Université Mohamed Khider de Biskra
Faculté des Sciences et de la Technologie
Département de génie électrique

MÉMOIRE DE MASTER

Sciences et Technologies
Telecommunication
Réseaux et Telecommunication

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Présenté et soutenu par :
ALLALI Charaf Eddine / Abu Daqqa Nour Mohamed

Le : **mercredi 4 juin 2025**

Design and simulation of wavelength division multiplexing system

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Année universitaire : **2024 - 2025**

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Acknowledgments

We wish to extend our heartfelt appreciation to Professor Zine Eddine Baarir for his indispensable guidance and unwavering support during our final year project. Your insightful advice, accessibility, and willingness to listen were crucial to the success of our work. We genuinely appreciate the chance you provided for us to grow both professionally and personally throughout this experience. Once more, thank you for your outstanding guidance.

I would like to thank each member of the committee for your valuable time and constructive feedback that helped improve the quality of the scientific work. Your contributions not only evaluated this research, but also inspired me in the field of scientific research. May Allah reward you for your dedication, and may you continue to be of great help and success.

Allali Charaf Eddine, Dagga Noor Ahmed

Dedications

To my cherished mother, the source of love and sanctuary for my spirit, who has enveloped me with her prayers and her generous heart throughout all phases of my life. Mere words of gratitude fall short, and I dedicate every success to you. I pray to God to safeguard you and grant you endless joy.

To my beloved father, my initial source of support and my guide, from whom I gain strength and insight. Your presence in my life is a priceless gift, and your guidance has consistently served as a lighthouse that brightens my path. I ask God to bless you with health and happiness and to reward you in the best possible way for me.

To my family, I extend my heartfelt appreciation for your unwavering support and patience during every moment I sought strength. You are the foundation I rely on and the rhythm that brings me stability. I pray to God to sustain our love and keep us united.

To my dear friends, you are the brightness in the shadows of my days and the source of joy during tiring times. Your support, through your words and deeds, has greatly influenced my ability to overcome obstacles. I pray to God to grant you success in your lives and to fulfill all your dreams.

To my colleagues, who have traveled this academic journey alongside me and have enriched this endeavor with their knowledge and encouragement. My heartfelt gratitude to you, and I hope that the future holds more achievements together.

Lastly, to my fellow colleague and partner in this project, Dagga Noor, who has been by my side and embodied the resolve to tackle challenges. Thank you for every collaborative effort and the spi

rit of teamwork that united us. I pray to God to bless your path and guide you in your future pursuits.

ALLALI Charaf eddine

Dedications

Every individual's journey is marked by milestones, which are achieved through God's assistance and the support of those who have had the greatest influence. Dear mother, you who were the devoted prayer in your absence and the nurturing hand during your presence, I offer all my gratitude to you, praying that God grants you a long life filled with joy and fulfillment.

To my cherished father, the initial supporter and unwavering source of inspiration, I am grateful for your wisdom, patience, and guidance that have brightened my way. I pray that God blesses you with health and longevity, rewarding you with the very best for me.

To my dear family members, your unwavering presence and support have been the driving force behind my perseverance and the wellspring of my strength in times of uncertainty.

To my steadfast friends, who have generously offered their support and smiles, your companionship has had the most beautiful impact on me, and you have all of my love and gratitude.

To my respected colleagues, with whom I shared both my struggles and aspirations, I appreciate your collaboration and encouragement.

Lastly, to my colleague, Allali charaf eddine, I thank you for the spirit of partnership and determination that united us. Your dedication and teamwork significantly contributed to the success of this journey, and I wish you all the best in your future pursuits.

