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Dedication

I dedicate this modest work, to my dear father; to my dear mother; to my brothers Khaled, Walid and Salah; to my cousins to the whole Aichouche family;
To all my friends and those who have helped me during my university life.

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Table of abbreviations:

LED	Light Emitting Diode
PIN	Positive-Intrinsic-Negative Diode
SMF	Single Mode Fiber
MMF	Multimode Fiber
WDM	Wavelength Division Multiplexing
DWDM	Dense Wavelength Division Multiplexing
EDFA	Erbium-Doped Fiber Amplifier
BER	Bit Error Rate
FCC	Federal Communications Commission

CW	Continuous Wave
Tbps	Terabits per second
SNR	Signal to Noise Ratio
OLT	Optical Line Terminal
RZ	Return to Zero
NRZ	Non-Return to Zero

General Introduction

GENERAL INTRODUCTION:

The evolution of communication systems has witnessed a dramatic transformation over the past few decades. In the early days, traditional copper-based transmission mediums such as coaxial cables were sufficient to meet the modest demands of digital communication [1]. However, as technology advanced and the need for higher data rates became essential, the limitations of these conventional systems became apparent [2]. High attenuation, limited transmission distances, and susceptibility to electromagnetic interference posed significant challenges, rendering them unsuitable for modern high-speed networks. With the rise of data-intensive applications such as high-definition video streaming, cloud computing, and 5G wireless technology, a more efficient and reliable transmission medium was required. This need gave rise to the adoption of optical fiber technology, which has ability to transmit vast amounts of data over long distances with minimal signal degradation.

Optical fiber communication relies on the transmission of light signals through a dielectric medium, typically made of glass or plastic. Unlike electrical signals in copper cables, optical signals suffer far less from attenuation and interference, making fiber optics the preferred choice for high-speed networking. However, despite its numerous advantages, optical fiber systems are not entirely free from limitations. Signal degradation due to attenuation, dispersion, and nonlinear effects remains a concern in long-distance transmission. To counter these issues, various optical components such as amplifiers, dispersion compensation modules (DCMs), and wavelength division multiplexing (WDM) systems have been integrated into modern optical networks to enhance performance [1].

This research aims to analyse and model a high-speed optical fiber transmission system using OptiSystem, a widely used simulation software designed for optical communication networks. The study is structured into four main parts: an exploration of different communication systems and their evolution, a comprehensive study of optical fiber technology and its characteristics, an in-depth examination of OptiSystem as a simulation tool, and finally, a practical implementation of a simulated high-speed optical transmission system. The final chapter presents a detailed performance analysis, evaluating key metrics such as bit error rate (BER), signal-to-noise ratio (SNR), eye diagrams, and Q-factor analysis. Through this research, we aim to provide a deeper understanding of fiber-optic communication challenges and propose optimization techniques to improve transmission efficiency, ultimately contributing to the development of next-generation optical networks.

Chapter I:

Introduction to Communication Systems

I. INTRODUCTION

In today's world, where information exchange is constant and instantaneous, communication systems play a vital role in facilitating seamless data transfer between individuals, organizations, and machines. From the early telecommunication systems that relied on wired infrastructure to the modern era of wireless communication, this field has undergone significant advancements [1]. These innovations have not only enhanced the speed and efficiency of data transmission but have also revolutionized global connectivity, enabling real-time communication across vast distances.

II. DEFINITION OF COMMUNICATION SYSTEMS

A communication system is a framework that enables the transfer of information from a source to a destination. This process involves multiple stages, including encoding, transmission, reception, and decoding [2]. The efficiency of a communication system is measured by its ability to minimize errors, maximize data rate, and optimize resource utilization. a basic communication system consists of the following key components:

- **Transmitter**

  The transmitter converts the electrical signal into a form that is suitable for transmission through the physical channel or transmission medium. For example, in radio and TV broadcasts, the FCC (Federal Communications Commission) specifies the frequency range for each transmitting station. Hence, the transmitter must translate the outgoing information signal into the appropriate frequency range that matches the frequency allocation assigned to the transmitter [3].

- **Channel**

  The communication channel is the physical medium that is used to send the signal from the transmitter to the receiver. In wireless transmission, the channel is usually the atmosphere (free space). On the other hand, telephone channels usually employ a variety of physical media, including wirelines, fiber optic cables, and wireless (microwave radio) [3].

- **Receiver**

  The function of the receiver is to recover the message signal contained in the received signal. If the message signal is transmitted by carrier modulation, the receiver performs carrier demodulation to extract the message from the sinusoidal carrier [3].

III. CLASSIFICATION OF COMMUNICATION SYSTEMS

Communication systems are broadly categorized based on different parameters [1]. such as transmission medium, signal type, and system structure; this classification provides a foundation for understanding how different communication systems function in various applications.

- ✓ In terms of signal type [4], analog systems transmit continuous signals, as seen in AM and FM radio, whereas digital systems convey discrete binary data (0s and 1s), dominating modern telecom, internet, and mobile networks due to their noise resistance and efficiency. Additionally, network structure divides systems into point-to-point (e.g., telephone calls) and broadcast (e.g., TV and radio), each serving distinct purposes. Analog systems excel in audio/video transmission by replicating natural signals, while digital systems offer superior robustness, security, and scalability. Together, these classifications highlight the diverse mechanisms and applications inherent in communication technologies.
- ✓ Regarding the transmission medium, wired systems rely on physical conduits like twisted-pair cables, coaxial cables, or optical fibers [4], while wireless systems use electromagnetic waves such as radio waves, infrared, and microwaves.

IV. MODULATION AND CODING TECHNIQUES

Low-frequency information signals are incapable of being conveyed across long distances. As a result, it is superimposed on a high-frequency wave at the transmission point. This high-frequency wave serves as a data carrier. This is called modulation. Advanced modulation and coding techniques are employed to enhance data transmission efficiency [2]. and there are deferent type of modulation and protocols in communication systems include:

- **Amplitude modulation:** The carrier wave's amplitude varies in response to the information signal.
- **Frequency modulation:** The carrier wave's frequency varies in response to the information signal.
- **Phase modulation:** The carrier wave's phase changes in response to the information stream.
- **Network Topologies and Protocols:** Efficient network topologies and protocols are essential for managing data flow in high-speed communication systems. Architectures like 5G and emerging 6G networks are designed to support higher data rates, reduced latency,

and increased connectivity. Protocols must be optimized to handle the increased data loads and ensure seamless communication between devices [5].

V. OVERVIEW OF DATA TRANSMISSION SYSTEM

Data transmission media refer to the physical or wireless channels that allow data to travel from one device to another within a network. The efficiency, speed, security, and reliability of data transfer depend largely on the type of transmission medium used. Choosing the right medium depends on factors such as bandwidth requirements, transmission distance, resistance to interference, and cost. Broadly, transmission media can be classified into two main categories:

- Wired Transmission systems: Involves physical cables that provide a direct path for data transmission.
- Wireless Transmission systems: Uses electromagnetic waves to transmit data without the need for cables.

V.1 Wired Transmission systems

These systems use physical cables (guided media) to transmit data, providing fast and secure communication. They are widely employed in wired networks and include several types:

V.1.1 Twisted Pair Cable

Twisted Pair Cable, simply referred to as “Twisted Pair,” is a type of copper cable composed of two insulated copper wires twisted together in a helical manner. The twisting of the wires is not merely for aesthetics but serves a crucial purpose – reducing electromagnetic interference and enhancing signal integrity [6].

The **Figure I.1** illustrates a cross-sectional view of a shielded Ethernet cable, highlighting its complex structure designed for network communications.

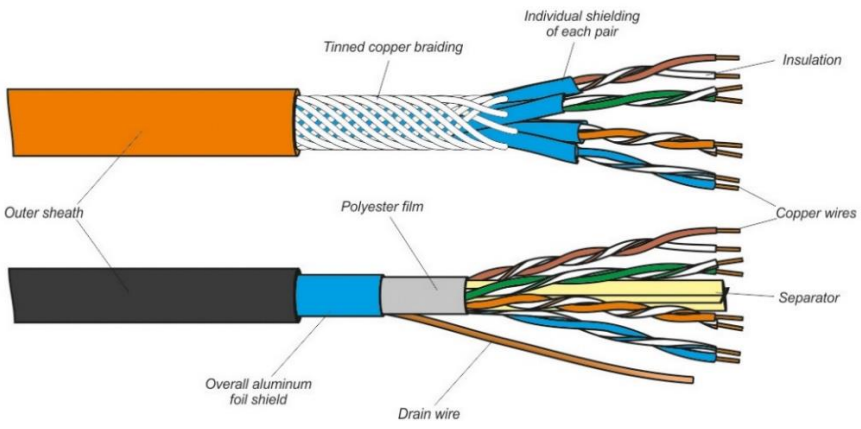
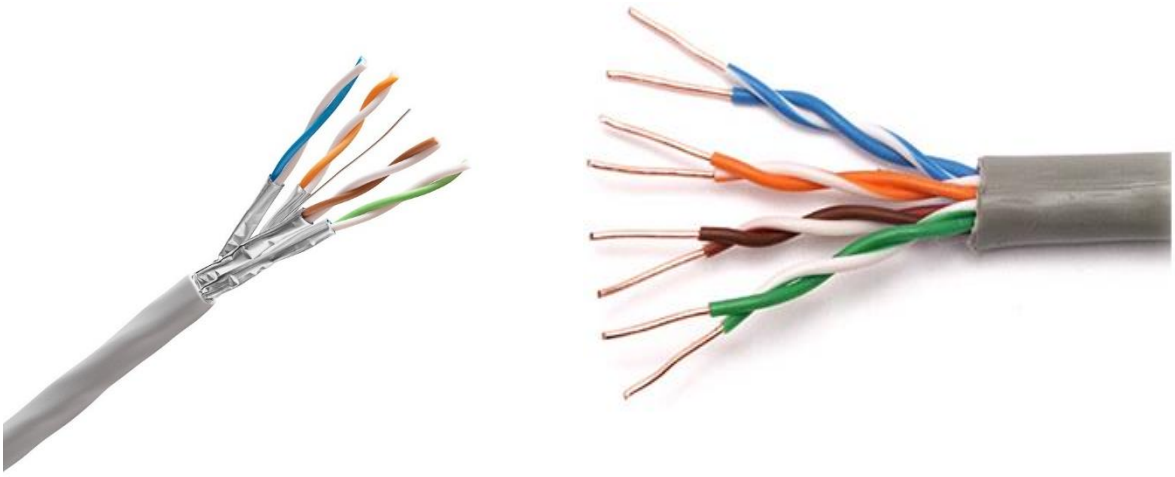


Figure I.1: *Twisted pair cable.*

Types of Twisted Pair Cables

- **Unshielded Twisted Pair (UTP):** UTP is the most common type of Twisted Pair Cable used in everyday applications. It consists of two twisted copper conductors, each insulated with a color-coded plastic sheath. UTP cables are cost-effective and suitable for short to medium-distance data transmission, making them ideal for Ethernet connections in homes, offices, and data centres [1].
- **Shielded Twisted Pair (STP):** STP features a layer of metallic shielding around the twisted copper pairs, which provides better protection against external electromagnetic interference. The shielding prevents crosstalk between adjacent cables and makes STP more suitable for environments with high electromagnetic interference, such as industrial settings [1].



Shielded Twisted Pair (STP) **Unshielded Twisted Pair (UTP)**

Figure I.2: *Types of Twisted Pair Cables*

Advantages	Disadvantages
✓ **Cost-effective**: Affordable and widely available. ✓ **Easy installation**: Simple to set up and maintain. ✓ **High-speed capable**: Supports fast data transfer (especially newer categories)	✕ Susceptible **to interference**: Disposed to EMI/crosstalk without proper shielding. ✕ **Distance limitations**: Shorter transmission range compared to fiber optics.

Table I.1: *Twisted Pair Cable Advantages and Disadvantages.*

V.1.2 Coaxial Cable

Coaxial cables feature a central copper conductor surrounded by an insulating layer, a metallic shield, and an outer protective cover. They are widely used for cable television (CATV), broadband internet, and networking applications [1].

The **Figure I.3** illustrates the structure of a coaxial cable, which is designed for transmitting high-frequency electrical signals. It consists of an inner conductor, surrounded by an insulator, an outer conductor serving as a shield, and a protective plastic cover.

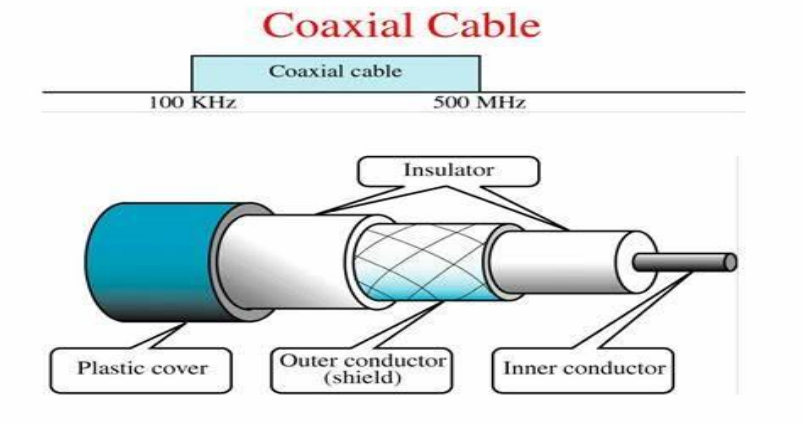


Figure I.3: *Coaxial Cable.*

- **Advantages and Disadvantages of Coaxial Cable:**

✓ Provides better shielding against interference compared to twisted pair cables.

✓ Offers higher bandwidth and supports longer transmission distances.

✓ More stable and reliable, especially for video and broadband applications.

V.1.3 Fiber Optic Cable

Fiber optic cables transmit data as light pulses through thin strands of glass or plastic fibers [2], they are known for their incredibly high speeds, long-distance capabilities, and minimal signal loss, making them ideal for high-speed internet, secure data transmission, and telecommunications. Figure I.4 illustrates the structure of a fiber optic cable, designed for high-speed data transmission using light. It features a glass core at the center, where light travels, surrounded by glass cladding to facilitate total internal reflection.

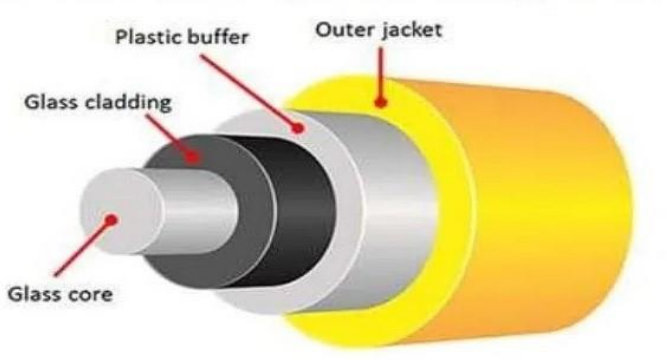


Figure I.4: *Fiber Optic Cable.*

Types of Fiber Optic Cables:

1. **Single-Mode Fiber (SMF):** Has a narrow core that allows only one light signal (mode) to pass through. Ideal for long-distance communication, reaching up to hundreds of kilometres. Offers higher bandwidth than multi-mode fiber [2].
2. **Multi-Mode Fiber (MMF):** Has a wider core that allows multiple light signals (modes) to travel simultaneously. Supports shorter distances (usually up to a few kilometres). Commonly used in LANs, data centres, and short-range network connections [2].

- **Advantages and Disadvantages of Fiber Optic Cable:**

Supports extremely high-speed data transmission, reaching terabits per second. Immune to electromagnetic interference, making it reliable in environments with high electrical noise. Provides secure data transmission, as signals are difficult to intercept. Minimal signal loss, allowing for long-distance communication without frequent repeaters.
Installation and maintenance are expensive and require specialized expertise. More fragile than copper cables, as glass fibers can break easily if bent excessively. the installation process is more complex compared to traditional copper cables [2].

V.1.4 Copper Cables

Copper cables are widely used in wired communication networks due to their ability to conduct electrical signals efficiently. Copper is the electrical conductor in many categories of electrical wiring. Copper wire is used in power generation, power transmission, power distribution, telecommunications, electronics circuitry, and countless types of electrical equipment. Copper and its alloys are also used to make electrical contacts. Electrical wiring in buildings is the most important market for the copper industry. Roughly half of all copper mined

is used to manufacture electrical wire and cable conductors [1].

The Figure I.5 shows a set of electrical wires, each with a distinct coloured insulation. These wires are typically used in electrical installations for conducting electricity



Figure I.5: *Copper Cables.*

V.2 Wireless Transmission Systems

The wireless transmission systems, use electromagnetic waves to transmit data without the need for physical cables. These are widely used in mobile networks, Wi-Fi connections, satellite communications, and radio broadcasting [3].

V.2.1 Radio Waves

Radio waves deal with the behaviour of radio waves when the waves travel from one end to another it refracted (or bent) when they propagate through the atmosphere. the principal difference between broadcast radio and microwave is that the former is omnidirectional and the latter is directional. Thus, broadcast radio does not require dish-shaped antennas, and the antennas need not be rigidly mounted to a precise alignment.

Applications Radio is a general term used to encompass frequencies in the range of 3 kHz to 300 GHz. the radio waves are using the informal term broadcast radio to cover the VHF and part of the UHF band: 30 MHz to 1 GHz. This range covers FM radio and UHF and VHF television. This range is also used for a number of data networking applications [3].

Radio waves offer several advantages including wide coverage (particularly at lower frequencies), making them excellent for long-distance communication, along with strong obstacle penetration that ensures reliable indoor and urban wireless connectivity. Additionally, they support seamless mobility, maintaining stable connections for moving devices. However, radio waves also have drawbacks: they are susceptible to interference from other wireless signals, which can degrade performance, and they pose security risks since unencrypted signals can be intercepted or hacked [3].

V.2.2 Microwaves

Microwaves used in satellite communications, point-to-point networking, and radar systems. Requires line-of-sight transmission, meaning obstacles can block the signal. Operates at higher frequencies than radio waves, enabling faster data transfer [6].

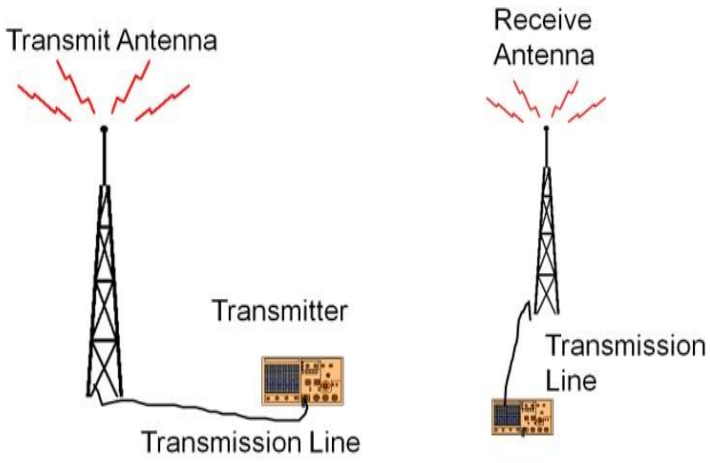


Figure I.6: *Microwaves*

Microwaves enable high-speed data transfer, making them suitable for long-distance networking. They provide reliable performance for satellite and wireless backbone communications. However, they require a clear line-of-sight, meaning obstacles like buildings or mountains can block the signals. Additionally, weather conditions such as rain and fog can negatively affect signal quality.

V.2.3 Infrared (IR) Waves

The infrared waves used in remote controls, wireless keyboards, and short-range data transfer (such as early mobile infrared ports). Requires direct line-of-sight between the sender and receiver for communication [4].

Infrared waves offer the advantage of not interfering with radio or microwave signals, while also consuming low power - making them ideal for small electronic devices. However, they have limited transmission range (typically just a few meters) and cannot penetrate walls or solid obstacles, which restricts their potential applications.

V.3 Electromagnetic Wave Transmission

When employing radio waves for communication, the transmitter antenna emits electromagnetic waves. These waves travel through space and eventually arrive at the receiving antenna on the other end. Some wave propagation methods have been briefly discussed below, three general ranges of frequencies of wireless transmission. Frequencies in the range of about 1 GHz to 40 GHz are referred to as microwave frequencies. At these frequencies, highly directional beams are possible, and microwave is quite suitable for point-to-point transmission [6]. The **Figure I.7** depicts an electromagnetic wave propagating through free space, illustrating the oscillating electric (E) and magnetic (H) fields. These fields are perpendicular to each other and to the direction of wave propagation, which is characteristic of transverse waves.

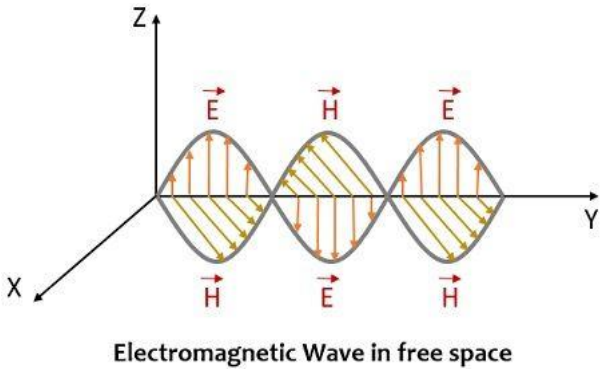


Figure I.7: *Electromagnetic Wave.*

Microwave is also used for satellite communications. Frequencies in the range of 30 MHz to 1 GHz are suitable for omnidirectional applications. We refer to this range as the radio range. Another important frequency range, for local applications, is the infrared portion of the spectrum. This covers, roughly, from $3 * 10^{11}$ to $2 * 10^{14}$ Infrared is useful to local point-to-point and multipoint applications within confined areas, such as a single room [4]. **Figure I.8** illustrates the concept of ground wave propagation, a method of radio wave transmission. In this mode, radio waves travel along the Earth's surface from a transmitting antenna to a receiving antenna.

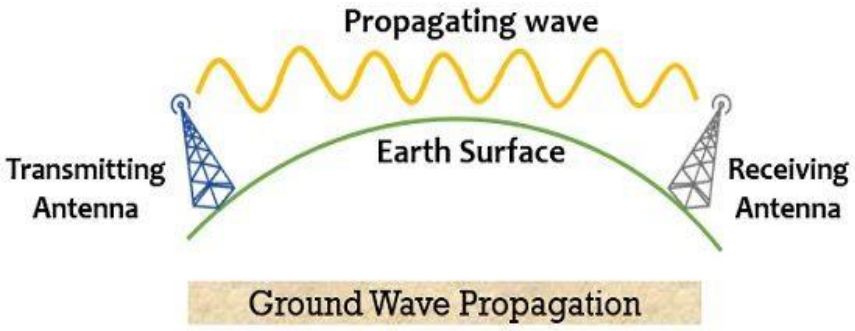


Figure I.8: *Propagating Wave.*

V.4 Satellite Microwaves :

A communication satellite is, in effect, a microwave relay station. It is used to link two or more ground-based microwave transmitter/ receivers, known as earth stations, or ground stations. The satellite receives transmissions on one frequency band (uplink), amplifies or repeats the signal, and transmits it on another frequency (downlink). A single orbiting satellite will operate on a number of frequency bands, called transponder channels, or simply transponders. The optimum frequency range for satellite transmission is in the range 1 to 10 GHz. Below 1 GHz, A microwave signal can be sent to a satellite in a geostationary orbit. These satellites are in orbit above the equator. The height of their orbit (around 36,000 km) is just the right distance so that it takes them one day (24 hours) to make each orbit. This means that they stay above the same point on the Earth's surface. Applications can be:

- Television distribution
- Long-distance telephone transmission
- Private business networks
- Global positioning [6].

