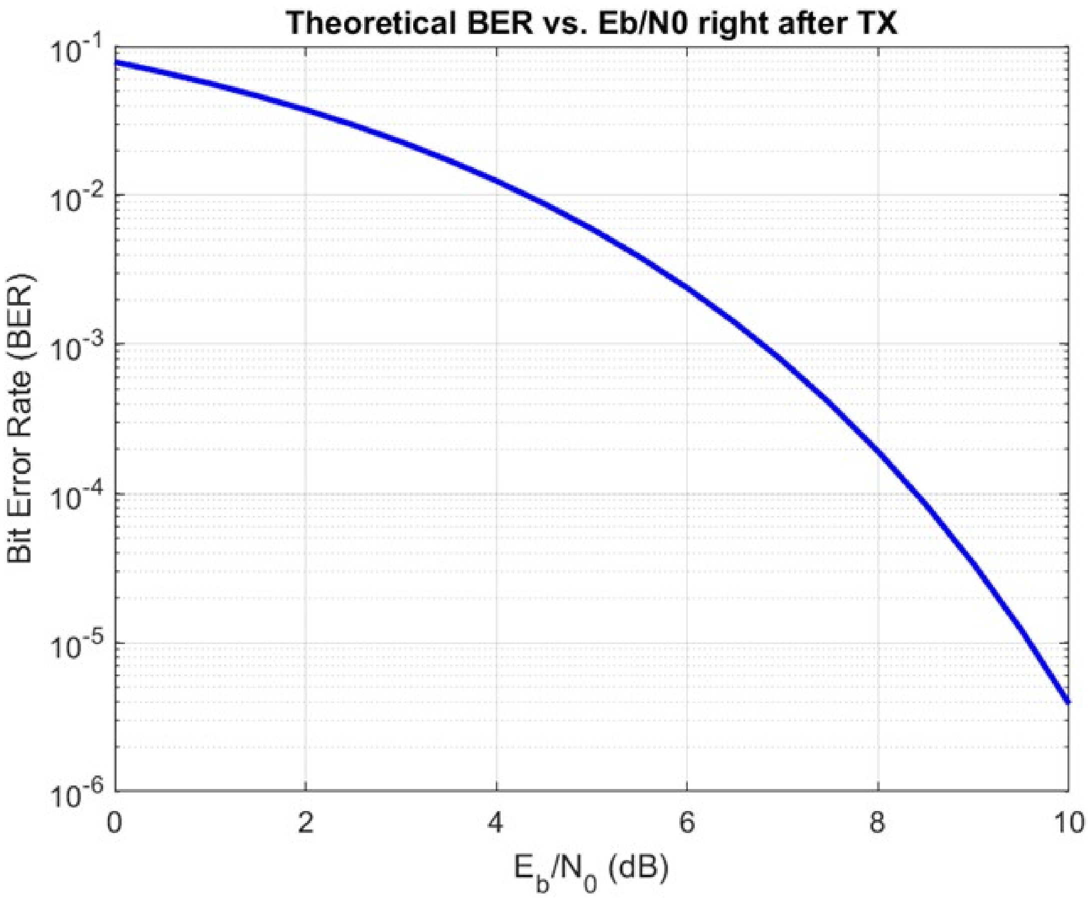

Figure 7.6: Theoretical BER of the transmitter

As shown in Figure 7.6 and confirmed by the numerical BER results, the error rate is extremely low. This supports the conclusion that the filters are performing effectively and significantly reducing transmission errors.

7.3.2 Exit from the optical channel

The same thing is done for the side after the optical channel. What is obtained is a total of 6272697 bit differences, leading to a BER of 0.314.