Dagga Noor

Abstract

The developing request for communication inside a restricted transfer speed has driven to the application of WDM (Wavelength Division Multiplexing) in different topologies or point-to-point systems. WDM is an optical communication technology that enables the transmission of multiple data streams simultaneously over a single optical fiber by using different wavelengths (or colors) of light. This technique significantly increases the capacity of fiber-optic networks, making it a crucial component in modern high-speed communication systems. WDM is divided into two types: Coarse WDM (CWDM), which uses fewer channels with wider spacing and Dense WDM (DWDM), which allows for a higher number of closely spaced channels, enabling long-distance and high-capacity transmission. In this project, we design and simulate a 32-channel DWDM network to simulate the characteristics of the DWDM system. We use the bit error rate (BER) as a test tool for different modulation formats using Optisystem simulation tools.

Keywords: WDM, DWDM, CWDM, BER, Optisystem.

Résume

La demande croissante de communication à débit de transfert limité a conduit à l'application du multiplexage en longueur d'onde (WDM) dans différentes topologies ou systèmes point à point. Le WDM est une technologie de communication optique qui permet la transmission simultanée de plusieurs flux de données sur une seule fibre optique en utilisant différentes longueurs d'onde (ou couleurs) de lumière. Cette technique augmente considérablement la bande passante et la capacité des réseaux à fibre optique, ce qui en fait un composant essentiel des systèmes de communication haut débit modernes. Le WDM se divise en deux types : le WDM grossier (CWDM), qui utilise moins de canaux avec un espacement plus important, et le WDM dense (DWDM), qui permet un plus grand nombre de canaux rapprochés, permettant une transmission longue distance et haute capacité. Dans ce projet, nous concevons et simulons un réseau DWDM à 32 canaux afin de simuler les caractéristiques du système DWDM. Nous utilisons le taux d'erreur binaire (TEB) comme outil de test pour différents formats de modulation à l'aide des outils de simulation Optisystem.

Mots-clés : WDM, DWDM, CWDM, taux d’erreur binaire, Optisystem.

ملخص

أدى الطلب المتزايد على الاتصالات داخل سرعة نقل مقيدة إلى تطبيق WDM (مضاعفة تقسيم الطول الموجي) في طوبولوجيات مختلفة أو أنظمة نقطة إلى نقطة.WDM هي تقنية اتصالات بصرية تتيح نقل تدفقات بيانات متعددة في وقت واحد عبر ليف بصري واحد باستخدام أطوال موجية (أو ألوان) مختلفة من الضوء. تزيد هذه التقنية بشكل كبير من عرض النطاق الترددي وسعة شبكات الألياف الضوئية، مما يجعلها مكونًا أساسيًا في أنظمة الاتصالات الحديثة عالية السرعة. ينقسم WDM إلى نوعين WDM: الخشن (CWDM) ، الذي يستخدم قنوات أقل بمسافات أوسع، و WDM الكثيف (DWDM) ، الذي يسمح بعدد أكبر من القنوات المتقاربة، مما يتيح نقلًا لمسافات طويلة وبسعة عالية. في هذا المشروع، نقوم بتصميم ومحاكاة شبكة DWDM ذات 32 قناة لمحاكاة خصائص نظام DWDM. نستخدم معدل خطأ البت (BER) كأداة اختبار لتنسيقات التعديل المختلفة باستخدام أدوات محاكاة Optisystem.

الكلمات المفتاحية: WDM، DWDM، CWDM، BER، Optisystem.

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List of abbreviations

LED: Light Emitting Diode

EAM: Electro-Absorption Modulators

PDM: Polarization Division Multiplexing

TDM: Time Division Multiplexing

SDM: Space Division Multiplexing

MZM: Mach-Zehnder Modulator

MMF: Multimode fiber

POF: Plastic optical fibers

TIR: Total internal reflection

APD: Avalanche Photo Diode

PIN: Positive Intrinsic Negative

SONET: Synchronous Optical Networking

SDH: Synchronous Digital Hierarchy

PDH: Plesiochronous Digital Hierarchy

EMI: Electromagnetic Interference

HD: High-definition

UHD: Ultra-high-definition

WDM: Wavelength Division Multiplexing

CWDM: Coarse Wave Division Multiplexing

BER: Bit Error Rat

DCF: Dispersion Compensating Fibers

DWDM: Dense Wavelength Division Multiplexing

EDFA: Erbium-Doped Fiber Amplifier

SMF: Single Mode Fiber

OADM: Optical add/drop multiplexer

OA: Optical amplifiers

PSK: Phase Shift Keying

ASK: Amplitude Shift Keying

FSK: Frequency Shift Keying

MMF: Multimode Fiber

O-E-O: Optical-Electrical-Optical (conversion)