The **Figure I.9**illustrates satellite communication, where a satellite in orbit facilitates the transmission of signals between a transmitting station and a receiving station on Earth.

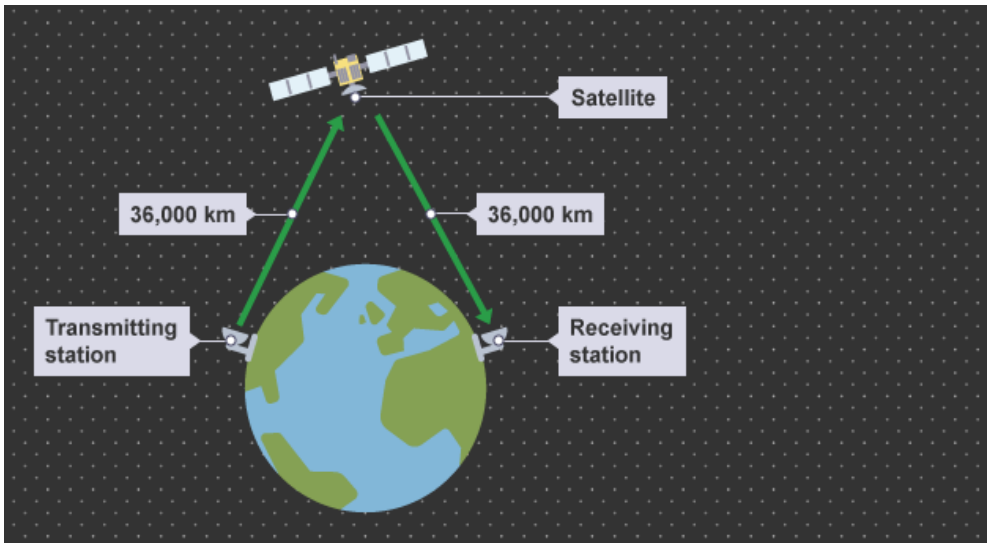


Figure I.9: *Satellite Microwaves.*

VI. HIGH-SPEED COMMUNICATION SYSTEMS

High-speed communication systems are pivotal in addressing the escalating demands for rapid and reliable data transmission across various applications, including high-definition video streaming, real-time data processing, and advanced wireless communications. Addressing the associated design challenges through meticulous engineering and novel approaches is essential

for realizing the full potential of these systems in meeting the ever-growing data transmission demands of modern applications. These systems leverage cutting-edge technologies to achieve unprecedented data rates, often reaching into the gigabit-per-second (Gbps) and terabit-per-second (Tbps) ranges [4]. The Figure I.10 illustrates a communication setup involving a high-speed train, relay stations, and base stations. The relay stations are positioned along the railway to facilitate continuous communication between the train and the base stations, which are elevated at a certain height and spaced at a specific distance from each other.

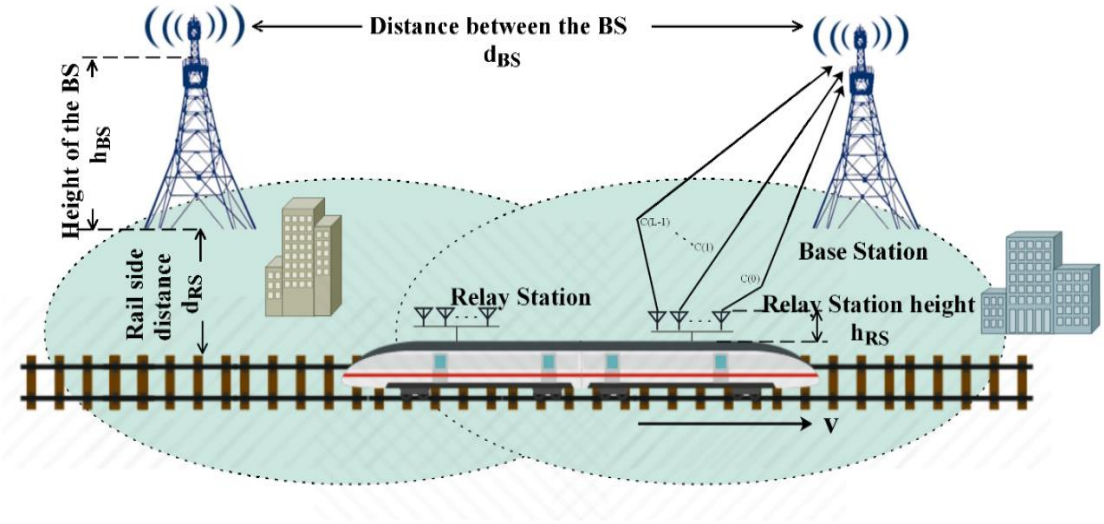


Figure I.10: *High-speed communication systems.*

VI.1 Silicon Photonics and Modulation Techniques

A significant advancement in this domain is the development of silicon photonic modulators compatible with the 800G standard. Researchers at McGill University and Ericsson Canada have demonstrated a silicon photonic modulator capable of net 1 Tbps transmission. This achievement utilizes a single-segment In-phase Quadrature (IQ) modulator operating at 105 gigabaud (G baud) with advanced modulation formats like dual-polarization 64-Quadrature Amplitude Modulation (DP-64QAM). The modulator's design focuses on enhancing bandwidth and reducing insertion loss, which are critical for achieving high data rates. The use of CMOS-compatible silicon photonics facilitates integration with existing semiconductor technologies, offering a scalable solution for high-speed data transmission.

VI.2 Terahertz Communication Systems

The terahertz (THz) frequency band, ranging from 0.1 to 10 THz, presents opportunities for ultra-high-speed wireless communication due to its vast available bandwidth. A notable implementation is a 0.22 THz communication system capable of delivering 84 Gbps over a

distance of 1.26 kilometres. This system integrates advanced signal processing techniques and optimized radio frequency components to overcome challenges such as high path loss and limited component performance inherent at THz frequencies. The successful real-time transmission of uncompressed 8K ultra-high-definition video using this system underscores its potential for applications requiring substantial data throughput.

VI.3 Visible Light Communication Systems

Visible Light Communication (VLC) is an emerging technology that utilizes light-emitting diodes (LEDs) for data transmission, offering a complementary solution to traditional radio-frequency communication. In particular, silicon-substrate LEDs with multiple superlattice interlayers have been investigated for their potential in high-speed VLC systems. These LEDs have demonstrated data rates of up to 3.37 Gbps over a 1.2-meter free-space link. The incorporation of superlattice interlayers enhances the wall-plug efficiency (refers to the ratio of optical output power to the total electrical input power, indicating how efficiently a device converts electrical energy into light.) and modulation bandwidth of the LEDs, thereby improving the overall performance of VLC systems [7].

VII. CHARACTERISTICS OF HIGH-SPEED COMMUNICATION SYSTEMS

To meet the growing demand for rapid data transmission, modern communication systems must satisfy key performance requirements. These systems rely on high-speed electronic circuits that enable various technologies, including satellite communications, wideband microwave radio systems, cellular networks, and fiber-optic light-wave communications. Two fundamental aspects govern their performance:

1. **Bandwidth and Data Rate** – The available bandwidth directly impacts the maximum achievable data rate, with higher bandwidth enabling faster communication. This is particularly crucial for bandwidth-intensive applications like video streaming and online gaming.

2. **Modulation and Multiplexing Techniques** – These optimize transmission efficiency through:

- **Modulation**: By converting signals into transmittable forms (AM, FM, PSK, QAM), it simplifies transmitter design and matches signal spectra to channel characteristics. This process shifts baseband signals to higher frequencies suitable for channel passbands.

- **Multiplexing**: Techniques like TDM, FDM, and OFDM allow multiple signals to share a single channel. For instance, amplitude modulation of a carrier wave (fc) enables frequency translation of message signals (m(t)) for efficient spectrum utilization [4].

VII.1 Challenges in High-Speed Communication Systems:

High speed system has several factors that control it and These factors must be optimized to enhance communication system performance, Recent developments explore the terahertz band for high-speed wireless communications, leveraging the large available bandwidth to achieve elevated data rates

- Noise and Interference: External signals that degrade communication quality.
- Latency: The delay in signal transmission and reception.
- Security Risks: The potential for data interception.

VII.2 Comparative Analysis of communication systems [1]:

The **Table I.2** presents a comparative analysis of various communication systems, highlighting their speed, interference, cost, and applications. Twisted-pair cables are noted for their low speed and high interference but are cost-effective and commonly used in telephony and LANs. Optical fiber stands out with very high speed and low interference, making it suitable for high-speed internet and networking despite its higher cost [1].

Medium	Speed	Interference	Cost	Applications
Twisted-Pair Cables	Low	High	Low	Telephony, LANs
Coaxial Cables	Medium	Medium	Medium	Cable TV, Broadband
Optical Fiber	Very High	Very Low	High	Internet, High-Speed Networking
Radio Waves	Medium	High	Medium	Broadcasting, Mobile Networks
Microwaves	High	Medium	High	Satellite, Military
Infrared/Li-Fi	High	Low	Medium	Wireless Communication

Table I.2: *Comparative Between Communication Systems.*

VIII. RECENT TRENDS IN COMMUNICATION SYSTEMS

❖ **5G networks on high-speed communication**

The fifth generation of mobile communication technology, offering significantly higher data rates, ultra-low latency, and massive connectivity compared to previous generations. One of the most notable impacts of 5G on high-speed communication is its ability to deliver gigabit-per-second speeds, making it ideal for bandwidth-intensive applications such as real-time video streaming, augmented reality (AR), virtual reality (VR), and autonomous vehicle communication. A key feature of 5G is its use of millimetre-wave (mm Wave) frequencies, which provide higher bandwidth and faster data transfer rates than traditional lower-frequency bands. Additionally, 5G networks leverage massive multiple-input multiple-output (MIMO) technology, which allows multiple antennas to transmit and receive signals simultaneously, enhancing data throughput and network capacity [9].

❖ **Internet of space ''Starlink''**

Starlink is the world's first and largest satellite constellation using a low Earth orbit to deliver broadband internet capable of supporting streaming, online gaming, video calls and more. Leveraging advanced satellites and user hardware coupled with deep experience with both spacecraft and on-orbit operations, Starlink delivers high-speed, low-latency internet to users all over the world, As the world's leading provider of launch services, SpaceX is the only satellite operator with the ability to launch its own satellites as needed. With frequent, low-cost launches, Starlink satellites are constantly updated with the newest technology [10].

- **How Starlink Works**

Most satellite internet services come from single geostationary satellites that orbit the planet at 35,786 km. As a result, the round-trip data time between the user and satellite (also known as latency) is high, making it nearly impossible to support streaming, online gaming, video calls or other high data rate activities.

Starlink is a constellation of thousands of satellites that orbit the planet much closer to Earth, at about 550km, and cover the entire globe. Because Starlink satellites are in a low orbit, latency is significantly lower around 25 ms vs 600+ ms [10].

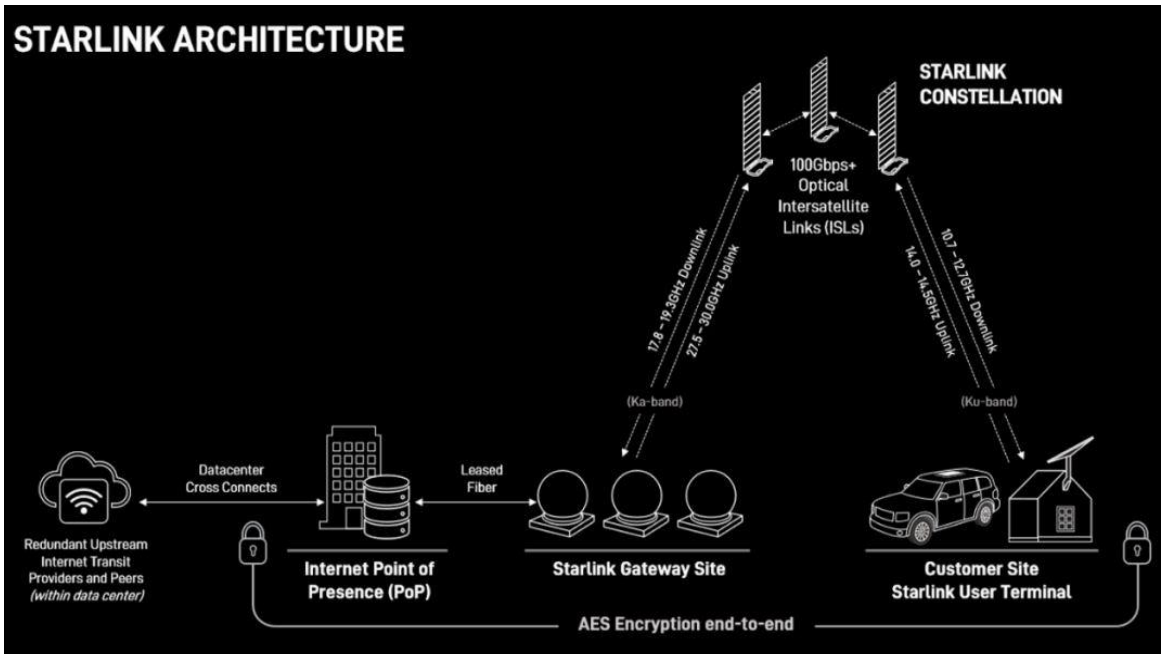


Figure I.11: *Starlink architecture.*

IX. Conclusion

In this chapter, we explored various communication systems, their fundamental components, and classifications, providing a broad perspective on how information is transmitted across different media. We also examined the characteristics of high-speed communication, emphasizing the importance of efficient transmission technologies also we discover Recent Trends in Communication Systems like Starlink. Among these, optical fiber communication emerged as a crucial technology for modern high-speed data transfer. As this study primarily focuses on optical fiber communication, the upcoming chapters will investigate deeper into its principles, advantages, and applications. Chapter Two will specifically provide a comprehensive analysis of optical fibers.

Chapter II:

High Speed Optical Fiber Communication Systems

I. INTRODUCTION

A communication system enables the transfer of information from one location to another, whether over short distances or across entire oceans. This information is typically transmitted using an electromagnetic carrier wave, with frequencies ranging from a few megahertz to several hundred terahertz. Optical communication systems, also known as Lightwave systems, operate at very high frequencies—around 100 terahertz—within the visible or near-infrared regions of the electromagnetic spectrum [2]. These systems are distinct from microwave systems, which use much lower carrier frequencies, around 1 gigahertz—approximately five orders of magnitude less. Fiber-optic communication systems, a type of Lightwave system, use optical fibers to transmit information. Since their introduction in the 1980s, these systems have been adopted globally and have profoundly transformed telecommunications technology [2].

II. STRUCTURE OF OPTICAL FIBERS

Optical Fibers play a crucial role in modern communication systems, enabling high-speed data transmission over long distances with minimal signal loss. Their development has significantly contributed to the expansion of global connectivity, allowing efficient and reliable information exchange across continents [11].

II.1 Basic Structure

An optical Fiber consists of three essential components that work together to ensure effective light propagation and signal integrity**,** The **Figure II.1** depicts a cross-sectional view of a fiber optic cable, illustrating its various structural components. From the centre outward, these components include the core, which is the central element for light transmission, surrounded by the cladding that helps to contain the light within the core. Further layers consist of the coating for protection, strengthening fibers to provide tensile strength, and an outer cable jacket for additional protection against environmental factors.

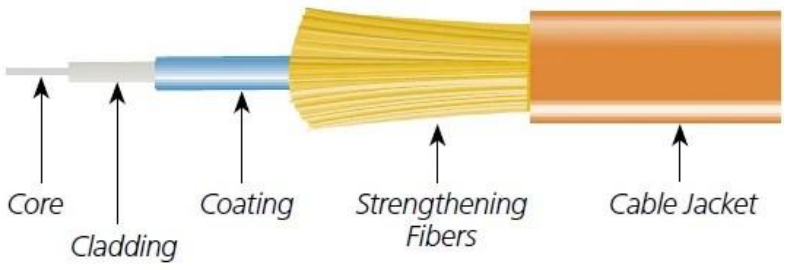


Figure II.1: *Basic Structure of an optical fiber.*

- **Core:** The central region where light propagates. It is typically made of high-purity silica (SiO_2) and serves as the primary transmission medium. The core's diameter determines the Fiber type and its transmission characteristics [11].
- **Cladding:** A surrounding layer with a lower refractive index than the core. This refractive index difference is crucial as it enables total internal reflection (TIR), ensuring that the light remains confined within the core and propagates efficiently over long distances [12].
- **Coating:** An outer protective layer made of polymer material. This layer provides mechanical strength, shields the Fiber from environmental conditions (such as moisture and physical damage), and enhances durability for long-term operation [12].

II.2 Components of Optical Fiber

II.2.1 Transmitter

The transmitter is a critical component of an optical Fiber communication system, responsible for converting electrical signals into optical signals for transmission through the Fiber. This process is primarily carried out using Laser Diodes (LDs) and Light-Emitting Diodes (LEDs), which serve as optical sources.

Laser Diodes (LDs) are widely used in high-speed and long-distance optical communication systems due to their high output power, narrow spectral linewidth, and ability to be modulated at high speeds. They produce coherent light with a well-defined wavelength, making them ideal for single-mode Fiber (SMF) transmission, where maintaining signal integrity over long distances is essential. Light-Emitting Diodes (LEDs), on the other hand, are typically used in short-distance and low-cost applications. LEDs emit incoherent light with a broader spectral width compared to LDs, making them more suitable for multi-mode Fiber (MMF) systems where modal dispersion is already a limiting factor. Though they are less efficient than LDs in terms of power and modulation speed, LEDs offer advantages such as lower cost, longer operational lifetime, and greater reliability [11].

- **Modulation Techniques:**

To effectively transmit data, optical signals must be modulated to carry information. Various modulation techniques are employed in Fiber optic communication systems, including:

- **Amplitude Modulation (AM):** Varies the optical power (intensity) of the transmitted signal to represent data. This method is commonly used in intensity modulation and direct detection (IM-DD) systems.

- **Frequency Modulation (FM):** Alters the frequency of the optical carrier in accordance with the input signal, providing improved resistance to signal degradation.
- **Phase Modulation (PM):** Modifies the phase of the optical wave, often utilized in coherent optical communication systems for advanced data transmission [13].

II.2.2 Optical Fiber Channel

The optical Fiber channel serves as the transmission medium in an optical communication system, guiding light signals over vast distances while maintaining signal integrity. However, due to inherent losses and signal degradation, various techniques and components are utilized to enhance performance and extend transmission reach. Two key technologies employed in optical Fiber channels are optical amplifiers and Wavelength Division Multiplexing (WDM) [11].

1. **Optical Amplifiers:**

Optical amplifiers are essential for compensating signal loss over long-distance Fiber optic links, reducing the need for optical-electrical-optical (OEO) regeneration. They directly amplify the optical signal without converting it into an electrical signal, improving efficiency and reducing latency. The two most widely used optical amplifiers are:

Erbium-Doped Fiber Amplifiers (EDFAs):

- Operate in the C-band (1530–1565 nm) and L-band (1565–1625 nm), which are optimal for long-haul optical communication.
- Utilize erbium-doped optical Fibers that amplify signals through stimulated emission when pumped with a laser.
- Provide high gain, low noise, and wide bandwidth, making them a standard choice for long-distance transmission.

Raman Amplifiers:

- Utilize stimulated Raman scattering (SRS) to amplify signals by transferring energy from a high-power pump laser to the data-carrying signal.
- Offer broadband amplification and can be used in distributed configurations, where amplification occurs along the Fiber rather than at discrete points.
- Enhance signal-to-noise ratio (SNR) and allow for flexible wavelength operation [11].

2. **Wavelength Division Multiplexing (WDM)**

WDM is a critical technology that significantly increases the data capacity of optical Fiber systems by enabling the simultaneous transmission of multiple wavelengths over the same Fiber

[12]. This technique maximizes bandwidth utilization and supports the high data rate demands of modern communication networks. WDM is categorized into:

- **Dense Wavelength Division Multiplexing (DWDM):**

DWDM technology is an extension of optical networking and is designed to maximize the capacity and efficiency of fiber-optic networks. It achieves this by allowing multiple data streams to be transmitted simultaneously over a single optical fiber using different wavelengths of light [14]. DWDM is a subset of wavelength-division multiplexing (WDM) that typically uses the spectrum band within 1530nm and 1625nm, or more commonly the C-band and L-band, to input 40, 88, 96, or even 160 wavelengths, or channels, onto a single strand of fiber optic cable.

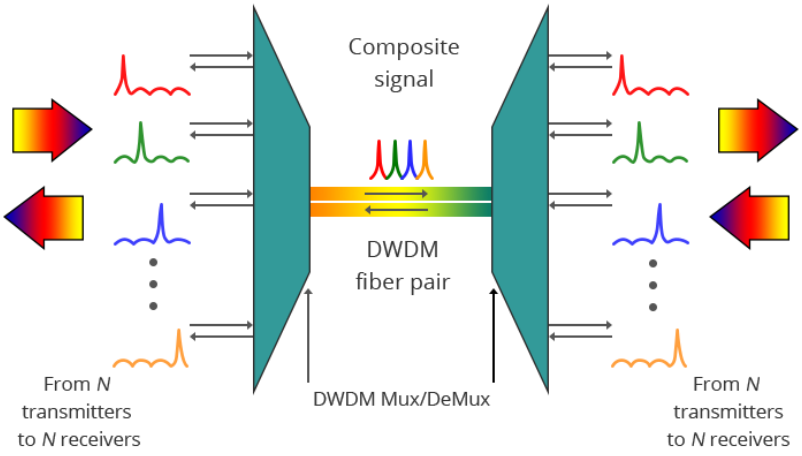


Figure II.2: *Dense Wavelength Division Multiplexing.*

- **Coarse Wavelength Division Multiplexing (CWDM):**

Uses wider wavelength spacing (typically 20 nm apart) and supports fewer channels than DWDM. More cost-effective and suited for shorter-range applications, such as enterprise and metro-area networks [14].

The **Figure II.3** illustrates a schematic of a Wavelength Division Multiplexing (WDM) system setup, highlighting the use of different wavelengths for data transmission over a single fiber core. On the left side, four channels (Ch A, Ch B, Ch C, and Ch D) are shown, each associated with specific wavelengths: 1470 nm, 1490 nm, 1510 nm, 1530 nm, 1550 nm, 1570 nm, 1590 nm, and 1610 nm.