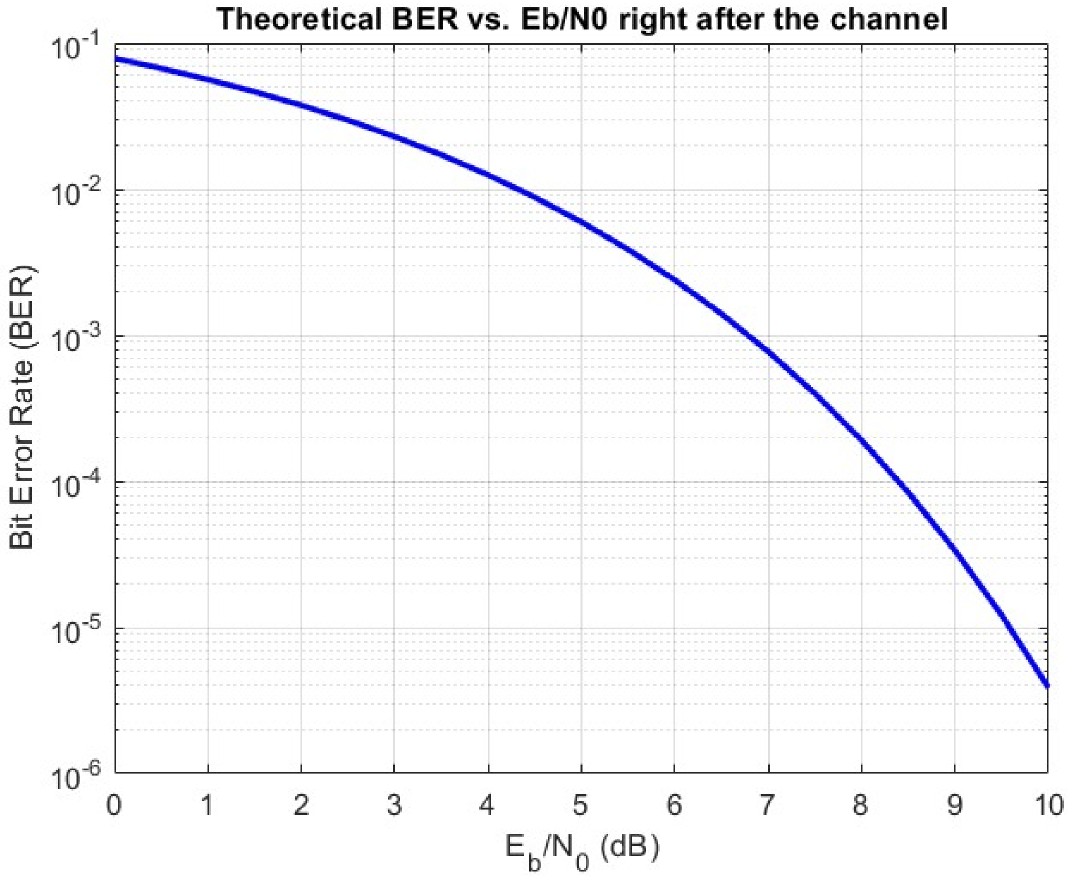

Figure 7.7: Theoretical BER after the optical channel

Since the signals exiting the optical channel are more distorted and have a complex shape, the BER is higher compared to that at the transmitter side; however, it still remains at an acceptable level.

These results show that the LMS filter can be an optimal solution to signal distortion and degradation, the filter's ability to adapt and correct the signal ensures that the output remains consistent with the original after the initial transient.

Conclusion

In conclusion, this thesis has provided an in-depth analysis of the main factors contributing to signal transmission over fiber optic channels, analyzing the principal components of an optical transmission system. Through a combination of theoretical modeling and practical simulations, this work examined the propagation characteristics within an optical fiber, identifying key factors that contribute to signal deterioration over long distances. In particular it was taken into account the distortion and the degradation of the signals in optical fiber transmission systems, with a specific focus on chromatic dispersion (CD) and polarization mode dispersion (PMD). These effects, inherent to the optical transmission medium, significantly influence the quality and integrity of the transmitted signal, resulting in increased bit error rates (BER) and posing challenges to high-speed data transfer.

A MATLAB model was a fundamental tool for simulating optical fiber behaviors under the influence of CD and PMD, while VHDL was exploited to implement a robust testing environment for the OTDR system. This approach enabled accurate generation and injection of laser pulses inside the optical channel, within which the signals have been modulated in order to be used in MATLAB.

To overcome the signal distortion, an adaptive LMS (Least Mean Squares) filter was implemented. The adaptive filter, designed and simulated within a MATLAB environment, showed considerable success in mitigating the effects of dispersion, reducing the BER to acceptable levels. Despite some divergence between theoretical BER and empirical findings at lower signal-to-noise ratios (SNR), the LMS filter consistently stabilized performance, highlighting its effectiveness in preserving signal integrity within high-speed optical transmission systems.

This work also introduced a detailed examination of transient events and their propagation through the system, analyzing how different amplitude glitches influenced transmission errors. Using statistical methods, sensitivity and vulnerability factors were computed, providing insights into the resilience of various system nodes against transient events. The results indicate that higher amplitude glitches result in greater signal distortions, further underscoring the importance of robust error mitigation techniques in optical communication.

The outcome of this thesis emphasize the critical role of dispersion compensation and adaptive filtering in enhancing the reliability and robustness of optical fiber communication systems. Such methods are essential for maintaining high-quality transmission in modern telecommunications networks, where increasing data rates and transmission distances continue to drive the demand for performance improvements. By demonstrating the application of adaptive filtering and signal processing techniques, this study contributes to the growing body of knowledge on optimizing optical transmission systems.

Bibliography

[1] *Optical fiber*. URL: https://issuu.com/molex/docs/polymicro-technolgies.