E-O: Electrical to Optical (conversion)

2R: Reamplify, Reshape

3R: Reamplify, Reshape, Retime

General introduction

General introduction

In recent years, the massive amount of information transported globally has increased the demand for transmission rates in telecommunications systems. A variety of multimedia applications and services have been created, which now requires elevated transmission capacities. Applications such as data transfer, voice-over-IP telephony, and video require high transmission speeds.

The establishment of upcoming high-speed telecommunications infrastructures requires the creation of novel optoelectronic devices and designs suited for these transmission rates. The strategic and financial implications associated with these advancements arise mainly from the necessity to produce economically feasible components and tools within a relatively short timeframe, particularly concerning low manufacturing and operational expenses.

Optical fiber is a modern advancement that has swiftly become a dominant technology in telecommunications, due to its capacity to transmit substantial quantities of data over great distances more effectively than other media, such as coaxial cables and radio transmission.

Wavelength Division Multiplexing (WDM) allows several optical signals to be sent at the same time over a single fiber by utilizing various wavelengths of light, significantly enhancing transmission capacity without requiring additional fiber installations. This technology enables operators to maximize their current infrastructure while fulfilling the growing demands for higher throughput.

This study focuses on Wavelength Division Multiplexing (WDM) technology as an innovative approach to enhance data transmission capacity in optical fiber networks. Through this investigation, we aim to comprehend the fundamental principles of optical fibers and their function in delivering data at high speeds with exceptional reliability, and to analyze the workings of WDM technology and its utilization to potentially double the capacity by employing multiple wavelengths within the same optical fiber. Additionally, we will differentiate between various types of WDM, such as Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM), concerning their technical features and applications.

This dissertation emphasizes the key elements and principles of an optical transmission system. It is divided into three primary sections, each addressing a critical facet of optical communications technology. This arrangement aims to facilitate a gradual and comprehensive grasp of the topic, starting from theoretical underpinnings to more complex applications, especially wavelength-division multiplexing (WDM).

The first chapter focuses on the theoretical examination of optical fibers and includes an overview of the wave-splitting methods that have been utilized in the past (PDH-SDH).

The second chapter focuses on defining and analyzing wavelength division multiplexing (WDM). It describes two primary types of this technology: Dense Wavelength Division Multiplexing (DWDM) and Coarse Wavelength Division Multiplexing (CWDM), which are differentiated by their technical features, performance, and application areas.

The third chapter presents the OptiSystem simulation software, a powerful tool for modeling and analyzing optical communication systems. Within this framework, an optical telecommunication chain will be simulated, taking into account several key parameters such as fiber length, bit rate, attenuation and other factors influencing system performance.

Finally, the project is ended by a general conclusion with an overall overview of the findings, emphasizing the key insights gained from the research. In light of the results obtained from this research.

Chapter 1: Optical fiber transmission system

I.1 Introduction

A telecommunications network is the technical infrastructure that lets two users exchange information securely and effectively. This happens no matter how far apart they are, in the quickest time possible, and at a sensible price. Optical transmission is a usual and well-established method in telecommunications.

Optical fiber is now one of the most dependable and cost-effective ways to transmit large amounts of data over long distances. Modern communication systems depend on optical transmission systems as their foundation. Similar to other communication systems, optical links use basic elements to transmit data. We will define these elements, explain the entire system, and its blocks in this chapter.

I.2 Optical fiber transmission Chain

Optical transmission is the transmission of data between two ends, by a light signal using a light channel (optical fiber). Any optical system is based on three blocks necessary to ensure data transfer: Transmitter, Communication channel and Receiver.