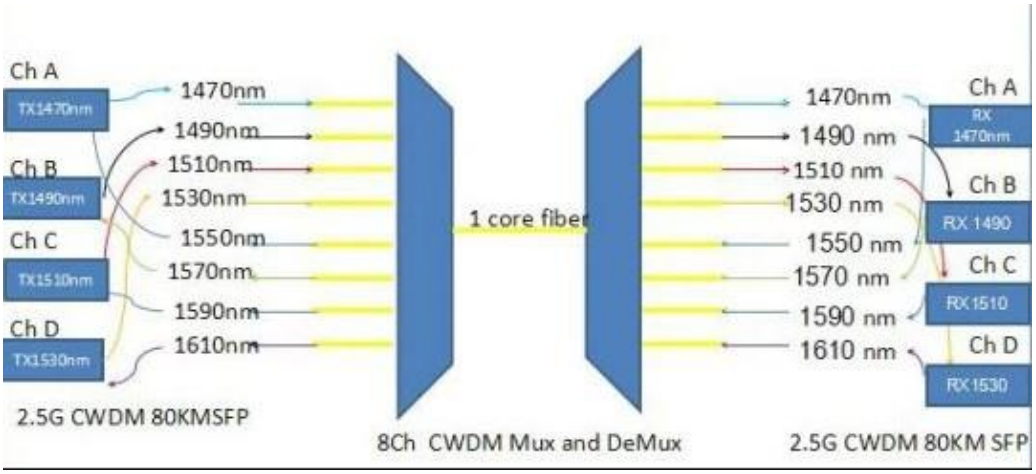


Figure II.3: *Coarse Wavelength Division Multiplexing.*

II.2.3 Receiver

The receiver is a crucial component in an optical Fiber communication system, responsible for converting the transmitted optical signal back into an electrical signal for further processing. The efficiency of the receiver significantly impacts the overall system performance, particularly in terms of sensitivity, signal-to-noise ratio (SNR), and bit error rate (BER). The receiver's performance parameters, such as responsivity, dark current, and noise-equivalent power, are critical in determining the overall efficiency of the optical communication system. The combination of high-performance photodetectors and precise optical filtering techniques ensures accurate and low-noise signal detection, allowing for high-speed and long-distance data transmission Components of Optical Fiber Receiver [11].

1. Photodetectors

Photodetectors are semiconductor devices that detect optical signals and convert them into electrical current. The two most commonly used photodetectors in optical Fiber communication are:

a) PIN Photodiode (Positive-Intrinsic-Negative Photodiode):

A simple and widely used photodetector that consists of a p-type, intrinsic, and n-type semiconductor structure. The intrinsic layer enhances the absorption of incident photons, improving quantum efficiency. Operates in photovoltaic or photoconductive mode, where an external bias increases response speed.

Low cost and ease of fabrication. High-speed operation with low noise. Suitable for moderate-speed, short-haul, and metro networks. Limited internal gain, which may reduce sensitivity in long-haul applications [13].

b) Avalanche Photodiode (APD):

APDs provide internal gain through an avalanche multiplication process, where a single absorbed photon can generate multiple charge carriers. Operates under a high reverse bias voltage, causing secondary electron multiplication, thereby enhancing sensitivity [13].

2. Demultiplexers:

In Wavelength Division Multiplexing (WDM) systems, multiple data streams are transmitted using different wavelengths on the same optical Fiber. At the receiver end, these signals need to be separated before detection.

a) Optical Filters: Used to eliminate unwanted wavelengths and improve signal quality. The Bandpass Filters that Allow only specific wavelength ranges to pass while blocking others. Notch Filters Suppress specific unwanted wavelengths.

b) Demultiplexers: Essential in DWDM and CWDM systems for separating multiple wavelengths into individual channels [15].

III. OPTICAL SIGNAL GUIDANCE IN A FIBER

In a standard optical Fiber, the index difference between the core and the sheath is often low of the order a few 10^3, We then carry out the approximation in low guidance When:

$$\Delta = \frac{\boldsymbol{n1 - n2}}{\boldsymbol{n1}} \qquad (\boldsymbol{II.1})$$

With:

Δ: Relative difference in index

n1: Refractive index of the core (center region of the fiber).

n2: Refractive index of the cladding (outer layer around the core).

The guidance of the optical signal is based on the law of Descartes. Light propagates through the fiber by successive internal reflections between the core and the cladding. This is only possible if both the core and the cladding are made of transparent materials, and the refractive index of the cladding is lower than that of the core.

The second condition is to send the light signal to the Fiber with an angle, with respect to the axis, less than the digital opening. Digital opening (O.N) represents the limit angular opening before a transmission and not a total reflection on the dioptre heart of the Fiber [16]. The image illustrates the phenomenon of light refraction as it transitions between different mediums with varying refractive indices. Initially, light travels through air with a refractive index denoted as

n_0, entering a medium with a refractive index n1$n1$ at an angle θ_{0L}. Upon entering this new medium, the light ray bends according to Snell's Law, changing its angle to θ_L.

$$\boldsymbol{ON = sin(\theta) = \sqrt{n_1^2 - n_2^2}} \qquad (\boldsymbol{II.2})$$

The **Figure II.4** illustrates the principle of light refraction as it passes through different mediums with varying refractive indices. Initially, light travels through air, which has a refractive index denoted as $n0$. Upon entering a medium with a refractive index $n1$, the light ray bends at an angle θL according to Snell's Law. As the light ray continues and encounters another boundary, it enters a medium with a refractive index $n2$, which is greater than $n1$, causing the light to bend again. This diagram demonstrates how light changes direction when it transitions between materials with different refractive indices, a fundamental concept in optics.

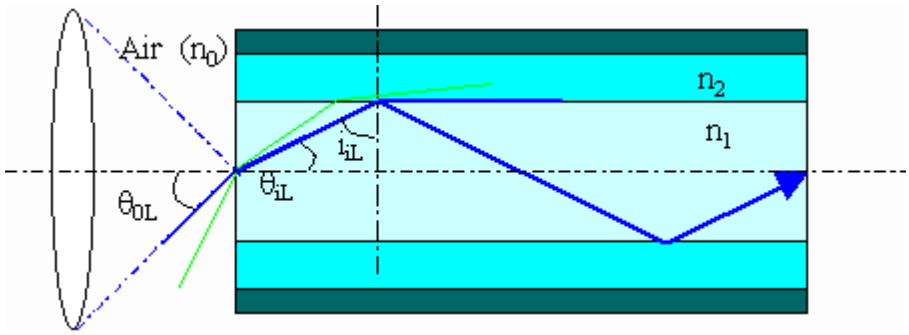


Figure II.4: *The guidance of the optical signal.*

In order to facilitate the injection of light into the fiber at the entrance, it is in your interest in having the limit angle Acceptance Angle θ_0 as large as possible. This is practically obtained by choosing very close n1 and n2 indices.

III.1 Internal total reflection

The principle of internal total reflection is the basis of the propagation of light waves in optical Fiber. According to this principle, when a light radius goes from one environment to another whose refractive index is lower, it can be reflected. In addition, when the angle of incidence of the light radius is greater than the critical angle, the light is reflected in whole and there is no loss of light. The internal total reflection is governed by two factors: the refraction indices of the two environments and the critical angle. These factors are connected by the following equation:

$$\boldsymbol{sin\,\theta = \frac{n2}{n1}} \qquad (\boldsymbol{II.3})$$

By knowing the refraction indices of the two interface materials, the critical angle can easily be calculated [16].

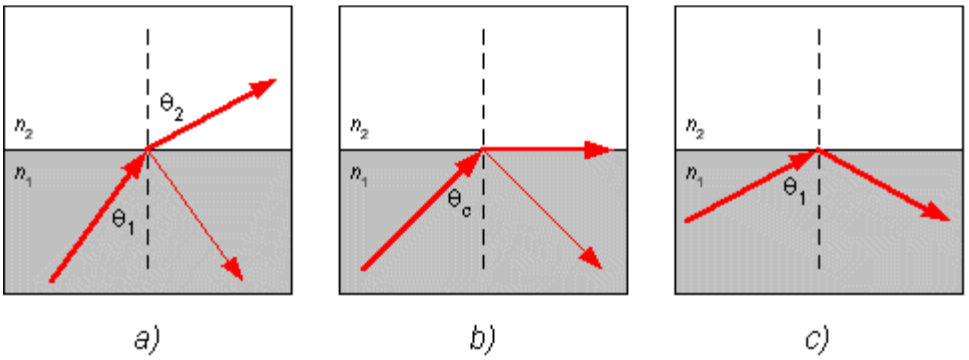


Figure II.5: *Internal total reflection.*

a) Refraction of a light radius for $\theta_1 < \theta c$, the incident radius is also partially reflected in the first environment.

b) Critical radius when $\theta_1 = \theta c$.

c) Internal total reflection for $\theta_1 > \theta c$.

Physically, the refractive index of a substance is the ratio between the speed of light in the void c and its speed in the material v. so:

$$n = \frac{c}{v} \qquad (II.4)$$

Light travels faster in a material with a smaller refraction index. It should be noted that the vacuum refraction index is 1. It is also said that the air index is equal to 1 since the speed of light in the air is almost equal to that in the void. In comparison, the water refraction index is 1.33. Note that the refraction index is a quantity that has no unit, since it is a relationship between two speeds, and that it is always greater or equal to 1 [16].

III.2 Characterization of Fiber

The main characteristics of optical Fibers are the attenuation, dispersion and bandwidth that we will present:

III.2.1 Attenuation

Attenuation in optical Fibers results from several mechanisms:

- Intrinsic losses: depend on the physic chemical nature of optical Fiber.
- Molecular absorption losses: they are caused by the absorption of optical rays by silica and impurities contained in it.
- Involuntary structural irregularities cause diffusion losses (Rayleigh diffusion).

- Extrinsic losses: depend Fiber-component coupling.
- losses due to the conditions of Fiber use. Any too tight curvature creates losses by radiation.
- Microcubes are very low curvatures, but repeated and practically uncontrollable, due to the packaging of the Fibers in the cables.
- The Fibers are always used by sections of finished length, connected to each other. Each junction can cause a loss of connection [13].

The **Figure II.6** depicts a graph illustrating the spectral attenuation characteristics of a fiber optic cable, with the y-axis representing attenuation in decibels per kilometre (dB/km) and the x-axis representing the wavelength of light in nanometres (nm). The graph shows two significant regions of increased attenuation: one around 850 nm and another around 1300 nm to 1550 nm.

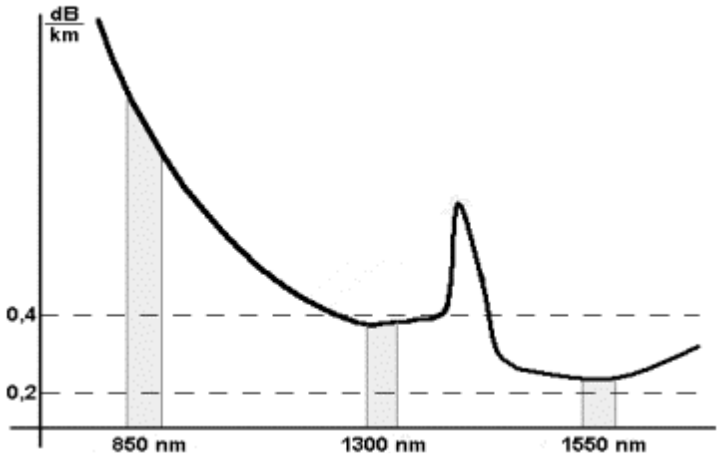


Figure II.6: *The spectral attenuation of a silica fiber.*

The minimum attenuation of 0.22 db/km is not very far from the theoretical minimum for silica. The difference is explained by the fact that one cannot use pure silica. We must boost either the heart or the sheath and this increases composition fluctuations and therefore losses by absorption.

III.2.2 Dispersion

Optical pulses experience dispersion when they travel through optical Fibers because this effect results in signal distortion and subsequent data transmission errors.[16] The propagation of optical pulses inside communication systems results in decreased performance because of bandwidth restriction and elevated bit error rates, with:

$$\boldsymbol{BER = \frac{N_e}{N_T}} \qquad (\boldsymbol{II.5})$$

Where:

N_e: Number of bit errors

N_T: Total number of transmitted bits

A phenomenon called Polarization Mode Dispersion (PMD) forms due to Fiber birefringence which produces dissimilar refractive index experiences between two orthogonal polarization states that results in separate group delay times [16].

III.2.3 Bandwidth

The bandwidth is one of the most important parameters to define the transmission properties of an optical fiber.

The definition of the total bandwidth (B_T) which depends on the connective effect of the two modal and chromatic dispersion phenomena, will stabilize the maximum frequency transmissible online. The total band is defined by the expression:

$$B_T = \sqrt{\frac{1}{\frac{1}{Bm^2} + \frac{1}{Bc^2}}} \qquad (II.6)$$

Where:

B_m: Resulting band of the modal dispersion

B_c: strip derivative of chromatic dispersion

In multimode fiber the total strip only depends on the modal band.

Multimode fiber $B_T = B_m$

In monomodal fiber the total band is determined only by the chromatic band.

monomodal fiber $B_T = Bc$ [16].

III.3 Modal band

The value of the modal band normally referenced to 1000 m in length noted BMO is given by the manufacturer. To calculate the modal band (BM) of an optical fiber link we must apply the relationship:

$$B = \frac{Bm_0}{L^{\gamma}} \qquad (II.7)$$

Where:

Bm_0: Modal band per unit of length.

L: length of the optical fiber link.

γ: Mode concatenation factor provides information on the degree of coupling.

III.4 Chromatic band

The chromatic dispersion is all the more important since the width of the light spectrum of the

source is wider. For this we must take into account in the calculation of the Bc chromatic band.

$$Bc = \frac{0.44.10^{-6}}{\mu \Delta\lambda L} \qquad (II.8)$$

$\Delta\lambda$: spectral width from the source to mid amplitude.

L: FO bound length.

μ : chromatic dispersion coefficient.

IV. TYPES OF OPTICAL FIBERS

Optical fibers can be classified into two primary types based on their core dimensions and light propagation characteristics, these structural and functional differences between SMF and MMF significantly impact the performance, cost, and application scope of optical fiber systems, making the selection process crucial in network planning and deployment:

IV.1 Single-Mode Fiber (SMF)

Features a small core diameter, typically ranging from 8 to 10 µm. Supports a single propagation mode, eliminating modal dispersion and allowing for long-distance and high-speed transmission with minimal signal degradation [17]. Commonly used in backbone networks, submarine communications, and high-speed metropolitan-area networks (MANs).

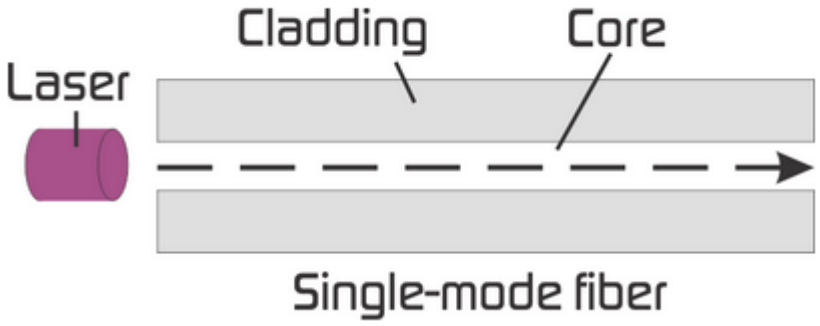


Figure II.7: *Single-Mode Fiber (SMF).*

IV.2 Multimode Fiber (MMF)

Multimode fiber Has a larger core diameter, usually in the range of 50 to 62.5 µm, allowing multiple light modes to propagate simultaneously. This enables higher coupling efficiency and easier light injection from inexpensive light sources such as LEDs and VCSELs (Vertical-Cavity Surface-Emitting Lasers). Exhibits modal dispersion, where different light paths (modes) travel at varying speeds, leading to inter-symbol interference (ISI) and signal distortion over long distances. As a result, MMF transmission distances are typically limited to a few hundred meters. Typically operates at wavelengths of 850 nm and 1300 nm, with 850 nm being

the most commonly used due to compatibility with VCSELs. Available in multiple categories such as OM1, OM2, OM3, OM4, and OM5, with OM3 and OM4 supporting higher data rates up to 100 Gb/s over shorter distances. OM5 is designed for wavelength-division multiplexing (WDM), further enhancing data capacity [14].

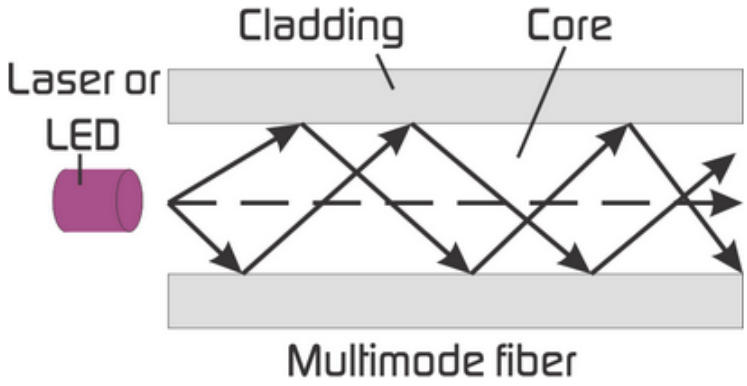


Figure II.8: *Multimode Fiber (MMF).*

IV.3 Multimode Clue Gradient Fiber

In a single mode fiber, a single mode is obtained thanks to the very low dimension of the core (diameter of 10 µm and less), Thus the path of light is imposed it is the TEM00 mode the number of modes propagating in an optical fiber is given by the following relation**:**

$$\boldsymbol{m = \frac{2d}{\lambda}.ON} \qquad (\boldsymbol{II.9})$$

Where:

d: the diameter of the heart of the fiber,

λ: the wavelength of the light used,

ON: The digital opening of the fiber [16].

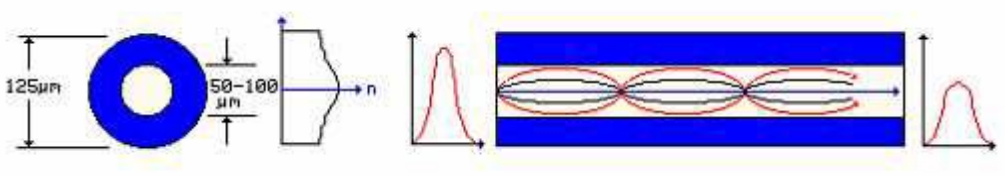


Figure II.9: *Multimode gradient index fiber.*

IV.4 Comparison between monomodal and multimode

This comparison underscores the advantages and limitations of each fiber type, guiding their use in different networking scenarios. Monomodal fibers are typically used for long-distance communication due to their low attenuation and high throughput, whereas multimode fibers are more commonly used in local networks due to their ease of connection and higher attenuation.

Fiber monomodal	Fiber multimode
weak dispersion	butter dispersion
Hard connection	Esay connection
Low attention	High attention
High throughput, long distance	Local network

Table II.1: *Comparison between monomodal and multimode.*

V. OPTICAL TRANSMISSION PRINCIPLES

V.1 Propagation in Optical Fibers

Light propagates through optical fibres based on the principle of total internal reflection (TIR). The fibre consists of a core with a higher refractive index, surrounded by a cladding with a lower refractive index. When light enters the core at an angle greater than the critical angle, it undergoes repeated reflections at the core-cladding interface, ensuring it remains confined within the fiber and travels over long distances with minimal loss.

The propagation of light in optical fibres can be described by Snell's Law, which governs the angle at which light rays reflect within the fiber. The efficiency of propagation depends on factors such as the numerical aperture (NA) of the fibre, which defines the acceptance angle for incoming light, and the mode structure, which varies between single-mode and multi-mode fibers. In single-mode fibers (SMF), light follows a nearly straight-line path, reducing dispersion effects, whereas in multi-mode fibers (MMF), multiple modes travel through the fiber, leading to modal dispersion and limiting the transmission distance [12]. By taking the velocity of propagation, $\boldsymbol{v = c/n1}$, the time delay is given by:

$$\Delta T = \frac{n1}{c}\left(\frac{L}{\sin \phi_c} - L\right) = \frac{L}{c}\frac{n_1^2}{n_2^2}\Delta \qquad (II.10)$$

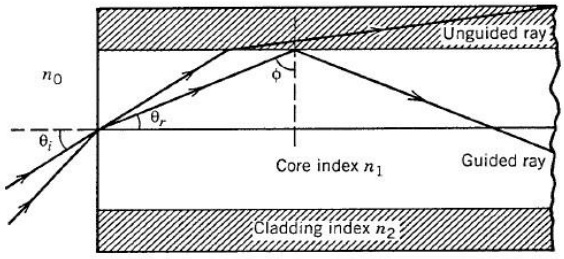


Figure II.10: *Propagation in Optical Fibers.*

V.2 High-Speed Optical Fiber Communication Systems

V.2.1 Evolution of High-Speed Optical Networks

The evolution of high-speed optical networks has been driven by the increasing demand for higher data rates, lower latency, and greater bandwidth efficiency. This progression has led to the development of advanced transmission technologies, allowing for terabit-scale communication over long distances with minimal signal degradation.

- **From SONET/SDH to Dense Wavelength Division Multiplexing (DWDM)**

Early optical networks were based on Synchronous Optical Networking (SONET) and Synchronous Digital Hierarchy (SDH), which provided standardized time-division multiplexing (TDM) frameworks for optical communication. However, SONET/SDH had limited scalability due to its reliance on rigid time-slot allocations and lower data rates (OC-192 at 10 Gbps). The introduction of Wavelength Division Multiplexing (WDM) and later Dense Wavelength Division Multiplexing (DWDM) allowed multiple wavelengths (channels) to be transmitted simultaneously on a single optical fiber, drastically increasing the capacity. DWDM systems now support 80 to 160 wavelengths per fiber, with each wavelength carrying data at 100 Gbps or higher, enabling multi-terabit networks [18].

- **Emergence of 100G, 400G, and Beyond Optical Transmission Systems**

With the rapid growth of cloud computing, 5G networks, and high-definition video streaming, the industry transitioned to 100G optical networks, which became the standard in long-haul and metro networks.

Key advancements in 100G transmission:

- Coherent Detection: Uses phase and polarization modulation techniques to improve spectral efficiency.
- Advanced Modulation Formats: Quadrature Phase Shift Keying (QPSK) and higher-order modulation schemes (16QAM, 64QAM) allow more bits per symbol.

- Forward Error Correction (FEC): Enhances signal integrity over long distances [18].

V.2.2 High-Speed Optical Transmission Technologies

Optical communication systems operating at high-speed face various problems which need solutions to maintain the continuous growth of data transport and ensure robust data delivery. The critical issue within optical fibers remains nonlinear effects because they worsen with increased power levels and longer transmission distances. These nonlinear effects occur in fiber transmission because the intensity-dependent refractive index of the medium triggers SPM and XPM together with FWM. Optical signals that undergo self-modulation because of their intensity rate experience Phase Modulation leading to spectral spreading and elevated dispersion known as SPM. XPM originates in WDM systems from the mutual wavelength channel interactions that convert intensity fluctuations into phase alterations that generate cross-channel interference [11].

VI. OPTICAL FIBRE EN INDUSTRIEL FIELD

Optical fibers have become a cornerstone of modern industrial electronics, because of their unique capabilities in transmitting data at high speeds, over long distances, and with immunity to electromagnetic interference. Below is a detailed breakdown of several important applications:

- **Industrial Automation and Control Systems:**

PLC Communication: They connect programmable logic controllers (PLCs) in real-time industrial systems, especially in noisy environments.

SCADA Systems: In Supervisory Control and Data Acquisition (SCADA) systems, fiber optics are used to transmit data between sensors, control units, and remote terminals.

Real-time Monitoring: High-speed optical communication enables real-time feedback from machines and sensors on factory floors.

- **Robotics and Automated Machinery**

Robot Communication: Optical fibers provide reliable, fast communication between robot controllers and actuators.

Motion Control Systems: Low-latency communication improves the precision and responsiveness of motion control systems.

- **Medical Equipment Manufacturing**

Precision Machinery: Used in the fabrication and calibration of sensitive diagnostic

devices, lasers, and imaging systems.

Fiber Laser Systems: Optical fibers are also used as part of industrial laser systems for cutting, welding, or engraving in medical equipment production

- **Industrial Sensor Networks**

Fiber Optic Sensors (FOS): These are used to measure temperature, pressure, strain, and vibration in real-time. They are particularly useful in power plants, aerospace testing, and structural health monitoring.

Distributed Sensing: Optical fibres themselves act as sensors along their entire length, useful in pipelines and tunnels.