[2] *Structural properties of glass*. URL: http://www1.chim.unifi.it/u/signo/did/glass-structure/glass_structure.pdf.

[3] *Fiber Optic Cable Types* URL: https://www.vcelink.com/blogs/focus/fiber-optic-cable-types.

[4] *Snell's law*. URL: https://www.geeksforgeeks.org/snells-law-formula/.

[5] *Signal Attenuation and Distortion*. "Le Nguyen Binh, Optical Fiber Communication Systems with MATLAB® and Simulink® Models", Second edition: Taylor & Francis group, 2015

[6] *Splice losses*. URL: https://www.fiberoptics4sale.com/blogs/archive-posts/95039494-optical-fiber-splice-loss

[7] *Chromatic Dispersion*. URL: https://ascentoptics.com/blog/understanding-optical-fiber-dispersion-and-its-compensation-methods/.

[8] *Polarization Mode Dispersion*. URL: https://www.degruyter.com/document/doi/10.1515/joc-2024-0136/html.

[9] *Kerr Effect*. "Digital Coherent Optical System : Architecture and Algorithm". Darli Augusto De Arruda Mello, Fabio Aparecido Barbosa, Springer Nature, 2021.

[10] *Antenna Polarization*. URL: https://jemengineering.com/blog-intro-to-antenna-polarization/#:~:text=Vertical%20polarization%20refers%20to%20the,angle%20to%20a%20reference%20plane..

[11] *Optical Transmitter*. URL: https://www.sciencedirect.com/topics/engineering/optical-transmitter.

[12] *Bit Error Rate Optimization in Fiber Optic Communications*. URL: https://www.ijmlc.org/papers/65-A163.pdf.

[13] *Analytical expression for BER*. URL: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=1232997.

[14] *Optical receiver*. URL: https://e2e.ti.com/cfs-file/__key/telligent-evolution-components-attachments/00-138-01-00-01-32-72-02/Optical-Receivers.pdf.

[15] *Optical transceiver.* URL: https://www.optcore.net/what-is-fiber-optic-transceiver/?srsltid=AfmBOoraVWzpFZZMy5s6ABSjJdHOx6iAbJEYtdZqGNLL-V8lEkNuXHsa.

[16] *Fiber Port Cluster.* URL: https://www.sukhamburg.com/documents/Article_Cluster.pdf.

[17] *Cluster*URL: https://www.bucap.it/news/approfondimenti-tematici/continuta-operativa/cluster-cos-e.htm.

[18] *Introduction to Optical Time-Domain Reflectometers (OTDR).* URL: https://www.exfo.com/en/resources/glossary/optical-time-domain-reflectometer-otdr/#:~:text=The%20Basics,different%20elements%20of%20the%20link.

[19] *OTDR Working Principles and Characteristics.* URL: https://www.viavisolutions.com/en-us/what-are-working-principles-and-characteristics-otdrs.

[20] *FPGA Fundamentals.* URL: https://www.ni.com/en/shop/electronic-test-instrumentation/add-ons-for-electronic-test-and-instrumentation/what-is-labview-fpga-module/fpga-fundamentals.html?srsltid=AfmBOopf2JaqDUSjmE7DMRz8iDPqJS8lruCFtBII7yTPWWCtDhBBiQ4v.

[21] *How Does an FPGA Work?* URL: https://learn.sparkfun.com/tutorials/how-does-an-fpga-work/all.

[22] *Real-time performance improvement approach based on FPGA in OFDR system.* URL: https://www.sciencedirect.com/science/article/pii/S1068520022003972?casa_token=hFjFruWCtZYAAAAA:FqtbMZ9V1hGDkHG-ntcEYtWrIRUcH4T4zzEhYDJmy5TlRLD7AR_zpXOtkt3_8lzKROKuSfVfZ9w.

[23] *Fiber Optic Mux/Demux: Introduction and Applications.* URL: https://www.gracyfiber.com/fiber-optic-mux-demux-introduction-and-application-overview/.

[24] *DWDM Mux/Demux Overview and Working Principle.* URL: https://community.fs.com/article/dwdm-mux-demux-overview-working-principle-and-different-types.html.

[25] *Glitch Detection in Hardware Implementations on FPGAs Using Delay Based Sampling Techniques.* URL: https://ieeexplore.ieee.org/document/6628380.

[26] *PMD Effects in Fiber Optic Transmission Systems.* URL: https://hal.science/hal-00365826/document.

[27] *LMS Filters in DSP.* URL: https://www.keil.com/pack/doc/CMSIS_Dev/DSP/html/group__LMS.html#:~:text=LMS%20filters%20are%20a%20class,%20equalizers,%20and%20noise%20removal..