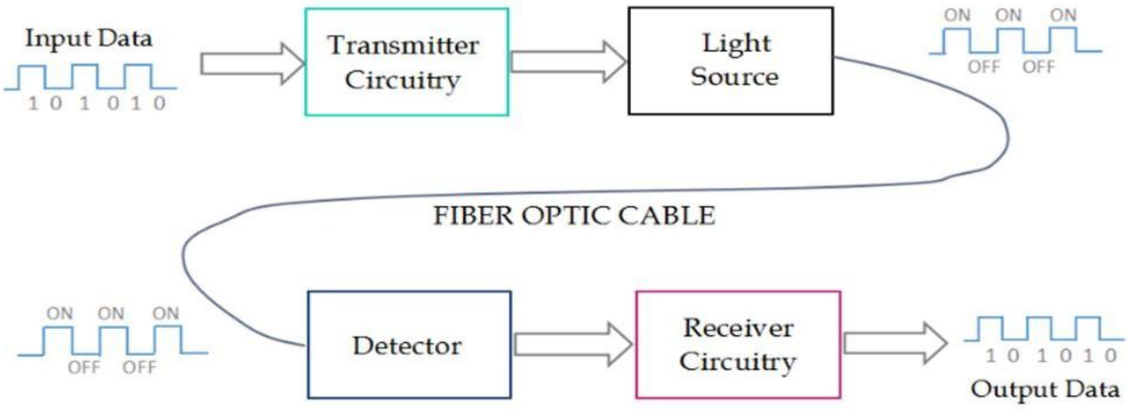


Figure 1: Optical fiber transmission system. [1]

I.2.1 Transmitter

An optical source and a modulator, its role is to deliver a signal to the optical fiber.

I.2.1.1 Optical sources (Laser / Diode)

It is the component responsible for converting the electrical signals (representing data) into light signals. Two types of light sources used: light- emitting diodes (LEDs) and laser diodes.

a) Light-emitting diode (LED): Light Emitting Diode (LED) is a commonly used light source in optical fiber communication systems. It converts electrical signals into optical signals by emitting incoherent light. LEDs are mainly used for short- distance, low-speed fiber-optic communication due to their lower power and wider spectral width compared to laser diodes.

b) **LASER:** means Light Amplification by Stimulated Emission of Radiation it is widely used light source in optical fiber communication systems. It converts electrical signals into optical signals by emitting coherent light through the process of stimulated emission. Laser diodes are preferred for long-distance, high-speed fiber-optic communication due to their higher power, narrow spectral width, and better coupling efficiency with single- mode fibers compared to LEDs**.**

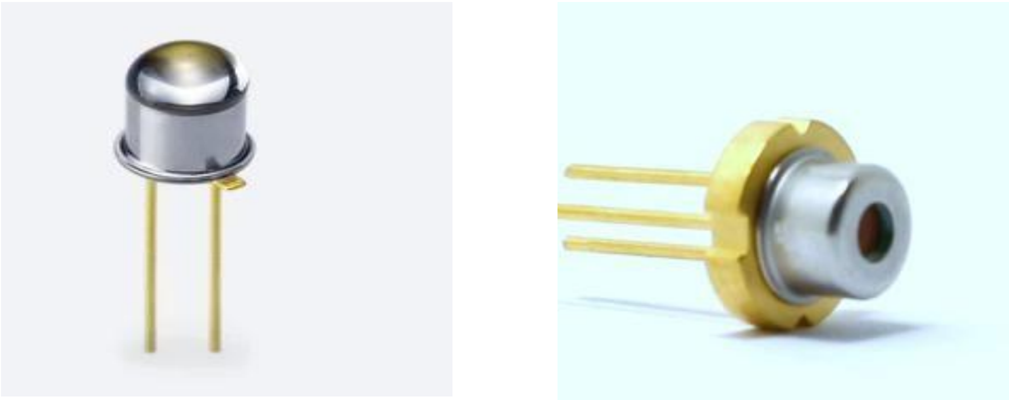


Figure 2: Optical LED and LAZER. [2]

I.2.1.2. Modulators

To transmit data via an optical fiber, the data must first be encoded or modulated. There are two main techniques: direct (internal) modulation and external modulation. [3]

a) **Direct modulation:**

In this type of modulation, the optical source performs the modulation in addition to the electro-optical conversion.