VI.2 ADVANTAGES AND DISADVANTAGES OF OPTICAL FIBERS

VI.2.1 Advantages

There are many, they can be classified as follows:

- **Transmission performance:** very low attenuation, very high bandwidth, possible multiplexing of several signals; they allow the systems to have a range and capacity much higher than those of the conductive cables.
- **Implementation advantage:** very small size, great flexibility, low weight, appreciable both in telecommunications and for wiring in computer science, aeronautics, industrial applications.
- **Electrical safety:** total insulation between terminals, possible use in explosive atmospheres or under high voltage.
- **Electromagnetic safety:** The optical fiber is not sensitive to parasites and does not create any itself.
- **Economic advantage:** contrary to popular idea, the overall cost of a fiber optic system and more and more often lower than that of a copper system [13].

VI.2.2 Disadvantages:

Optical fibre does not allow energy transport. Repeaters must be powered separately, either locally, by second electrical cable or by a mixed optical and electrical cable. Facilities technicians should protect their eyes. It is essential to wear infrared protective lenses to work closely on a device in operation. Loss of connection between different optical components of the system. Among the connection losses are:

Loss of coupling at the source: only part of the power emitted by the laser will be captured by

the fibre because of the mismatch between them.

Splice loss: it is due to a discontinuity of the rays, a spacing error, an eccentric error, an angular alignment error [13].

VII. CONCLUSION

Optical fiber communication systems offer numerous advantages for transmitting large volumes of information across long distances. However, they are not without limitations—issues such as chromatic dispersion and signal attenuation can affect performance. Over the years, several solutions have been developed to address these challenges, including dispersion-compensating fibers and optical amplifiers that enhance signal strength without electrical conversion. These innovations have significantly improved system efficiency and reliability.

To better understand and simulate such system, the next chapter will provide a comprehensive overview of the OptiSystem software, a powerful tool used for the design, analysis, and optimization of optical communication systems.

Chapter III:

Overview of the OptiSystem Simulation Environment

I. INTRODUCTION

Optical communication systems are increasing in complexity on an almost daily basis. The design and analysis of these systems, which normally include nonlinear devices and non-Gaussian noise sources, are highly complex and extremely time-intensive. As a result, these tasks can now only be performed efficiently and effectively with the help of advanced new software tools. OptiSystem is an innovative optical communication system simulation package that designs, tests, and optimizes virtually any type of optical link in the physical layer of a broad spectrum of optical networks, from analogy video broadcasting systems to intercontinental backbones.

II. OVERVIEW OF OPTIWAVE OPTISYSTEM

OptiSystem from Optiwave is widely recognized as one of the most powerful and specialized software tools for simulating the design, analysis, and optimization of optical communication systems. OptiSystem features a number of new features and enhancements to address the design of WDM passive optical networks (WDM-PON) based FTTx, Optical CDMA and radio over fibre systems (RoF).



Figure III.1: *OptiSystem logo*

II.1 Features of OptiSystem 7.0

Version 7.0 introduced several enhancements over its predecessors, including improved simulation accuracy, faster computation times, and expanded libraries of components [19].

The **Figure III.2** shows the "About" dialog box for OptiSystem 7.0 software by Optiwave, including company contact details and software version information. It highlights the software version as 7.0.0.469 and provides Optiwave's address, phone, fax, email, and website.

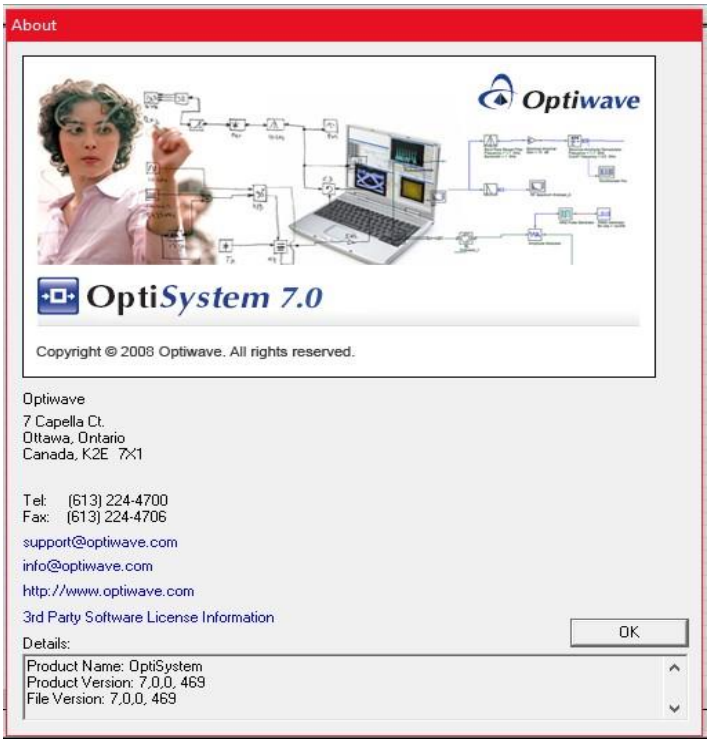


Figure III.2: *OptiSystem Version 7.0*

II.1.1 Component Libraries:

- **Optical Sources:** VCSEL Laser and Laser Rate Equations: A new adaptive step engine allows for fast convergence of high frequency analogy signals.
- **Filters:** A variety of electrical and optical filters are provided for sub-system and system design simulation including standard filter functions (Bessel, Gaussian, RC, Raised Cosine, etc.), digital IIR/FIR filters, periodic filters, reflective/FBG filters, measured filters, S-parameters filter, and acousto-optic.
- **Optical Fibers:** Bidirectional Optical Fibers: A new discretization parameter for broadband sampled signals offers improved performance, accuracy, and convergence for doped amplifier gain and Brillouin calculations. Multimode Fiber: Load measured group delays using the Cambridge file format, conforming to the current standards and extending the capabilities of Gigabit Ethernet simulations in OptiSystem.
- **Amplifiers:** A comprehensive suite of steady state and dynamic optical amplifier models is provided, including advanced doped fiber models (Er, Er multi-mode, Er-Yb, Yb, Yb multi-mode, Tm, Pr) for detailed physical fiber amplifier design; EDFA and EDFA black box (gain spectrum, noise figure measurements) for WDM network systems design; dynamic and average power Raman models; and 1D/2D semiconductor optical amplifier models (lumped rate equation, travelling wave, TLMM). Electrical

domain amplifiers are also provided for receiver design (transimpedance, automatic gain control and limiting amplifier applications).

- **Multiplexers:** AWG NxN Bidirectional: A sophisticated new AWG model facilitates the design of AWG based PON using the unique bidirectional capabilities of OptiSystem.
- **Microwave components:** 180- and 90-Degree Hybrid Couplers, DC blockers, power splitters and combiners: A new component library geared for ROF applications. Applications include mixers, power combiners, dividers, modulators, and phased array radar antenna systems. Control amplitude and phase balance of different components. Measured components: Bidirectional S-parameters components allow users to load s1p, s2p, s3p and s4p file formats, including s2p with noise figure data.
- **Passives:** Polarization Delay and Phase Shift components: New components which control the delay and phase shift for each polarization. Control the delay calculation, by using linear or discrete delay [20].

II.1.2 GUI and Integrated Design Environment:

- Display Results: Users can now select results to be displayed in the layout. Results can be set to trigger alarms indicating if a result is out of a pre-defined range. Improved Project Browser to setup and display results.
- Project Export: Export current list of components, parameters and results directly to Excel. Includes the option to export an OptiSystem file directly to a compressed file format.
- Memory Management: Enable/disable signal monitors and graphs to save memory when using large number of iteration sweeps.
- Nested Parameter Sweeps: In addition to the standard OptiSystem parallel sweep and the script editor, OptiSystem supports nested parameter sweeps. Combined with the report page, users can easily build 2D and 3D graphs using different nesting levels.
- Component Viewer: The new component viewer allows for easy access to component results and graphs.
- Component Script: Write your own calculation engine. For example, a new result can be added to a component or visualizer, offering unlimited possibilities in terms of post-processing. Script can access component parameters, results and graphs [20].

II.2 Working Environment in OptiSystem (User Interface):

The OptiSystem workspace is designed to be user-friendly yet highly functional. The

graphical interface allows users to build systems by dragging and dropping predefined components into a layout window. These components represent elements such as lasers, modulators, fibres, detectors, and analysers. Users can easily configure parameters, run simulations, and view results using various analysis tools including graphs, spectrum analysers, and eye diagram viewers. The modular design and visual representation make it accessible for beginners while still powerful for advanced users [19].

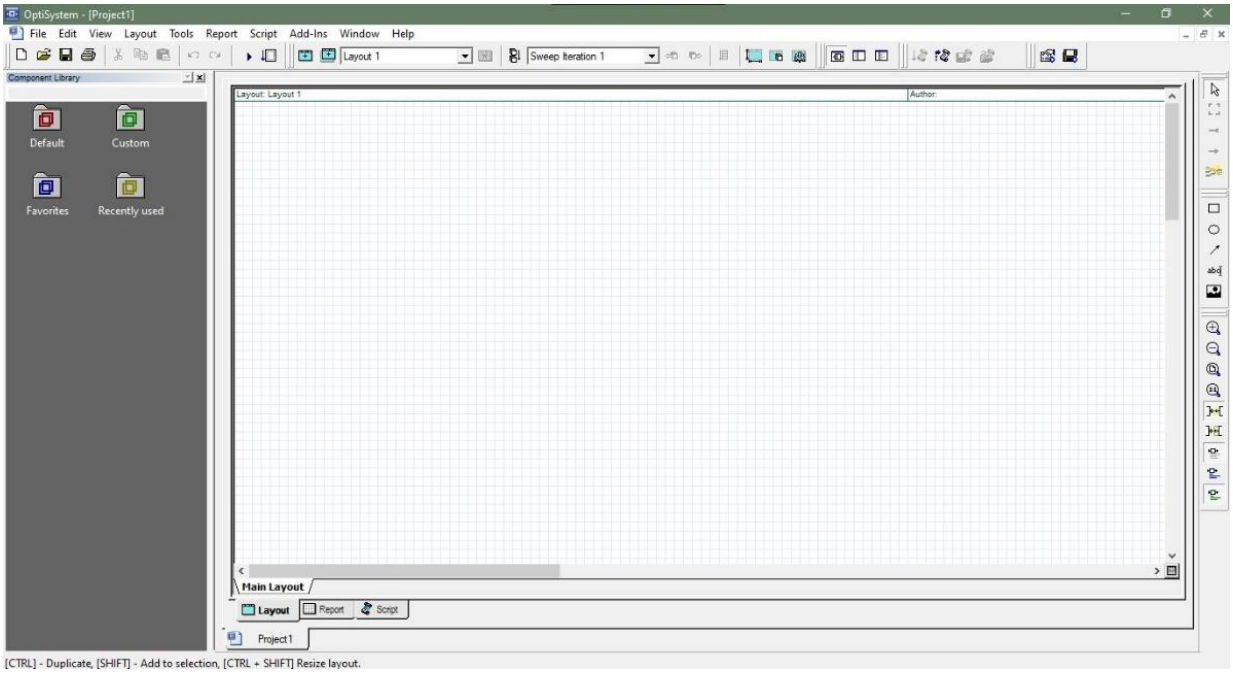


Figure III.3: *OptiSystem Version 7.0 User Interface.*

III. DESIGNING AND ANALYSING OPTICAL FIBER SYSTEMS

OptiSystem provides a powerful and flexible environment for designing, simulating, and analysing a wide range of optical communication systems. Users can visually construct systems by dragging components onto a layout, configuring their parameters, and running simulations to observe system performance. The software supports both linear and nonlinear simulations, allowing detailed analysis of signal behaviour, dispersion, attenuation, noise, and other physical effects.

Engineers and researchers can model real-world scenarios such as long-haul transmission lines, metro networks, passive optical networks (PONs), and high-speed short-reach links. Through built-in analysis tools like BER analysers, eye diagram visualizers, and signal spectrum analysers, users can evaluate system quality and optimize designs accordingly [19].

- **Customizing and Adding New Components:**

OptiSystem allows users to customize existing components by adjusting parameters such as wavelength, power level, gain, bandwidth, noise figure, and more. Each component comes with an editable properties window, making it easy to adapt elements for specific research needs or experimental conditions. Additionally, users can create custom components by integrating mathematical models using script-based definitions. These can be implemented using MATLAB co-simulation, user-defined DLLs, or OptiSystem's scripting interface, enabling advanced users to simulate novel or proprietary devices not found in the standard library [19].

VI. SIGNAL PROCESSING & VISUALIZATION

VI.1 Tools for Optical Signal Analysis:

OptiSystem 7.0 offers a robust set of tools specifically designed for analysing and processing optical and electrical signals within communication systems. These tools help users evaluate system performance, detect impairments, and optimize signal quality throughout the transmission path. Built-in processing blocks and analysers allow simulation of various stages such as modulation, detection, equalization, and error correction. The software supports both coherent and direct detection schemes, as well as digital signal processing (DSP) blocks for advanced modulation formats and signal recovery techniques.

VI.2 Data Visualization Methods:

Visualization and post-simulation analysis tools include BER test sets and analyzers, eye diagram analyzers, spectrum analyzers, oscilloscopes, optical time domain viewers, power meters, polarization analyzers, spatial visualizers, encircled flux, DMD analyzer, photonic all parameter analyzer, filter analyzer, and S-parameter extractor [20].

V. INTEGRATION WITH MATLAB

V.1 Integrating OptiSystem with MATLAB

One of the most powerful features of OptiSystem is its seamless integration with **MATLAB**, in order to create an optical component in MATLAB for co-simulation with OptiSystem, first we need to understand the optical signal format that OptiSystem can generate and the structure of that signal launched into the MATLAB workspace. Using the MATLAB Library, we can add a MATLAB component to the layout. By clicking on the component properties, on the Main tab, we can choose the Sampled Signal in the time or frequency. This integration is achieved by embedding MATLAB Script components within the OptiSystem layout.

These components can perform real-time processing during simulation runs, enabling users to

model unique system behaviours, apply custom DSP algorithms, or test novel modulation and coding techniques. The users can:

- Create custom signal generators or filters using MATLAB code.
- Process optical signals using user-defined DSP algorithms.
- Evaluate performance metrics using advanced mathematical functions from MATLAB's extensive libraries [21].

V.3 Applications and Case Studies

V.3.1 Simulation of a DWDM System

One of the most practical and widely-used applications of OptiSystem is in the design and simulation of DWDM systems, where multiple optical signals are transmitted simultaneously over a single fiber using closely spaced wavelengths.

OptiSystem allows users to:

- Model the entire DWDM architecture, including transmitters, WDM multiplexers/demultiplexers, optical fibers, and receivers.
- Simulate and analysed channel spacing, crosstalk, filter characteristics, and spectral efficiency.
- Optimize parameters such as channel power levels, amplifier placement, and dispersion compensation to ensure reliable and high-capacity transmission [19].

V.3.2 Signal representation

To make the simulation tool more flexible and efficient, it is essential that it provides models at different abstraction levels, including the system, subsystem, and component levels. OptiSystem features a hierarchical definition of components and systems, allowing you to employ specific software tools for integrated and fiber optics in the component level and allowing the simulation to go as deep as the desired accuracy requires [19].

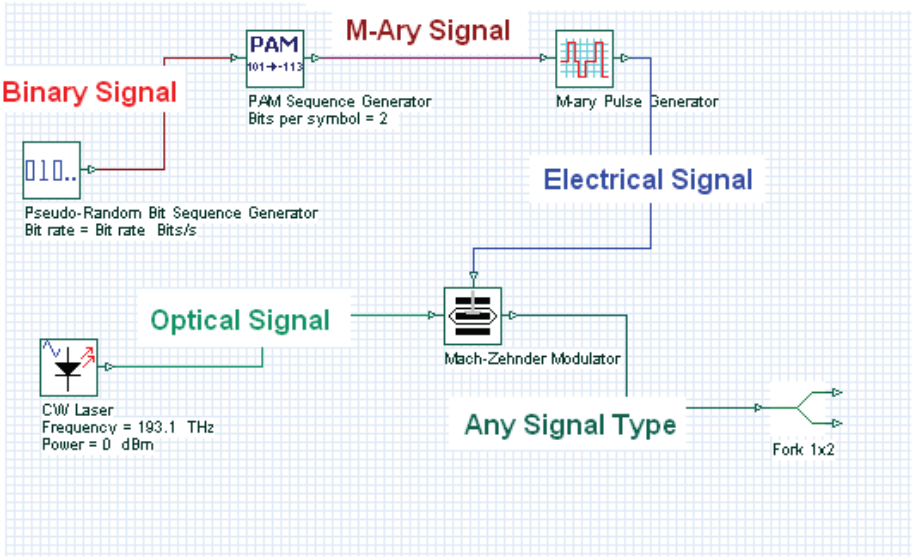


Figure III.4: *Signal representation.*

1. Electrical signals:

Electrical signals are generated by components such as pulse generators in the Transmitters Library and photodetectors in the Receivers Library. Electrical signals consist of the sampled signal waveform in time domain. The main properties of the electrical signal are the signal noise variances in the time domain and the noise power spectral densities in the frequency domain [19].

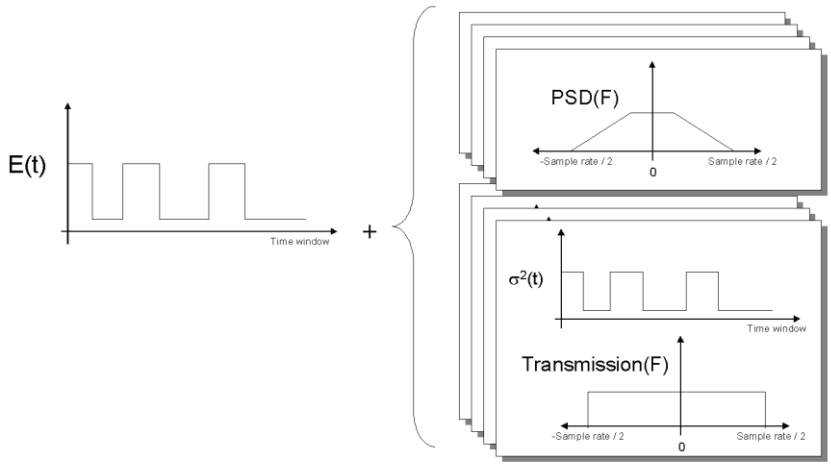


Figure III.5: *Electrical signals representation.*

2. Binary signals

Binary signals are generated by components such as bit sequence generators. Pulse generators in the Transmitters Library and digital switches in the Network Library use this signal as input

data. A binary signal consists of a sequence of ones and zeros, or marks and spaces. The main property of the binary signal is the Bit rate [19].

IIV.COMPONENT OF THE SYSTEM ADOPTED IN THIS STUDY

IIV.1 Transmitter parts:

This circuit is the transmitting part of the circuit that we will simulate in Chapter 4, where this represents a model for simulating an optical transmission system using direct modulation. The **Figure III.6** illustrates a schematic of an optical communication system, featuring a Pseudo-Random Bit Sequence Generator linked to an NRZ Pulse Generator, and a CW Laser connected to a Mach-Zehnder Modulator. This setup is used to modulate data onto an optical carrier for transmission.

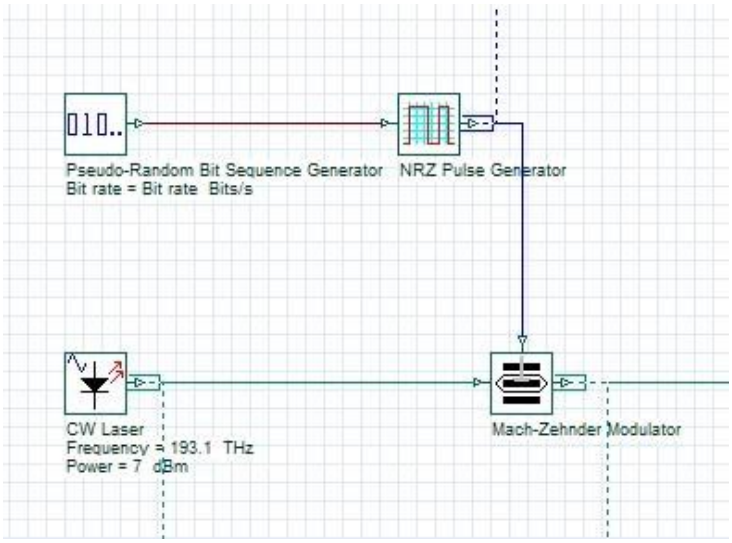


Figure III.6: *Transmitter parts.*

II.1.1 Pseudo-Random Bit Sequence Generator:

The generator used to create a binary sequence of pseudo-random bits. This bit sequence can connect to a binary sequence visualizer so that the output sequence can be seen.

Double-clicking the block shows its main properties. By double-clicking beside the bit rate, we can change the block's bit rate to base it on other parameters or to make it get its value from a function. Pressing Evaluate; we can see the current bit rate value. If we want to change the value of the bit rate defined for the entire project, we can double-click on our workspace, and the global parameters window will pop up. Before we use out the pseudo-random bit generator, we set up it [21].

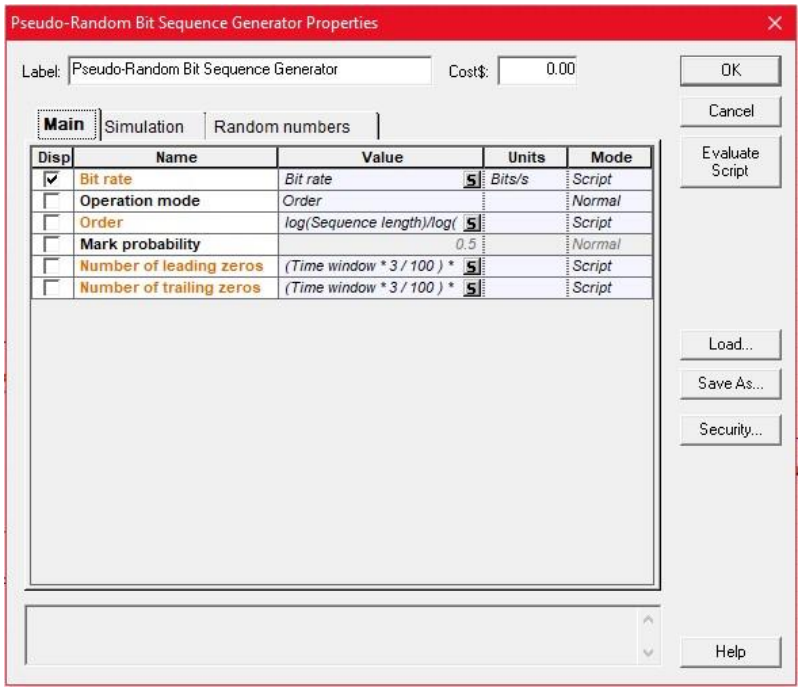


Figure III.7: *Pseudo-Random Bit Sequence Generator.*

Going back into the bit sequence generator and going into the random numbers tab we can choose to either generate a random seed each time or define our seed. A Seed is a number used to initialize a pseudo-random bit sequence generator. So, if we unchecked the Generate Random Seed box and instead choose our own random seed index, this means every time we run the random generator, we should receive the same set of random numbers because the seed used to generate them is the same.

II.1.2 NRZ Pulse Generator:

The NRZ pulse generator Generates a Non-Return to Zero coded electrical signal which is dependent on a bit sequence input. Since the pulse generator's output is dependent on a bit sequence the pulse generator outputs an electric signal so we can use an oscilloscope to visualize it. pulse generator replicates the input bit sequence as the output stays high when the input bit is 1 and goes low when the input bit is 0. The general properties of the pulse generator can be found by double clicking the block. In the main window we have parameters that alter properties of the pulse. Level "1" corresponds to a voltage of +E volts. Level "0" corresponds to a zero voltage [16].

Logical value	Voltage
0	0
1	+E

Table III.1: *Properties of NRZ pulse.*

The figure III.8 titled "NRZ Chronogram" likely illustrates the timing diagram of a Non-Return-to-Zero (NRZ) signal, which is commonly used in digital communications. This type of diagram typically shows how data bits are represented by the signal level over time, where a high level usually represents a binary '1' and a low level represents a binary '0', without returning to a neutral or zero level between bits.

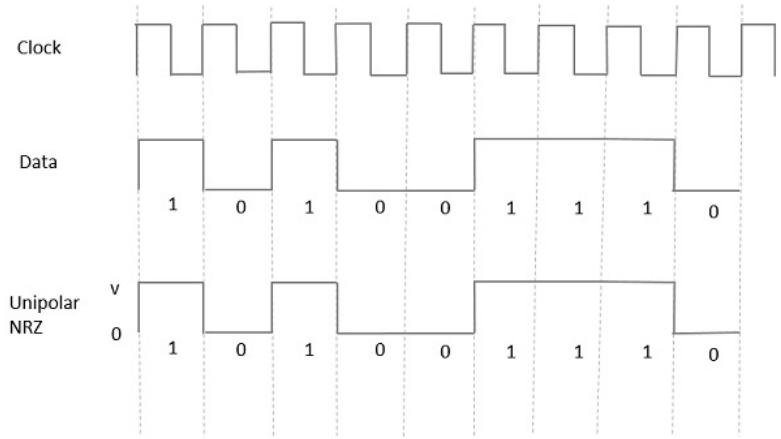


Figure III.8: *NRZ chronogram.*

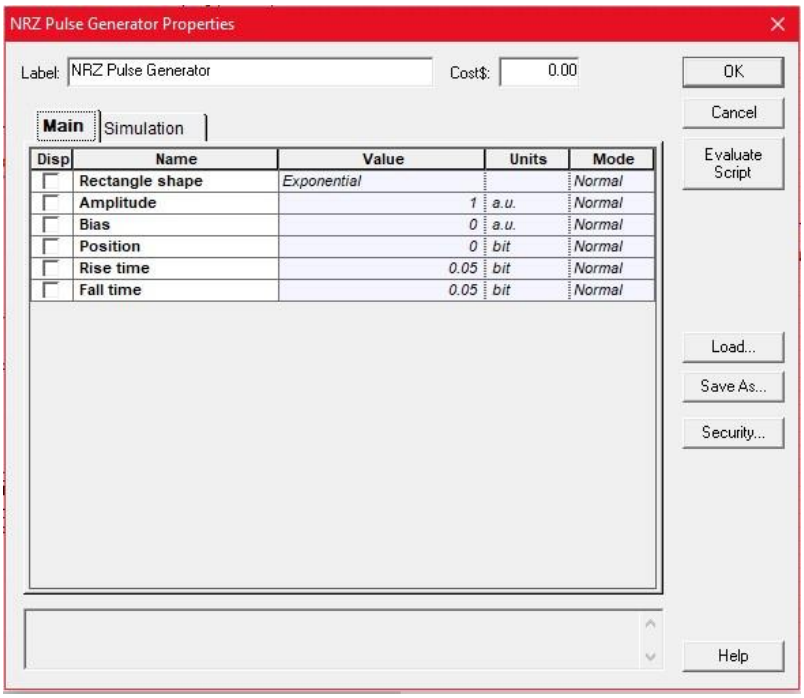


Figure III.9: *NRZ Pulse Generator.*

The rectangle shape property can change the shape of how pulse transitions from low to high and from high to low.

II.1.3 RZ Pulse Generator:

The RZ Generator pulse generator creates a sequence of return to zero pulses coded by an input digital signal, Level “1” corresponds to a voltage of +E volts during the first half period of $\boldsymbol{Tb}$ and +**0** volt during the second half period. Level “0” corresponds to a zero voltage [16]. The figure titled "RZ Chronogram" illustrates the timing diagram of a Return-to-Zero (RZ) signal used in digital communications.

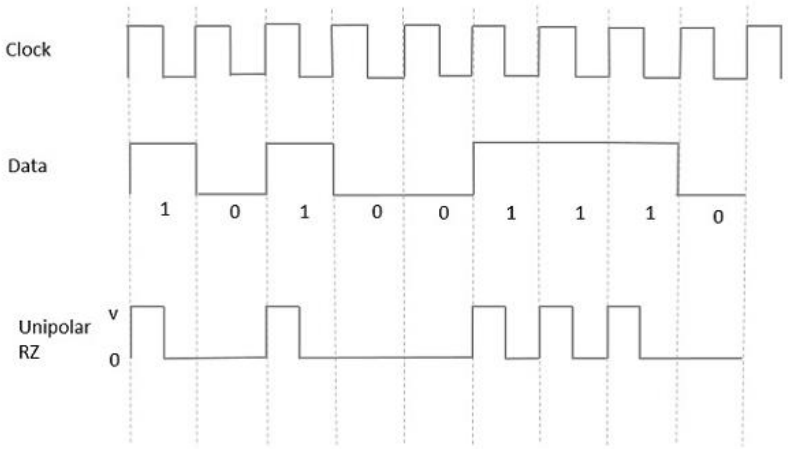


Figure III.10: *RZ chronogram.*

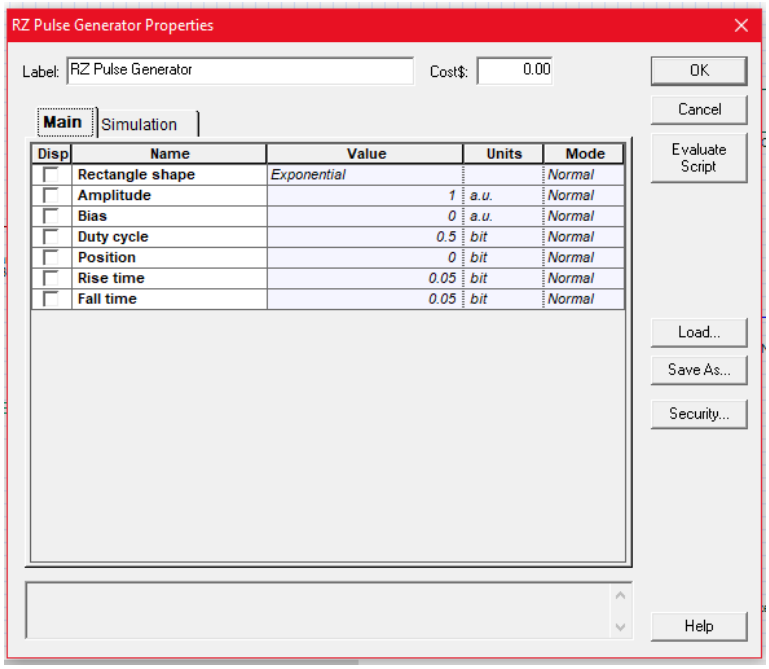


Figure III.11: *RZ Pulse Generator.*

II.1.4 Mach-Zehnder Modulator:

The Mach-Zehnder modulator (MZM) is an interferometric structure made from a material with strong electro-optic effect (such as LiNbO3, GaAs, InP). Applying electric fields to the arms changes optical path lengths resulting in phase modulation. Combining two arms with different phase modulation converts phase modulation into intensity modulation. The optical input Ein is split into the upper and lower modulator arms that are phase modulated with two phase shifters driven by the electrical signals V1 and V2 and then recombined into the optical output E_{out} [21].

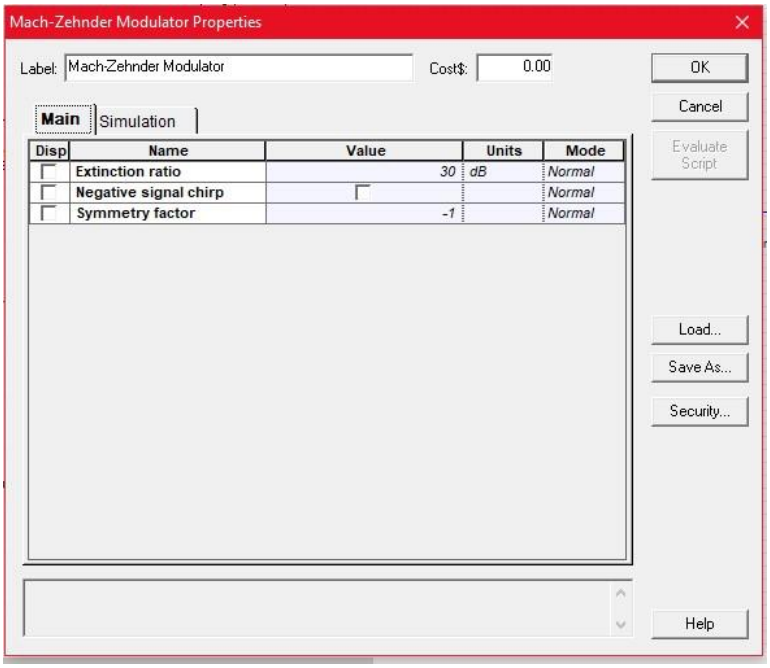


Figure III.12: *Mach-Zehnder Modulator.*

Mach-Zehnder Modulator with symmetric coupler and opposite driving voltages, the MZM structure, and assuming that the input optical field is equally split between the upper and lower arms, and that the voltages driving the phase shifters are opposite $\mathbf{V_2=-V_1}$, we can obtain the following simplified model equation:

$$E_{out} = \frac{E_{in}}{2}\left(e^{j\frac{\pi}{2}\frac{V_1}{V\pi}} + e^{-j\frac{\pi}{2}\frac{V_1}{V\pi}}\right) = E_{in}\cos\left(\frac{\pi}{2}\frac{V_1}{V_\pi}\right) \qquad (III.1)$$

II.1.5 CW laser:

As their name suggests, continuous-wave lasers produce a continuous, uninterrupted beam of light, ideally with a very stable output power. The exact wavelength(s) or line(s) at which this occurs is determined by the characteristics of the laser medium. For example, CO2 molecules readily lase at 10.6 µm, while neodymium-based crystals (like YAG or vanadate) produce wavelengths in the range between 1047 and 1064 nm. Each laser wavelength is associated with a linewidth, which depends on several factors: the gain bandwidth of the lasing medium and the design of the optical resonator, which may include elements to purposely narrow the linewidth, like filters or etalons [19].

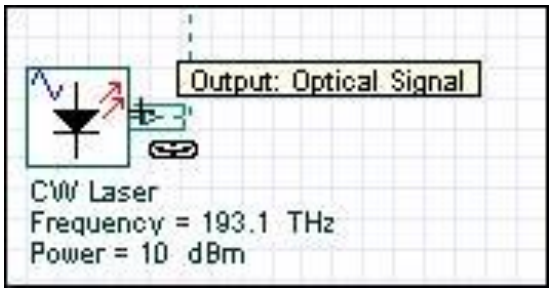


Figure III.13: *CW laser schema.*

If a laser can simultaneously produce different lines, the first step in determining the operating wavelength is to use cavity mirrors that are highly reflective only at the desired wavelength. The low reflectivity of the mirrors at all the other lines will prevent these from reaching the threshold for laser action. However, even a single laser line actually covers a range of wavelengths. For example, laser diodes produce light over a wavelength range of several nanometres corresponding to their "gain bandwidth." The specific wavelengths of the output beam within this gain bandwidth are determined by the longitudinal modes of the cavity. Figure 4 shows the behaviour of a two-mirror cavity, the most basic design. To sustain gain as light travels back and forth between the mirrors, the waves must remain in phase and "reproduce" their wave pattern, which means that the cavity round-trip distance must be an exact multiple of the wavelength:

$$N_{\lambda} = 2 \times \text{Cavity Length} \qquad (III.2)$$

where λ is the laser wavelength and N is an integer called the mode number. This is usually a very large integer, since the wavelength of light is so much smaller than a typical cavity length. In a high-power laser diode, for example, the IR output wavelength is 0.808 μm, yet the cavity length may be 1 mm, so that even in a very small laser resonator, N is ~2500. Wavelengths that satisfy this resonance equation are called longitudinal cavity modes [16].

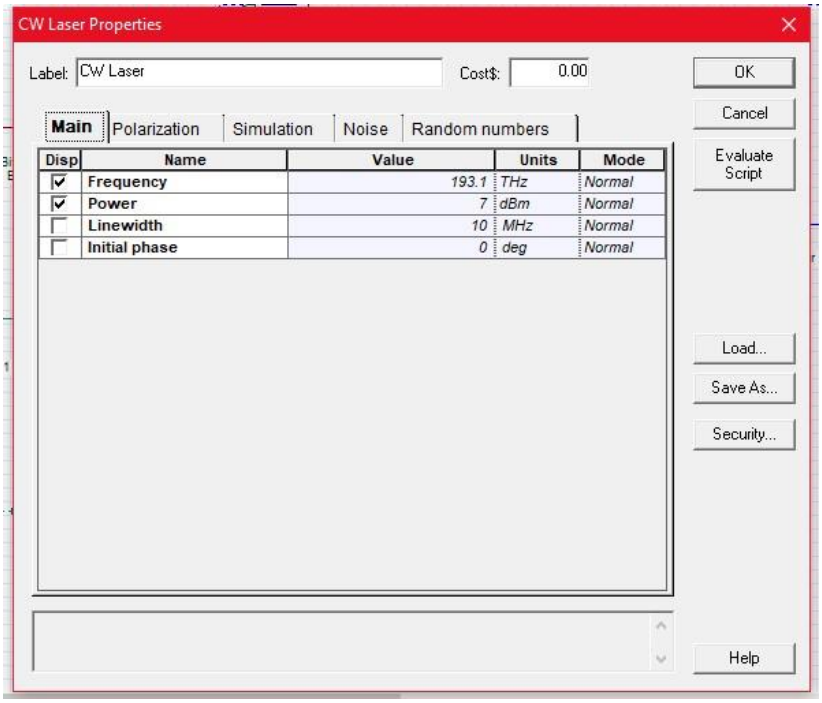


Figure III.14: *CW laser.*

II.2 Channel:

This is the transmission channel in our system, through which we will learn about its constituent elements, starting with the 90 km optical fiber, which is used to transmit optical signals over long distances. Next, we find the optical amplifier, which compensates for the power loss caused by signal propagation within the fiber.

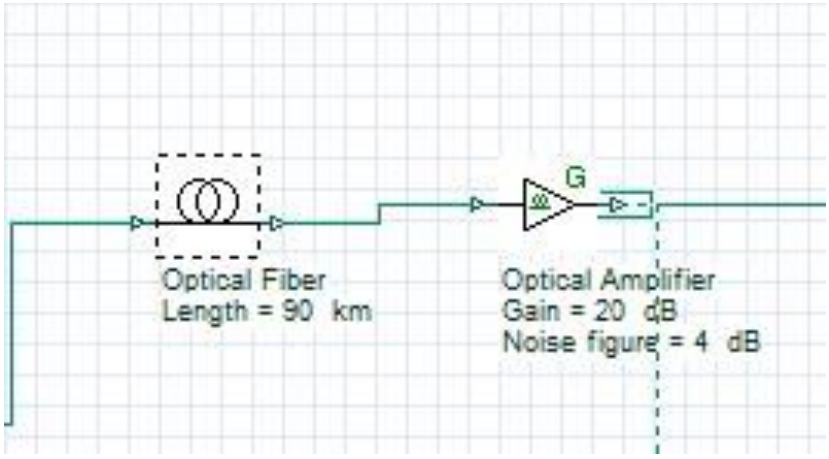


Figure III.15: *the transmission channel in our system.*

II.2.1 Optical Fiber:

The optimal design of a given optical communication system depends directly on the choice of optical fiber parameters. Dimensions of the fiber cross-section, material composition, and refractive index profile all influence important linear and non-linear phenomena [21].

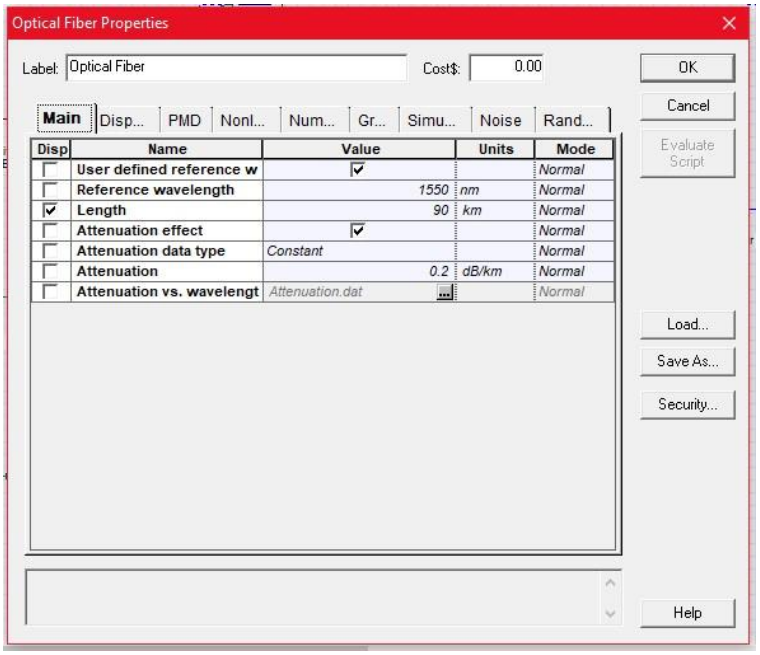


Figure III.16: *Optical Fiber.*

II.2.2 Optical Amplifier:

An Optical Amplifier, specifically the EDFA (Erbium-Doped Fiber Amplifier) found in the *Amplifiers Library/Optical/EDFA*, is a device used to amplify optical signals directly without converting them into electrical signals. It operates by injecting weak optical signals into a fiber doped with the rare-earth element erbium, which is then excited by a pump laser (typically at 980 nm or 1480 nm).

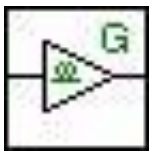


Figure III.17: *Optical Amplifier schema.*

When the signal passes through this doped region, it stimulates the emission of more photons, thereby amplifying the original signal. EDFAs are widely used in long-distance fiber optic communication systems due to their high gain, low noise, and ability to amplify multiple wavelengths simultaneously [21].

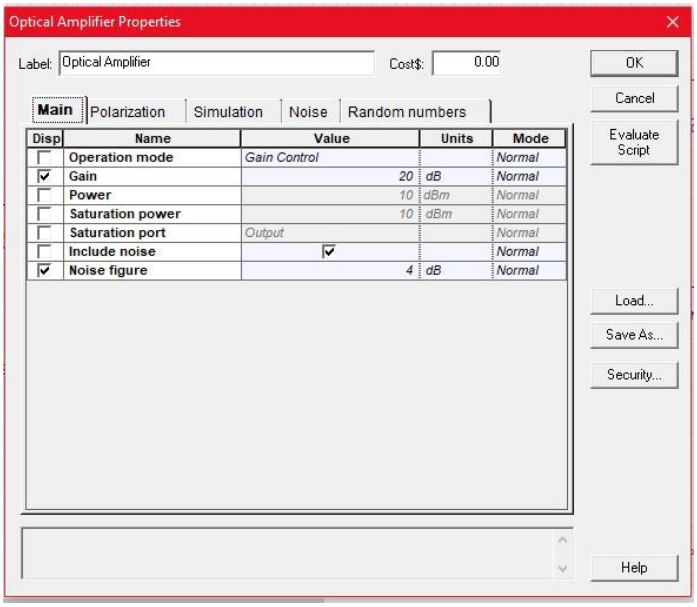


Figure III.18: *Optical Amplifier*

II.3 Reception parts:

This is the receiving part of our circuit, which consists of a PIN photodetector that converts the received optical signal into an electrical signal. The signal then passes through a low-pass Gaussian filter to remove noise and unwanted frequencies. This configuration improves the signal-to-noise ratio and ensures accurate data recovery.

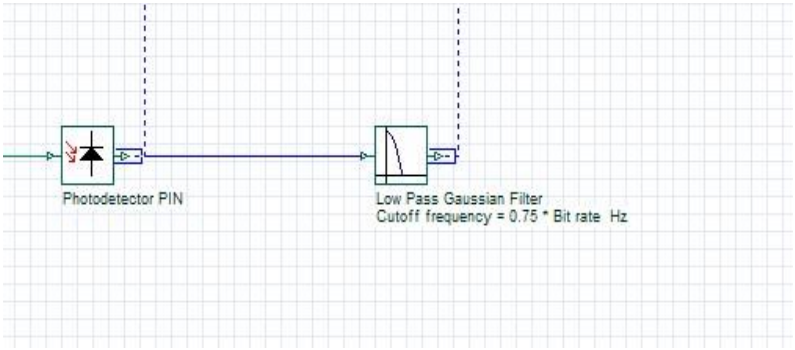


Figure III.19: *Reception parts.*

II.3.1 Photodetector PIN

PIN photodetectors are vital components in optical communication systems, converting optical signals into electrical signals for further processing. The name “PIN” comes from the three distinct layers of semiconductor material that form the device: the P-type, Intrinsic (I), and N-type layers. These photodetectors offer high sensitivity, fast response times, and the ability to handle a wide range of optical signals, making them indispensable in various applications like fiber-optic communication, environmental monitoring, and medical diagnostics [20].

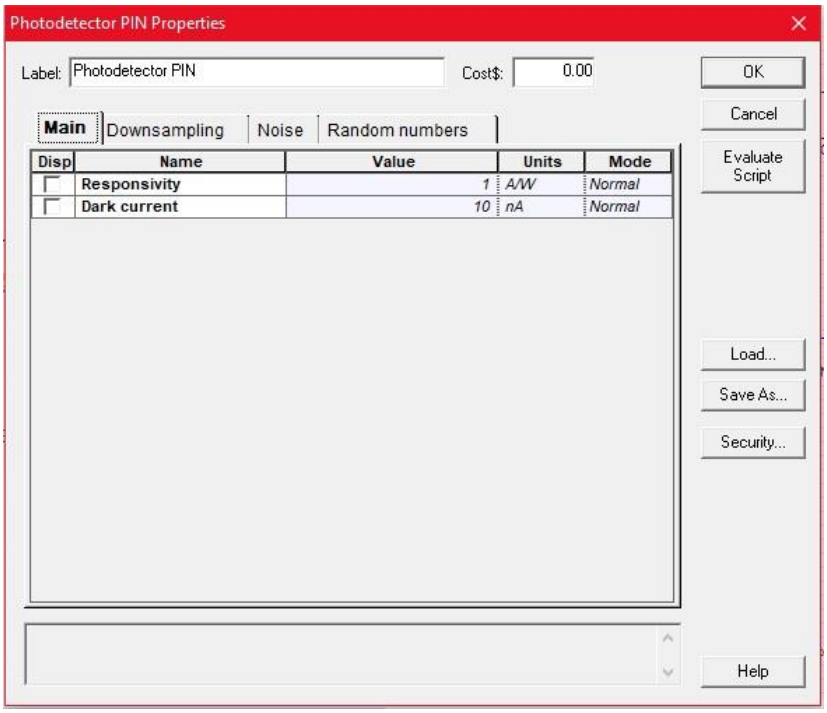


Figure III.20: *Photodetector PIN.*

II.3.2 Low Pass Gaussian Filter:

A Gaussian Filter is a low-pass filter used in image processing to reduce noise and blur regions of an image. It works by convolving the image with a Gaussian function, which gives more weight to the central pixels and less to the peripheral ones. This results in a smoothing effect that preserves edges while reducing high-frequency noise [19].