Direct modulation is simple, efficient, and cost-effective, requiring low voltage and power. However, it causes parasitic frequency modulation (chirp) when modulating the laser's amplitude.

b) **External modulation:**

External modulation directly modulates the laser's light output instead of its input current, enabling higher speeds (5–10 GHz). It is faster and improves transmission quality beyond 5 Gbps, were direct modulation

becomes insufficient. Mach-Zehnder (MZM) and Electro-Absorption Modulators (EAM) are commonly used.

I.2.1.3 Multiplexer

Multiplexers in optical transmission optimize fiber capacity by combining and separating multiple signals. Key techniques include Wavelength Division Multiplexing (WDM), with CWDM for lower-capacity networks and DWDM for high-speed, long-distance communication. Time Division Multiplexing (TDM) organizes data into time slots, while Space Division Multiplexing (SDM) and Polarization Division Multiplexing (PDM) enhance capacity using multiple fiber cores and light polarizations.

I.2.1.4 Boosters

Optoelectronic repeaters and optical amplifiers both enhance signal integrity in long-distance optical communication. Repeaters convert the optical signal to electrical form, amplify it, and convert it back to optical, while optical amplifiers directly boost the optical signal without conversion. Optical amplifiers are more efficient for long-haul systems, helping prevent signal degradation over distance.

I.2.2. Communication channel

This is the link between the sending block and the receiving block. The means of transmission used in an optical system is optical fiber.

I.2.2.1 Optical Fiber

Utilizing total internal reflection, optical fiber is a transparent, flexible strand of glass or plastic that efficiently transmits light signals over extended distances with minimal loss. It is commonly used in telecommunications, and internet infrastructure for high-speed data transfer with low attenuation.

Research on fiber-optic systems began around 1975, leading to significant advancements over the next 25 years. The progress, measured by the Bandwidth Length (BL) product, followed a trend of exponential growth, with each technological generation initially increasing BL before reaching saturation. Each new generation introduced fundamental improvements, enhancing system performance.[4][5]

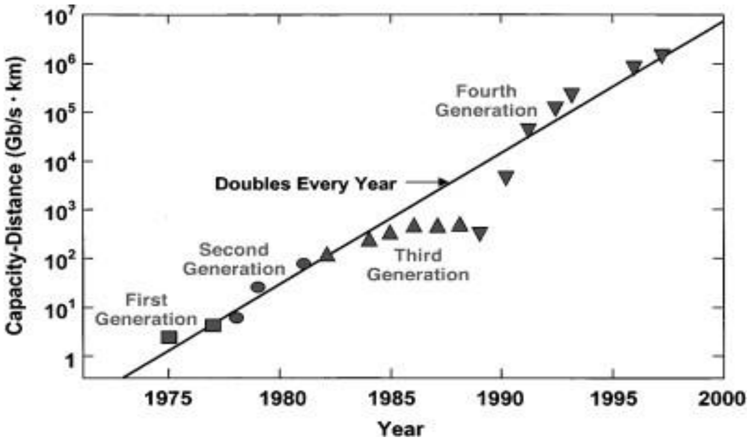


Figure 3: Increase in the BL product over the period 1975 to 1980 through several generations of light wave systems [5].

a) **Structure of optical fiber**

A fiber consists of a glass core surrounded by a dielectric cladding, which enables light guiding. A polymer buffer coating encases these layers, providing protection from mechanical and environmental effects.[4]