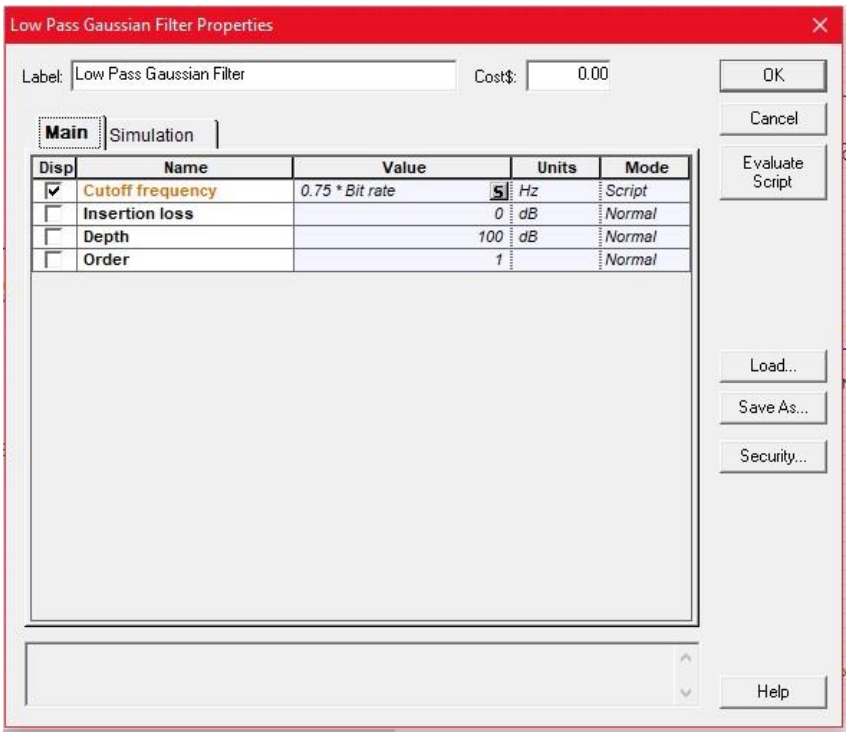


Figure III.21: *Low Pass Gaussian Filter*

An Optical Spectrum Analyzer (OSA) from Optiwave is a device used to measure the optical power of a light signal across a range of wavelengths. These instruments are crucial for analysing the spectral characteristics of optical signals in telecommunications, fibre optic networks, and other optical systems.

A Gaussian Optical Filter in OptiSystem, is an optical element used to filter optical signals based on their frequency. The Gaussian optical filter component acts as an optical filter with a Gaussian frequency transfer function, It has a Gaussian-shaped transition function. The advantage of the Gaussian filter over other types of filters is that it reduces time distortion and preserves the shape of the signal, making it ideal for applications that require precision in optical signal transmission.

This filter allows frequencies close to the centre frequency to pass while reducing or eliminating other frequencies farther from this frequency. It is commonly used in optical communications systems to select a specific channel from among multiple channels within an optical signal (such as in WDM multiplexing systems). The filter's properties include:
Centre Frequency: The frequency that is allowed to pass with maximum intensity.
Bandwidth: The range within which the signal effectively passes.
Frequency Response Shape: A smooth, Gaussian-shaped response, which reduces distortions in the signal [21].

IIIV. CONCLUSION

In this chapter, we introduced OptiSystem, a powerful and efficient simulation software for modelling optical transmission chains. We explored the various components that make up the software and how they are used to simulate optical systems. We also described the program's features and the various tools that will enable detailed simulations of optical communication systems in the future. Although we haven't yet performed any concrete simulations in this chapter, we highlighted OptiSystem's capabilities for performing performance analyses using criteria such as the eye diagram, quality factor, and bit rate.

This chapter has laid the foundation for working with OptiSystem and set the stage for the future simulations we will perform in the coming chapter.

Chapter IV:

Analysing the Performance of a Simulated High-Speed Optical Fiber Transmission System

I. INTRODUCTION

Simulation has become a crucial step in reducing costs and minimizing the need for complex field experiments. Additionally, it allows for the efficient exploration of multiple operational scenarios in a short timeframe. In this chapter, the performance of a high-speed optical transmission system between Bordj Bou Arreridj and Setif will be evaluated using OptiSystem. The study focuses on analysing the quality of the transmitted signal by comparing two distinct coding technologies—Non-Return-to-Zero (NRZ) and Return-to-Zero (RZ)—through a practical simulation of a 10 Gbit/s transmission system.

II. SIMULATION STEPS AND PHYSICAL PARAMETERS

II.1. Circuit Preparation and Configuration

We begin by setting up the circuit in OptiSystem, placing all necessary components, configuring their parameters, and connecting them in the correct sequence according to the system's signal flow.

a. **Initial Setup:**
   - Open the OptiSystem program and select the main design view.
   - From the component library, arrange the following elements in order:
     - Pseudo-random bit sequence (PRBS) generator
     - NRZ pulse generator
     - Continuous-wave (CW) laser
     - Mach-Zehnder modulator
     - Optical fiber
     - PIN photodetector
     - Low-pass filter
     - Oscilloscope visualizers
     - Optical spectrum analyzers

b. **Component Configuration:**
   - Set the bit rate for both the PRBS generator and the NRZ pulse generator.
   - Adjust the laser's wavelength and power.
   - Define the optical fibber's length and transmission properties.

c. **Connections:**
   - Link the PRBS generator's output to the NRZ pulse generator's input.
   - Connect the NRZ pulse generator's output to the Mach-Zehnder modulator's

input.

- Route the modulator's output to the optical fibber's input.
- On the receiver side:
  - Attach the optical fibber's output to the PIN photodetector's input.
  - Connect the photodetector's output to the low-pass filter's input.
  - Finally, link the filter's output to both the pulse counter and the optical spectrum analyzers.

II.2 Design Consideration:

The system is operated with the basic optical communication which consists of a transmitter, transmission link and a receiver. The system transmits information using optical carrier wave from transmitter to receiver via optical fiber. The input signal contains electrical data that is represented by 0's and 1's has been generated by a non-return-zero (NRZ) pseudorandom binary sequence in the first simulation and in the second we use (RZ). Then the input signal is modulated with semiconductor laser that is represented by Continuous Wave (CW) laser through Mach- Zehnder modulator. CW laser supplies input signal with 1550 nm wavelength and input power of 10dBm. The optical fiber used is single mode fiber because single mode fiber can yield higher data rate, less dispersion and also can operate in long distance, so it is suitable to be use as transmission link.

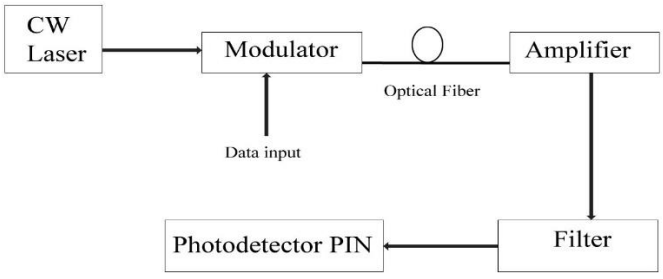


Figure IV.1: *The optical transmission system block diagram.*

Optical amplification is required to overcome the fiber loss and also to amplify the signal before receive by Photo detector PIN at the receiver part [5].

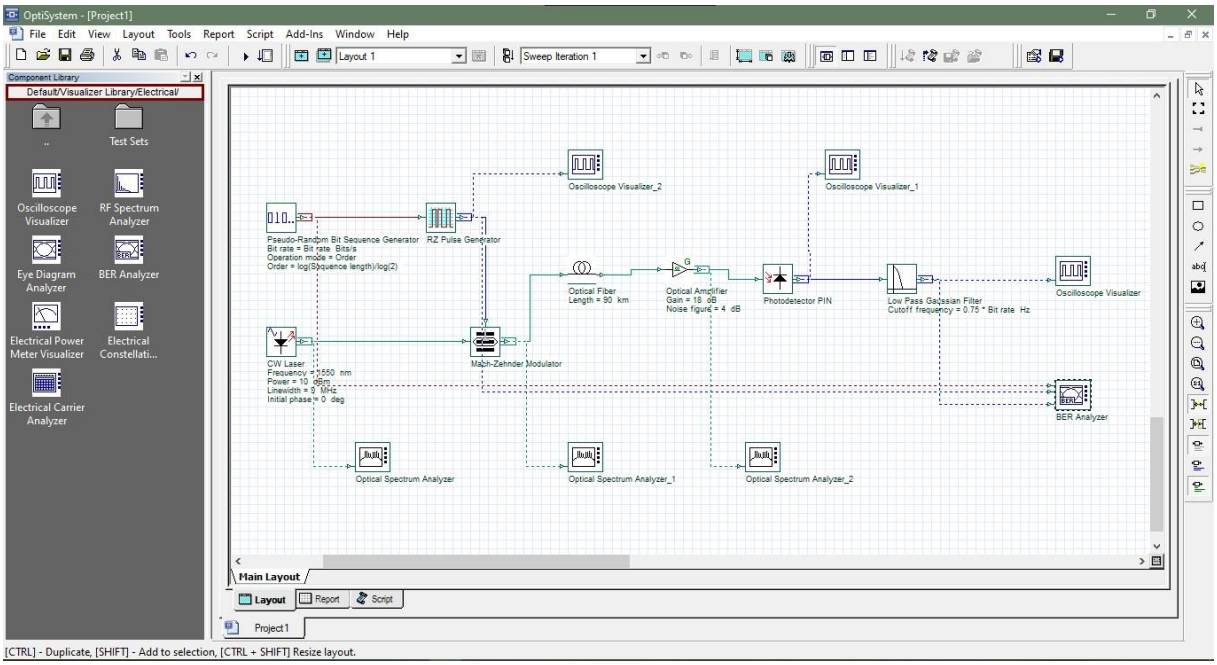


Figure IV.2: *Simulation circuit.*

Continuous Wave Laser (CW Laser)

In CW Laser we use these settings: 1550 nm wavelength: This is the low-loss window in standard single-mode fiber (SMF), with loss ~0.2 dB/km. Output Power (~10 dBm): A moderate launch power avoids nonlinear effects (like self-phase modulation and four-wave mixing) while ensuring enough signal level to survive the fiber and reach the detector. Linewidth ≤ 10 MHz: A narrower linewidth laser reduces phase noise, which is especially important in high-speed systems and when coherent detection is used.

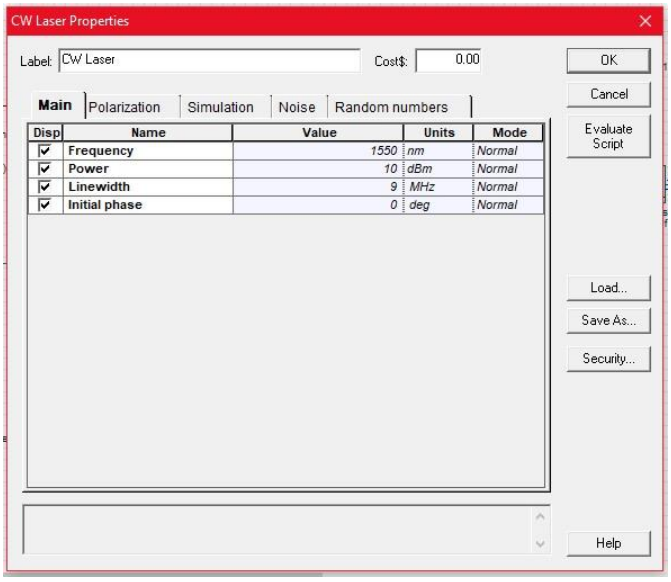


Figure IV.3: *CW Laser settings.*

Mach-Zehnder Modulator (MZM)

Mach-Zehnder Modulator (MZM) settings: Extinction Ratio ≥ 20 dB: This ensures a clear distinction between logical '0' and '1', improving the signal-to-noise ratio and reducing BER. Bias at quadrature (Vπ/2): It allows the MZM to linearly modulate the input electrical signal onto the optical carrier. Approximately 4 V (the value depends on the type of model used in the simulation). Drive Signal (NRZ or RZ): NRZ is more bandwidth-efficient.

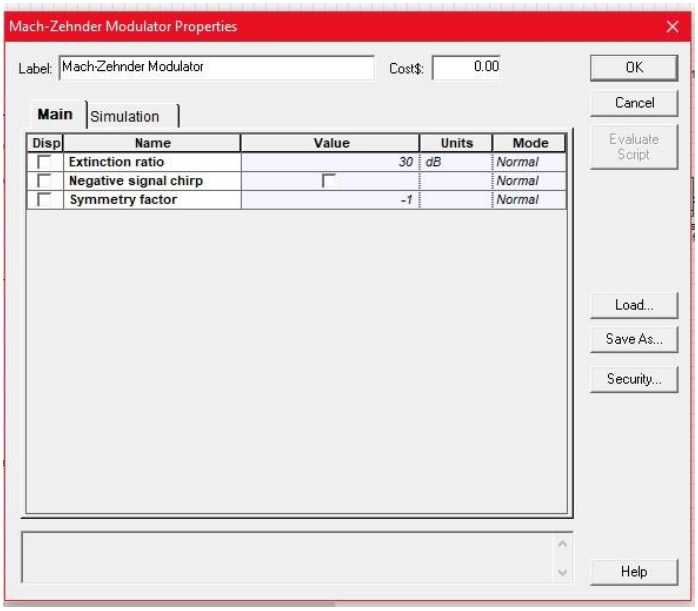


Figure IV.4: *Mach-Zehnder Modulator settings.*

Optical Fiber

In the simulation of a 90-kilometer optical data transmission system using OptiSystem, the transmission path is represented using standard optical fibers. This component is one of the most important elements of the system, as it determines the behaviour of the optical signal as it travels over the specified distance, taking into account the effects of attenuation, dispersion, and nonlinearity. The basic properties set in the fiber optic component within the software are:

- Length: 90 km
- Attenuation: 0.2 dB/km at 1550 nm (resulting in a total loss of approximately 18 dB over the entire distance)
- Dispersion: 16.75 picoseconds/nm/km (compared to DCF units or other techniques)
- Nonlinearity: Becomes significant when using high launch power (SPM and XPM effects should be taken into account in single-mode fibers)

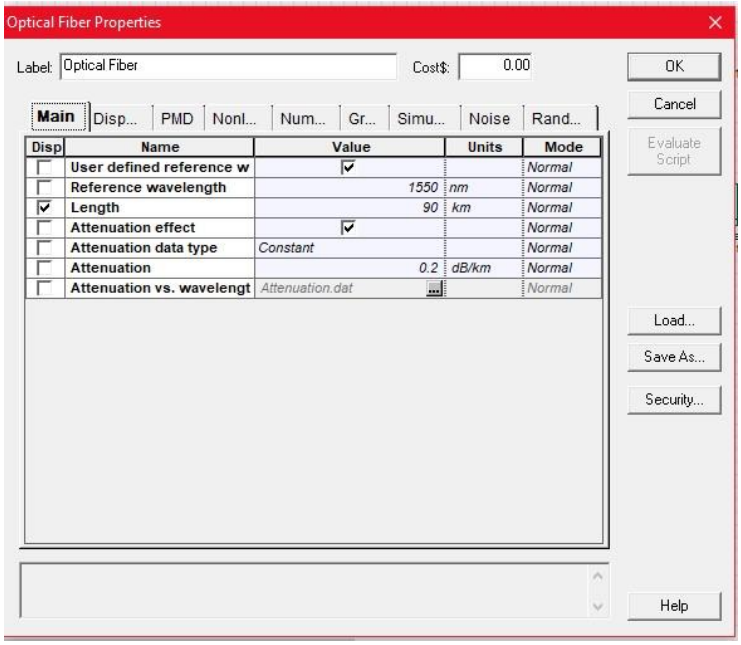


Figure IV.5: *Optical Fiber settings*

Optical Amplifier

In the simulation of a 90-kilometer optical data transmission system using OptiSystem, EDFA (Erbium-Doped Fiber Amplifiers) are employed to compensate for signal attenuation caused by fiber loss. These amplifiers are strategically placed along the transmission path to maintain a high Optical Signal-to-Noise Ratio (OSNR) and ensure signal integrity. Optical Amplifier (EDFA) two amplifiers spaced evenly are better: One amplifier at 45 km means the signal degrades for 45 km before being boosted, leading to poor OSNR. Two amplifiers (e.g., at 30 km and 60 km) keep the signal level more consistent, leading to better noise performance and Q-factor. Gain (15–18 dB): Compensates the loss of the preceding fiber span (~0.2 dB/km × distance). Noise Figure ≤ 5 dB: Low NF ensures amplifier noise doesn't dominate at the receiver.

Below are the main configuration parameters for the EDFA component in the software:

- **Placement Strategy:** Using two amplifiers placed at 30 km and 60 km is generally more effective than placing one at 45 km (This approach helps maintain a better OSNR throughout the link)
- **Gain:** Should be sufficient to compensate for fiber loss between amplifier stages (Typically around 15–18 dB depending on segment length)
- **Noise Figure (NF):** NF ≤ 5 dB (Lower values are preferred to minimize amplifier-induced noise)

- **Gain Flatness:** Important if WDM (Wavelength Division Multiplexing) is used (Ensures equal amplification across all wavelength channels)

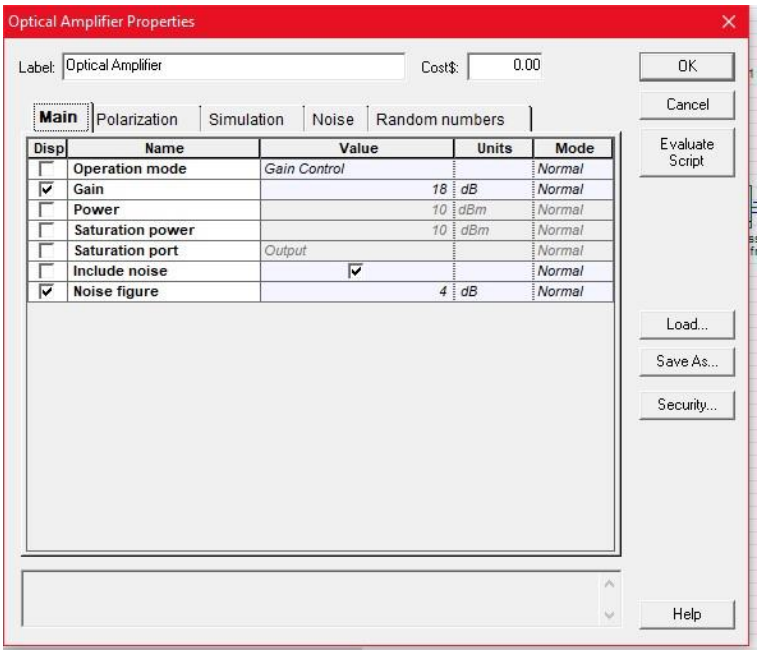


Figure IV.6: *Optical Amplifier (EDFA):settings.*

- **Photodetector PIN**

In this simulation of a 90-kilometer optical communication system, the PIN photodetector is used at the receiver side to convert the incoming optical signal into an electrical signal. The proper configuration of this component is critical to accurately recover the transmitted data with minimal noise and distortion. Proper tuning of the photodetector parameters is crucial for maintaining signal integrity and achieving accurate data detection in long-haul optical communication systems.

Below are the key parameters typically set for the PIN photodetector in the simulation:

- **Responsivity:** Approximately 0.8 A/W, Indicates the efficiency of converting optical power into electrical current.
- **Bandwidth:** Should be at least equal to the system's data rate, Ensures the detector can respond to all signal variations
- **Dark Current:** Should be kept minimal, Reduces the amount of noise introduced when no light is present.

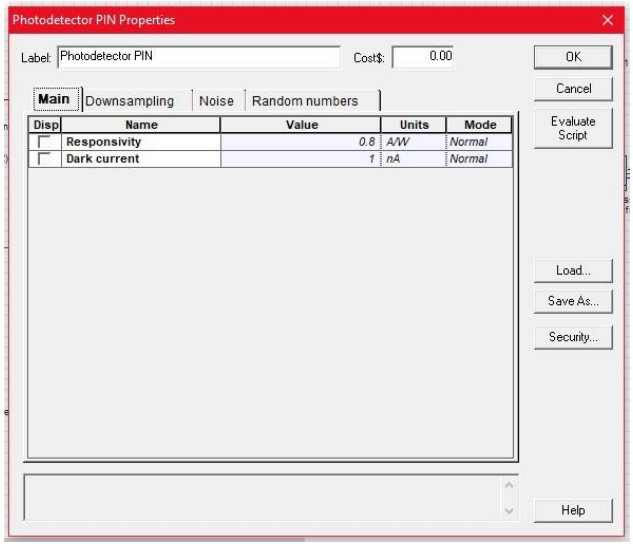


Figure IV.7: *Photodetector PIN settings.*

- **Low Pass Filter (LPF)**

In the simulation of a 90-kilometer optical transmission system using OptiSystem, the Low Pass Filter (LPF) is used after the photodetector to eliminate high-frequency noise and smooth the received electrical signal. Correct configuration of the LPF is essential to preserve the signal's integrity while minimizing intermember interference. Below are the key settings typically applied for the LPF component in the simulation:

- **Cutoff Frequency:** Approximately 0.75 × bit rate (For example, for a 10 Gbps system, set the cutoff around 7.5 GHz)
- **Filter Order:** 1st or 2nd order Bessel or Butterworth (Bessel filters are preferred when maintaining the waveform shape is critical)

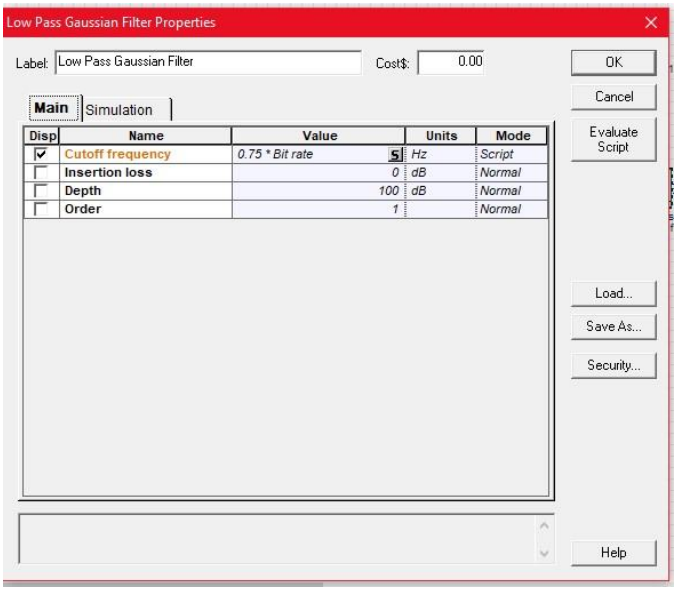


Figure IV.8: *Low Pass Filter (LPF) settings.*

III.SIMULATION PROCESS OF THE SYSTEM

III.1 Simulation I NRZ (Non-Return-to-Zero):

This simulation uses the NRZ (Non-Return-to-Zero) encoding format, where binary data is represented by two voltage levels without returning to zero between bits. The purpose of this simulation is to analyze the performance of an optical communication system using NRZ modulation. The key objective is to evaluate the signal quality and spectral characteristics after passing through key components like the Mach-Zehnder Modulator, optical fiber, amplifier, and photodetector. This helps in understanding how NRZ encoding affects the transmission and how the system handles dispersion and noise.

- **CW Laser Analyzer:**

The figure IV.9 shows the signal coming out of Optical spectrum analyzer of CW laser, the spectrum has a similar shape on both sides.

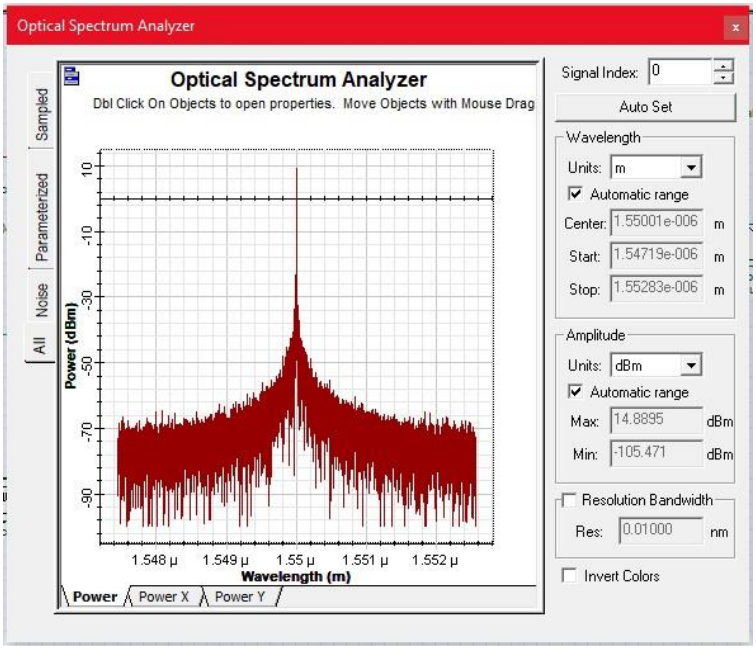


Figure IV.9: *CW Laser Analyzer.*

- **Mach-Zehnder Modulator (MZM) Analyzer:**

The figure IV.10 shows Mach-Zehnder Modulator (MZM) Analyzer the output spectrum from the Mach-Zehnder Modulator, centred around 1550 nm. The symmetric shape with a central peak and sidebands indicates effective modulation using an NRZ signal. The spectral distribution confirms successful optical signal transmission.

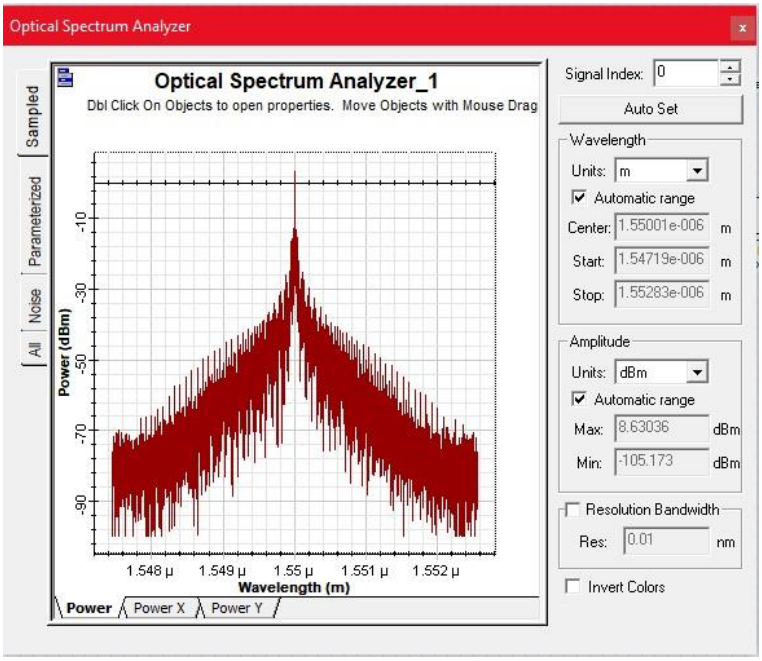


Figure IV.10: *Mach-Zehnder Modulator (MZM) Analyzer.*

- **Optical Amplifier Analyzer:**

Figure IV.11 Shows Optical Spectrum Analyzer_2 represents the optical signal spectrum after passing through the Optical Amplifier. The spectral peak remains centred around 1550 nm, but compared to the pre-amplified signal, the power level has significantly increased, indicating effective amplification

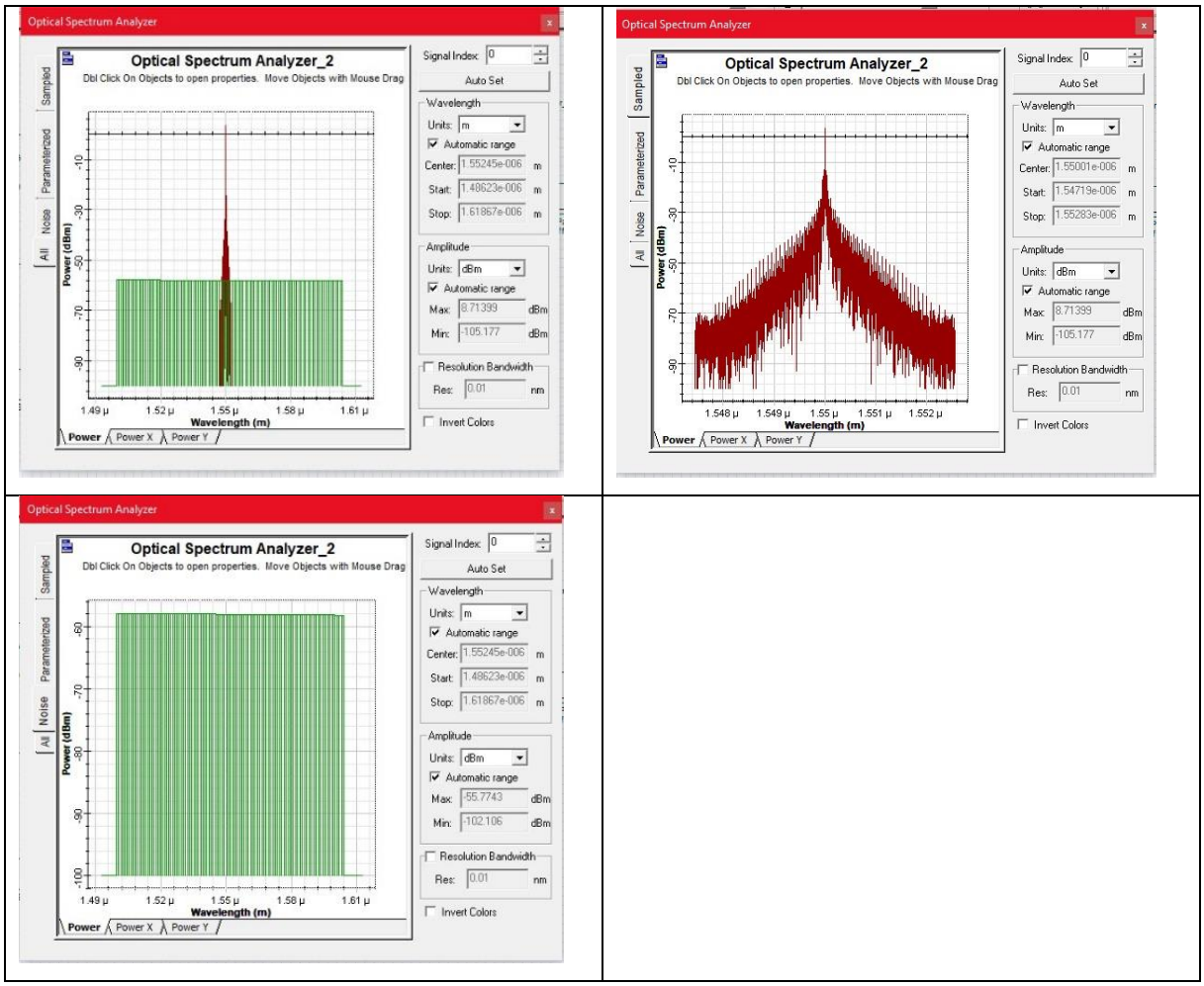


Figure IV.11: *Optical Amplifier Analyzer.*

- **NRZ Pulse Generator:**

the Figure IV.12 shows NRZ Pulse Generator, the signal coming out of the pulse generator using the NRZ encoder, as it appears on the signal sketch screen, the signal shows a binary pattern that remains constant during each bit period without going back to zero, which is what distinguishes the NRZ coding used in high-speed optical communication systems.

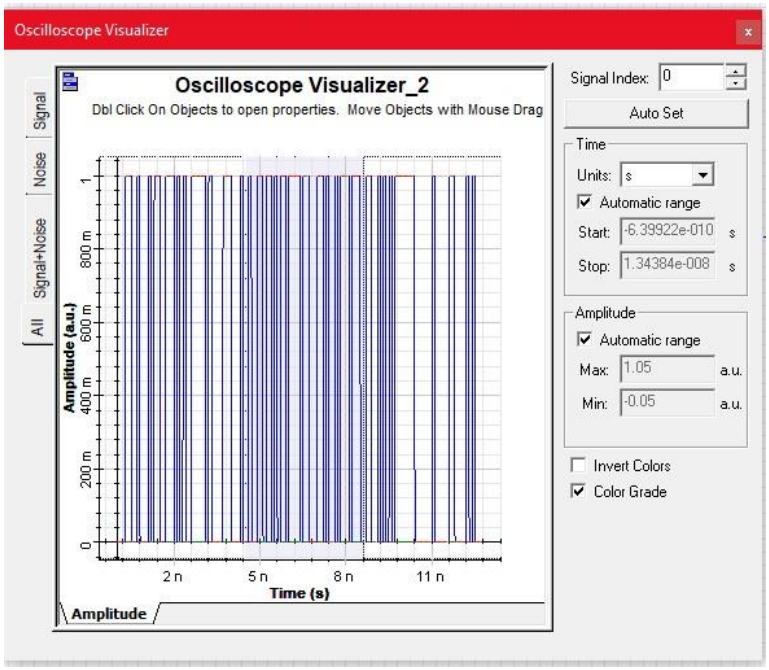


Figure IV.12: *NRZ Pulse Generator*

- **Photodetector PIN Oscilloscope:**

The figure IV.13 illustrates the signal observed at the output of the Photodetector PIN as shown on the oscilloscope. The waveform displays a noisy analog signal (in blue) resulting from the conversion of the received optical signal into an electrical one, along with a lower-amplitude noise signal (in green), representing the background noise present in the system.

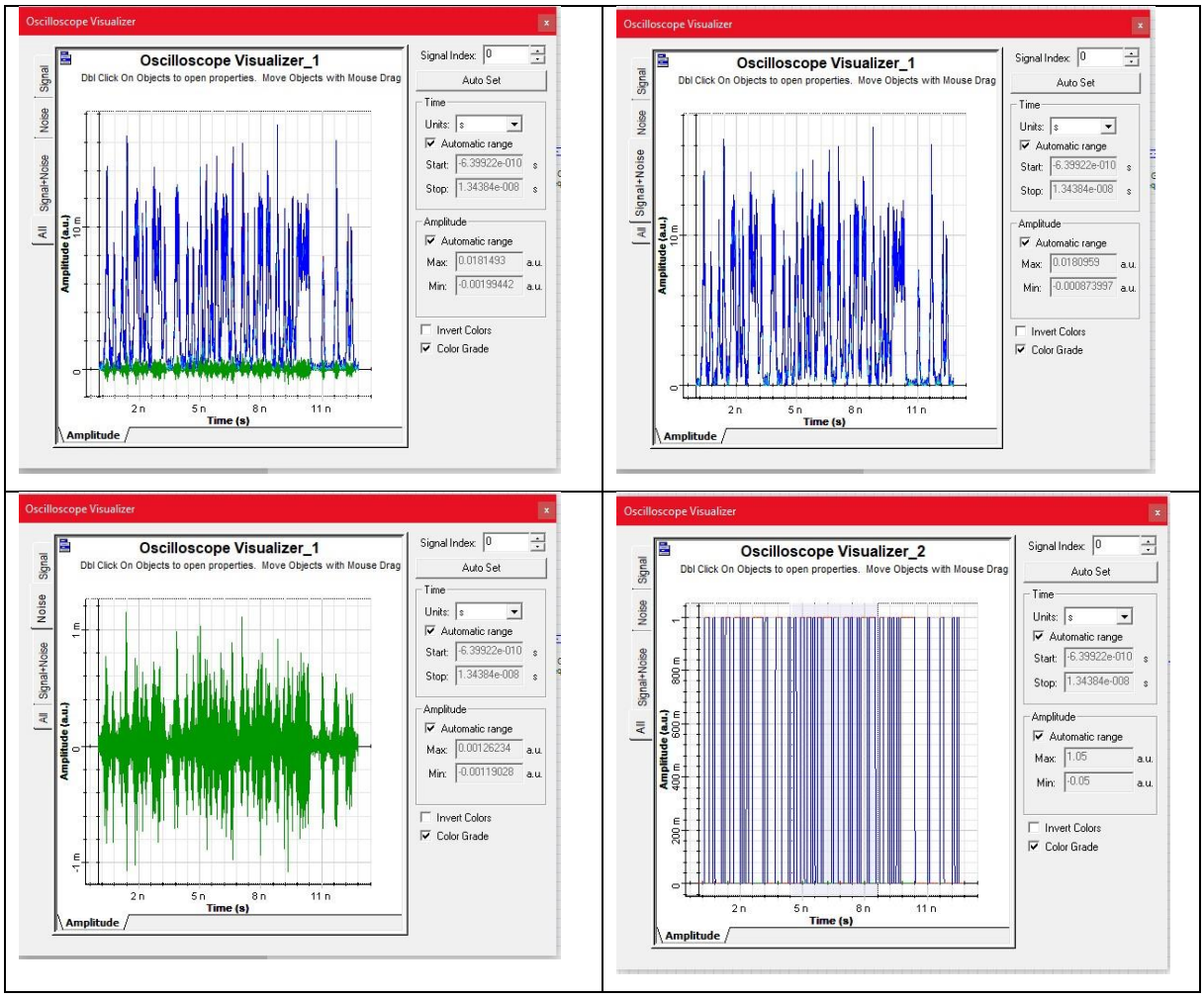


Figure IV.13: *Photodetector PIN Oscilloscope.*

- **Low Pass Filter (LPF) and *BER Analyzer*:**

The figure IV.14 shows the filtered signal after passing through the Low Pass Gaussian Filter, as displayed on the oscilloscope. Compared to the previous stage, the waveform is smoother and less noisy, indicating that high-frequency noise components have been effectively suppressed, allowing clearer recovery of the transmitted data.

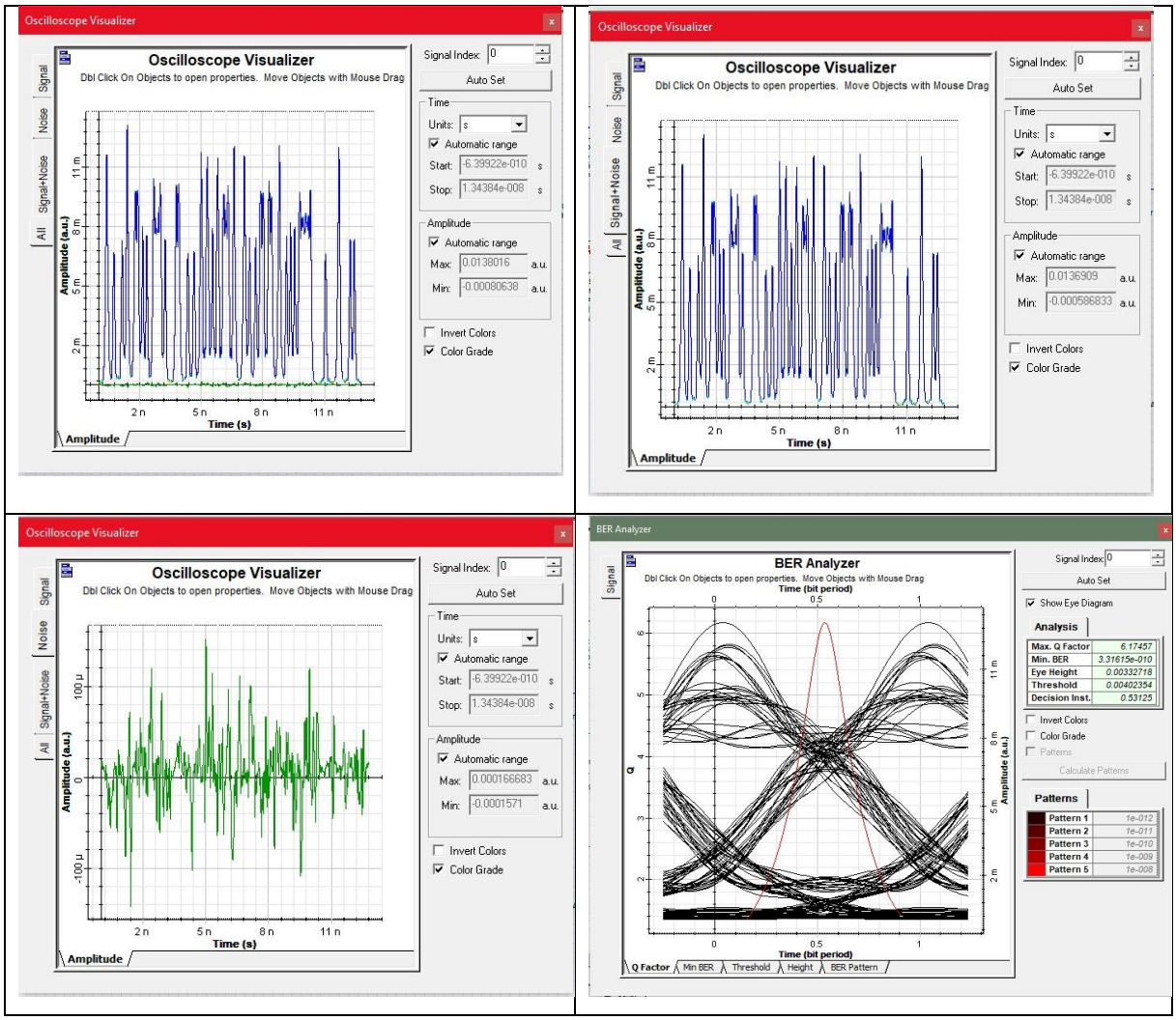


Figure IV.14: *Low Pass Filter (LPF) and BER Analyzer.*

- **Explanation:**

In this experiment, the OptiSystem software was used to simulate an optical communications system based on optical fibers. The main objective of the experiment was to study the performance of the Non-Return-to-Zero (NRZ) coding technique in transmitting data over optical fibers. The system consists of a laser source operating at a wavelength of 1550 nm with a power of 7 dBm. This source is connected to a pseudo-Random Bit Sequence (PRBS) generator with a speed of 10 Gbit/s. A Mach-Zender amplifier is then used to modulate the optical signal, an optical amplifier to boost the signal, and a PIN optical receiver to convert the optical signal to an electrical signal. A low-pass filter is also used to improve the signal-to-noise ratio (SNR).

III.2 Simulation II (RZ):

- **CW Laser Analyzer (RZ):**

The figure IV.15 shows the signal coming out of Optical spectrum analyzer of CW laser, the spectrum has a similar shape on both sides. There is high and narrow power peak in the middle of the spectrum figure at a wavelength it is close to 1.55 µm.

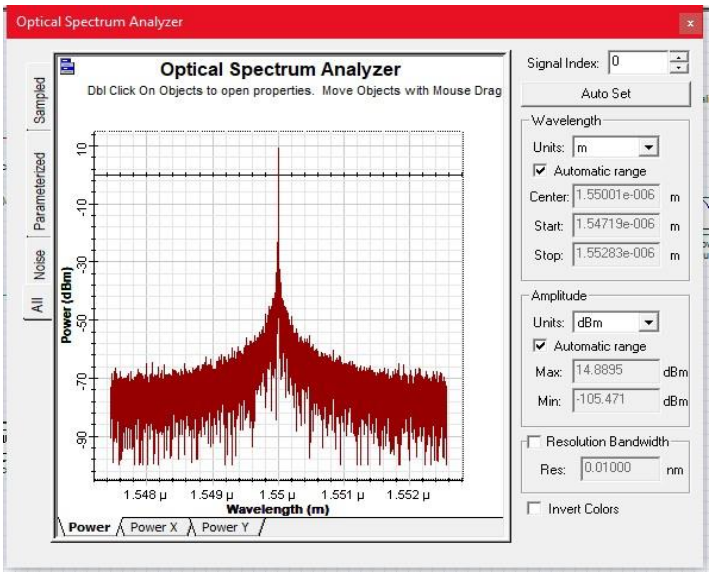


Figure IV.15: *CW Laser Analyzer (RZ).*

- **Mach-Zehnder Modulator (MZM) Analyzer:**

The figure IV.16 shows the optical spectrum analysis of Mach-Zehnder Modulator (MZM) Analyzer. The graph illustrates the power distribution of the signal across a range of wavelengths, providing insights into the characteristics and quality of the optical signal being analysed.

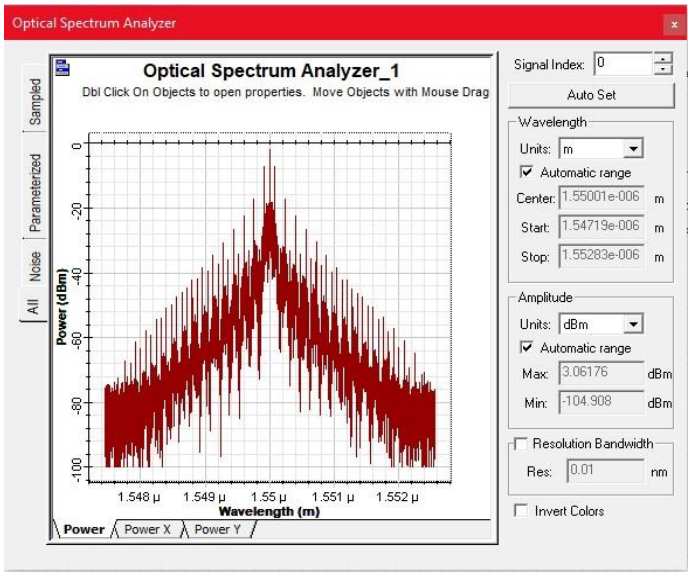


Figure IV.16: *Mach-Zehnder Modulator (MZM) Analyzer RZ.*

- **Optical Amplifier Analyzer:**

The figure IV.17 illustrates Optical Amplifier Analyzer The graph in the figure shows the power distribution of the optical signal across a range of wavelengths. Key details such as the centre wavelength, start and stop wavelengths, and the power levels (both maximum and minimum) are provided. This information is crucial for assessing the performance and quality of the optical signal.

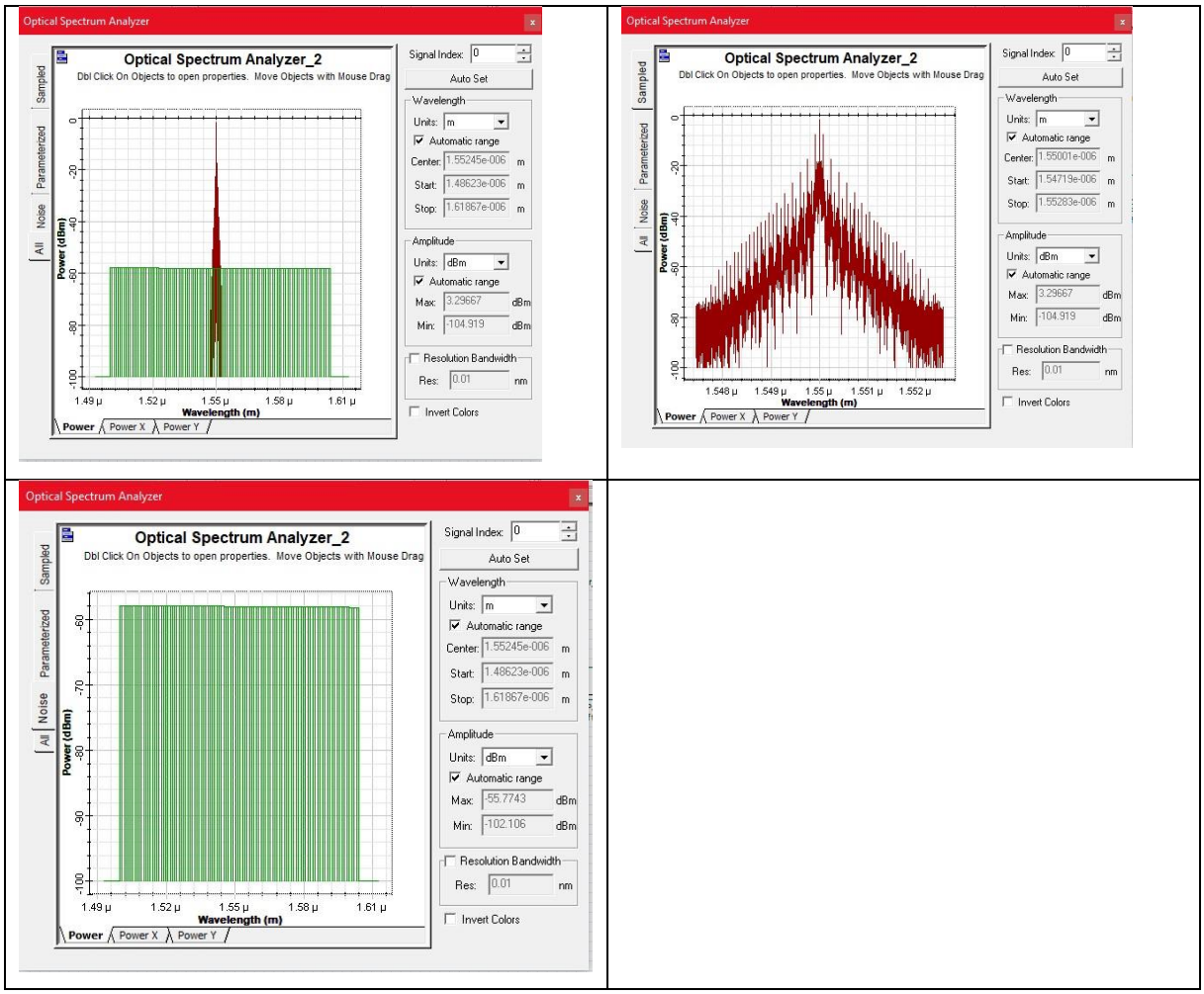


Figure IV.17: *Optical Amplifier Analyzer RZ.*

- **RZ Pulse Generator:**

The figure IV.18 shows the output of an RZ (Return-to-Zero) Pulse Generator. The graph illustrates the signal's amplitude on the y-axis and time on the x-axis. The RZ pulse format is characterized by pulses that return to a zero-amplitude level between each pulse, which helps in reducing inter-symbol interference in optical communication systems. This visualization is crucial for analysing the timing, shape, and consistency of the pulses generated by the RZ Pulse Generator.

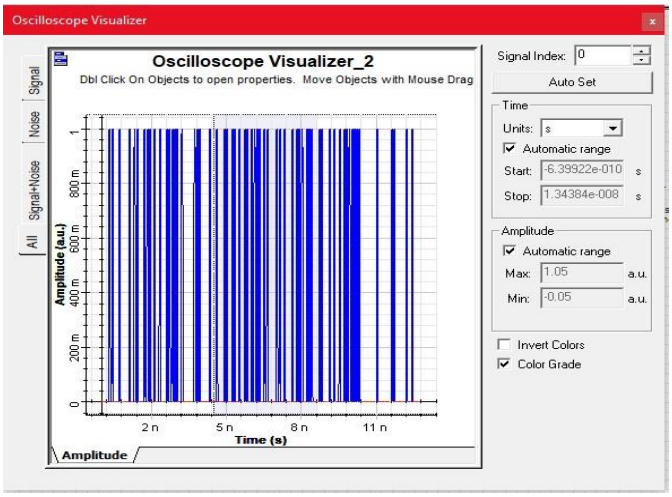


Figure IV.18: *RZ Pulse Generator.*

- **Photodetector PIN Oscilloscope:**

As shown in figure IV.19 the signal's amplitude on the y-axis and time on the x-axis. The photodetector PIN (Positive-Intrinsic-Negative) is a type of photodiode that converts optical signals into electrical signals. This conversion is crucial for further processing and analysis of the signal in an optical communication system.

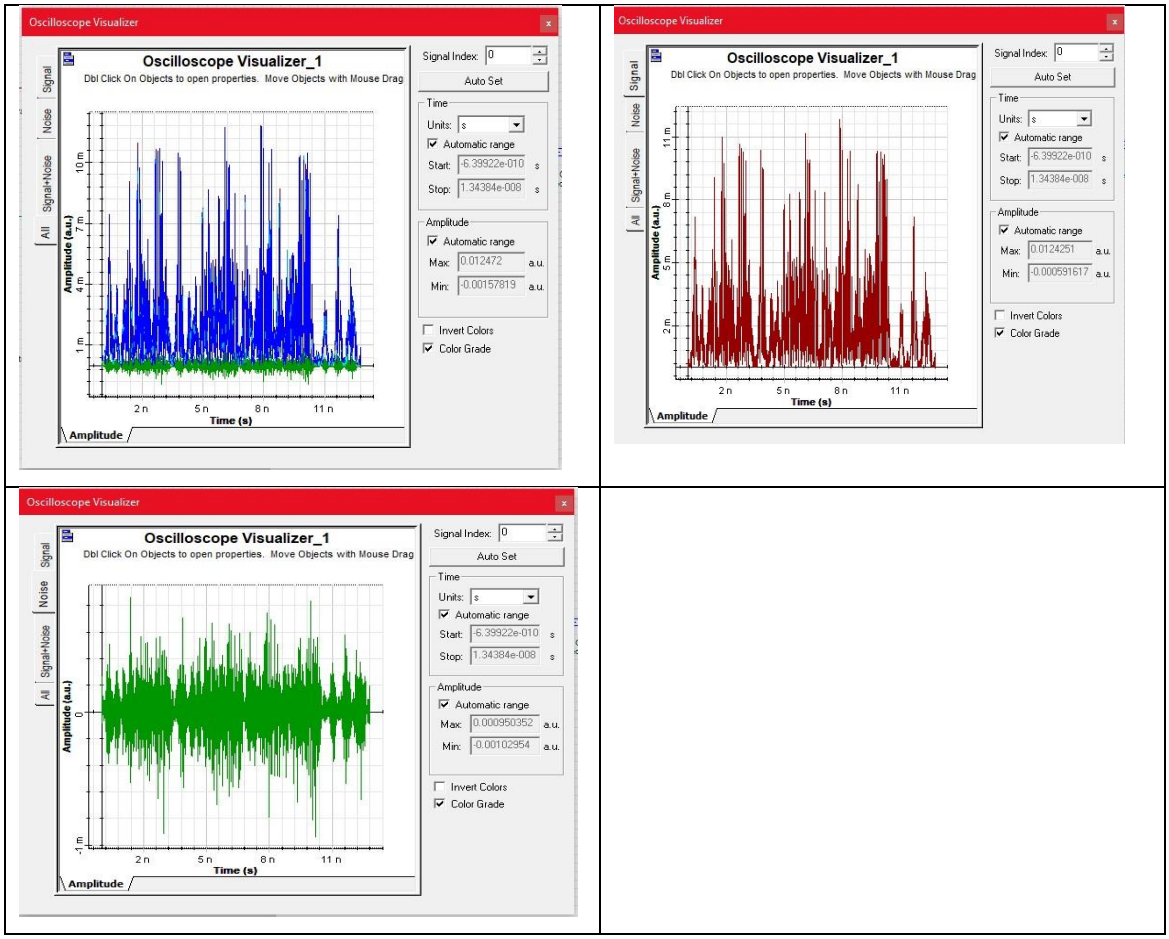


Figure IV.19: *Photodetector PIN Oscilloscope RZ.*

- **Low Pass Filter (LPF):**

The figure IV.20 illustrates the output of a system involving a Low Pass Gaussian Filter and a Bit Error Rate (BER) Analyzer the Oscilloscope Visualizer shows the amplitude of the signal over time after it has passed through a Low Pass Gaussian Filter.

This type of filter is used to remove high-frequency noise from the signal, allowing only the lower frequencies to pass through. The graph provides insights into the signal's behavior and quality post-filtration, with key parameters such as start and stop times, and amplitude values.

The BER Analyzer is used to evaluate the performance of the communication system by analyzing the Bit Error Rate, which is a key metric in assessing the number of bit errors per unit of time. The eye diagram in the BER Analyzer provides a visual representation of the signal quality, showing how well the receiver can distinguish between different signal levels.

This analysis is crucial for determining the effectiveness of the communication system in terms of data integrity and reliability. The BER Analyzer helps in identifying issues such as noise, distortion, and timing errors that can affect the overall performance of the system.

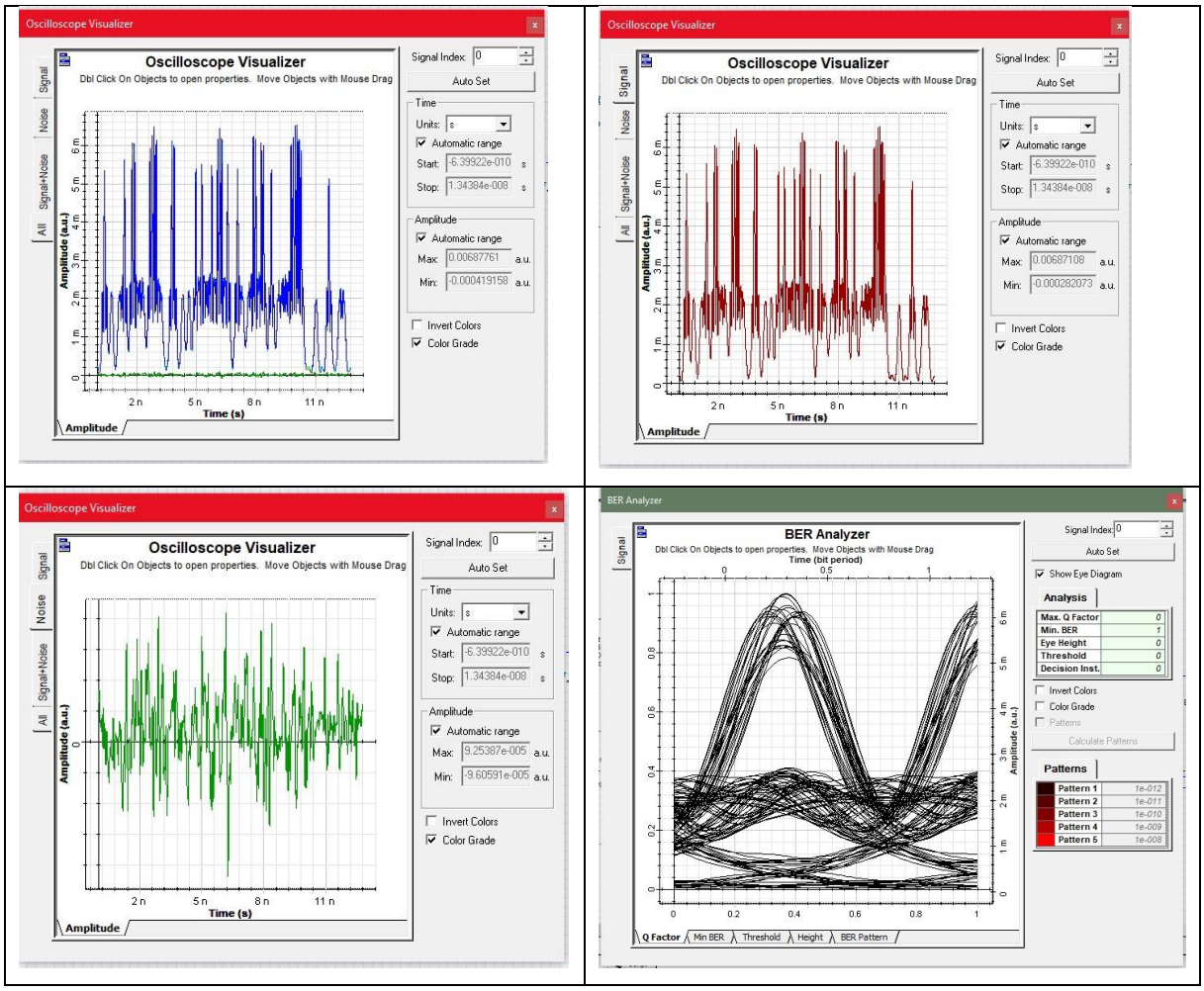


Figure IV.20: *Low Pass Filter (LPF) and BER analyser.*

IV. DISCUSSION:

Based on simulation results of the fiber optic data transmission circuit, it is clear that the NRZ (Non-Return-to-Zero) system offers significantly better performance than the RZ (Return-to-Zero) system, based on the values shown in the BER Analyzer plots.

In the RZ case, the simulation showed significant distortion and signal interference with a very narrow eye aperture. This was reflected in a Q Factor of zero and a very high Bit Error Rate (BER) of 1, indicating significantly poor signal quality and difficulty making correct decisions when receiving data.

In contrast, the NRZ system showed significantly improved performance characteristics, with a high Q Factor (6.17457) and a BER value that dropped to 3.31675e-10, demonstrating the clarity of the signal and the system's effectiveness in reducing errors. The eye aperture in the NRZ plot also showed a clear widening, reflecting signal stability and easy

discrimination between logic states, in contrast to the distortion and interference seen in the RZ plot.

These results demonstrate that NRZ is more resistant to optical dispersion and interference effects caused by limited laser sources or insufficient Bessel filters, making it an ideal choice in high-speed optical communication environments that require reliable, stable signal quality, and high performance. The results indicate that NRZ modulation technology exhibits better performance in noisy environments and where distortions affect transmitted signals, enhancing its efficiency and reliability in modern optical communication systems.

V. COMPARISON BETWEEN THE TWO SYSTEMS

We found that at 90 km, the NRZ (Non-Return to Zero) modulation scheme performed better than the RZ (Return to Zero) modulation scheme, due to its greater resistance to interference and signal degradation over long distances. RZ was shown to have a shorter pulse width, which reduces inter-symbol interference (ISI) and maintains signal quality, resulting in a higher Q-factor and lower bit error rate (BER). While NRZ is bandwidth-efficient over short distances, RZ has proven its superior performance at longer distances, such as 90 km, due to its clearer and more stable signal.

IV.1 Advantages/ disadvantages of each configuration

- **NRZ (Non-Return-to-Zero)**

Advantages

- Lower bandwidth consumption.
- Simpler modulation and demodulation circuitry.

Disadvantages

- Susceptible to Inter-Symbol Interference (ISI) in long optical fibers due to lack of pulse separation.
- Performance degrades in the presence of dispersion and jitter.
- Eye diagram shows partial closure, indicating signal degradation.

- **RZ (Return-to-Zero)**

Advantages

- Clearer pulse distinction enhances timing recovery.

- Improved BER and better eye diagram clarity due to reduced ISI.
- Higher resilience to dispersion and nonlinearities.

Disadvantages

- Requires wider bandwidth.
- More complex generation due to the need for additional clocking or pulse shaping circuits.

IV.2 Results table:

The **Table IV.1** compares NRZ and RZ systems, highlighting differences in signal representation, bandwidth efficiency, complexity, Peak Amplitude (V), Amplitude Range (V), Q. factor Noise Observed, Bit Error Rate (BER).

Metric	NRZ	RZ
Amplitude Range (V)	-0.00103 to 0.00095	-0.0016 to 0.0129
Peak Amplitude (V)	~0.00095	~0.0129
Noise Observed	Moderate to High	Moderate
Eye Diagram Clarity	Partially closed eye	Open and clear eye pattern
Bit Error Rate (BER)	$\sim 3.2 \times 10^{-4}$	1
Signal Jitter	Present due to overlapping pulses	Lower jitter, distinct pulse edges
Q. factor	6.17457	0

Table IV.1: *Comparison Between the Two Systems.*

VI. CONCLUSION

The simulation results clearly demonstrate that NRZ encoding outperforms RZ in terms of signal quality, bit error rate (BER), and resilience to noise. Although RZ is theoretically more resistant to dispersion due to its return-to-zero behavior within each bit interval, the practical performance showed significant signal degradation and a higher BER. In contrast, NRZ provided more stable and clearer signals even after transmission through key optical

components such as the Mach-Zehnder Modulator, optical fiber, amplifier, and photodetector.

These findings highlight the importance of choosing the appropriate modulation format based on the system's requirements, fiber length, and noise conditions. NRZ has proven to offer a balanced trade-off between spectral efficiency and performance stability, making it a more reliable option for optical communication systems that demand high signal quality and low error rates.

General Conclusion

GENERAL CONCLUSION

Through this work, we have built a comprehensive and progressive understanding of fiber optic communication systems. We began with a general study of communication systems, their components, and classifications, focusing on the importance of modern, high-speed transmission technologies and notable developments such as the Starlink project, which reflects the global trend toward improving communications infrastructure. Next, we delved into the characteristics of fiber optic communication systems, given their significant capacity to transmit large amounts of data over long distances with high efficiency. We also reviewed some technical shortcomings, such as chromatic dispersion, and discussed solutions currently available on the market, such as compensated fibers and optical amplifiers, which have significantly improved system performance.

We then moved on to introduce OptiSystem, an advanced tool for simulating optical communication chains. We explained its components and performance analysis capabilities using tools such as the eye diagram, quality factor, and bit rate, paving the way for accurate simulations in the coming chapters.

In the final chapter, we conducted a practical simulation comparing NRZ and RZ coding. The results demonstrated NRZ's superiority in terms of signal quality and lower error rate. Although RZ is theoretically known for its resistance to dispersion, practical results demonstrated its weakness under established test conditions.

In conclusion, it is clear that fiber optic communication is one of the most efficient and reliable means of modern communications. With the availability of advanced simulation tools, it has become possible to continuously improve its performance and meet the growing data transmission needs of the digital age.

Thesis Summary

Telecommunication systems have witnessed tremendous development over time, as traditional copper cables, such as coaxial cables, are no longer able to meet the high-speed data transmission requirements. This has driven the adoption of more efficient technologies such as optical fibers. The results of the dissertation showed that the analysis and modeling using OptiSystem demonstrated the superiority of the NRZ encoding technique over RZ in terms of signal quality, bit error rate (BER), and system resilience to noise and interference, especially when transmitting data over long distances up to 90 kilometers. The performance simulation relied on precise criteria such as the signal-to-noise ratio (SNR) and Eye Diagrams, which confirmed that NRZ provides a clearer and more stable signal, enhancing its efficiency in high-speed optical networks.

The study also explored the historical development of communication systems and the advantages of fiber-optic technology, focusing on the major challenges facing data transmission such as attenuation and dispersion, and the need for advanced solutions like optical amplifiers and dispersion compensation modules. The comparison between encoding schemes confirmed that NRZ offers an ideal balance between spectral efficiency and performance reliability, making it the best choice for long-distance transmission, while RZ showed performance degradation in high-noise environments. These findings highlight the importance of selecting the most appropriate encoding technique to ensure maximum efficiency and reliability in modern optical communication networks.

ملخص المذكرة

أنظمة الاتصالات شهدت تطورًا هائلًا مع مرور الزمن، حيث لم تعد الكابلات النحاسية التقليدية، مثل الكوابل المحورية، قادرة على تلبية متطلبات السرعة العالية لنقل البيانات، مما دفع نحو تبنّي تقنيات أكثر كفاءة مثل الألياف البصرية .وأظهرت نتائج المذكرة أن التحليل والنمذجة باستخدام برنامج OptiSystemبيّنا تفوّق تقنية الترميز NRZعلى RZمن حيث جودة الإشارة، ومعدل الخطأ في البت(BER) ، ومرونة النظام في مواجهة الضوضاء والتشويش، خاصة عند نقل البيانات لمسافات طويلة تصل إلى 90كيلومترًا .وقد تم اعتماد محاكاة الأداء باستخدام معايير دقيقة مثل نسبة الإشارة إلى الضوضاء (SNR) ومخططات العين(Eye Diagrams) ، حيث أثبتت النتائج أن NRZتوفر إشارة أكثر وضوحًا واستقرارًا، مما يعزز كفاءتها في الشبكات الضوئية عالية السرعة.

كما تناولت المذكرة التطور التاريخي لأنظمة الاتصالات ومميزات تقنية الألياف البصرية، مع التركيز على أبرز التحديات التي تواجه نقل البيانات مثل التوهين والتشتت، وضرورة الاستعانة بتقنيات متقدمة كالمضخمات الضوئية ووحدات تعويض التشتت. وأكدت المقارنة بين أنماط الترميز المختلفة أن NRZتوفر توازنًا مثاليًا بين الكفاءة الطيفية وموثوقية الأداء، مما

يجعلها الخيار الأمثل لنقل البيانات على المسافات الطويلة، في حين أظهرت RZضعفًا في الأداء داخل بيئات التشويش العالية. وتبرز هذه النتائج أهمية اختيار أسلوب الترميز الأنسب لضمان أقصى درجات الكفاءة والموثوقية في الشبكات الضوئية الحديثة.

Résumé de la Mémoire

Les systèmes de télécommunication ont connu un développement considérable au fil du temps, car les câbles en cuivre traditionnels, tels que les câbles coaxiaux, ne sont plus capables de répondre aux exigences de transmission de données à haute vitesse. Cela a conduit à l'adoption de technologies plus performantes comme la fibre optique. Les résultats du mémoire ont montré que l'analyse et la modélisation réalisées avec le logiciel OptiSystem ont démontré la supériorité de la technique de codage NRZ par rapport à RZ, en termes de qualité du signal, de taux d'erreur binaire (BER) et de résistance du système au bruit et aux interférences, notamment lors de la transmission sur de longues distances allant jusqu'à 90 kilomètres. La simulation des performances s'est basée sur des critères précis tels que le rapport signal/bruit (SNR) et les diagrammes de l'œil (Eye Diagram), qui ont confirmé que NRZ offre un signal plus clair et plus stable, renforçant ainsi son efficacité dans les réseaux optiques à haute vitesse.

Le mémoire a également traité de l'évolution historique des systèmes de communication et des avantages de la technologie à fibre optique, en mettant l'accent sur les principaux défis de la transmission de données, tels que l'atténuation et la dispersion, ainsi que sur la nécessité de recourir à des solutions avancées comme les amplificateurs optiques et les modules de compensation de dispersion. La comparaison entre les schémas de codage a confirmé que NRZ offre un équilibre idéal entre l'efficacité spectrale et la fiabilité des performances, ce qui en fait le choix optimal pour la transmission sur de longues distances, tandis que RZ a montré des limites de performance dans les environnements fortement perturbés.

Ces résultats soulignent l'importance de choisir une technique de codage adaptée pour garantir un maximum d'efficacité et de fiabilité dans les réseaux de communication optique modernes.

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