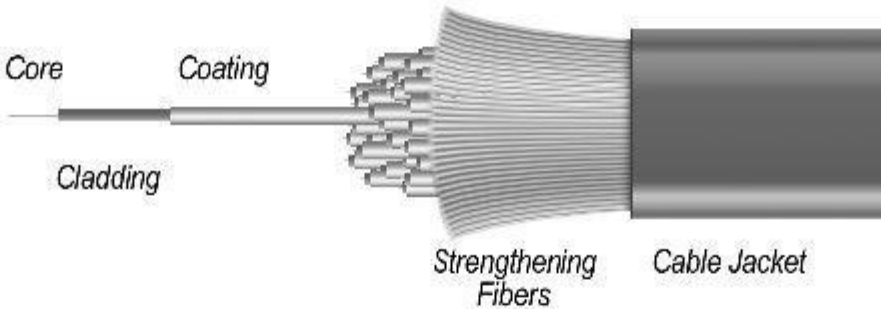


Figure 4: Basic structure of an optical fiber [6].

b) **Types of optical fiber**

Optical fibers are classified into different types based on their mode of transmission and material composition. [7]

- **Mode of Transmission**

Single-mode fiber (SMF) has a small core diameter (5–10 µm) and supports the transmission of a single light mode, making it ideal for long- distance communication with high capacity and low attenuation, typically operating at 1310 nm and 1550 nm wavelengths. It is commonly used in long-haul telecommunications, internet backbone infrastructure, and high-speed data networks. In contrast, multimode fiber (MMF) has a larger core diameter (50–200 µm), allowing multiple light modes to propagate, which leads to signal dispersion and attenuation, limiting its transmission range to

A few hundred meters. MMF operates at 850 nm and 1300 nm and is mainly used in short-distance networks such as LANs and data centers. MMF is further classified into step-index and graded-index types.

- **Material composition**

Optical fibers can be classified into glass and plastic fibers. Glass fibers, made of silica, provide low attenuation, high bandwidth, and long-distance transmission but are expensive and fragile. Plastic optical fibers (POF) are flexible, cost-effective, and ideal for short-range applications, though they have higher attenuation and lower bandwidth.

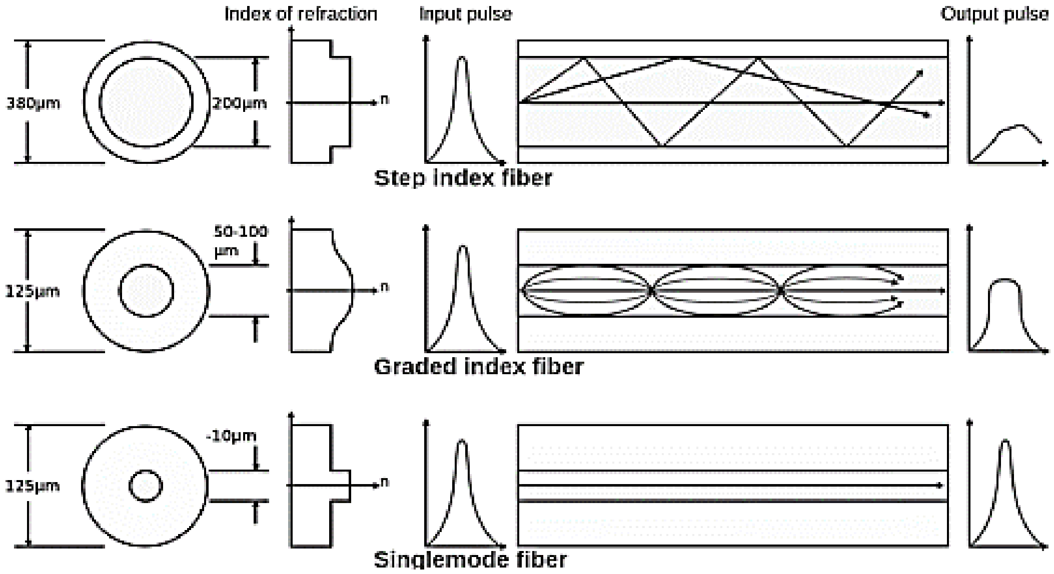


Figure 5: Different types of optical fiber [8].

a) **Characteristics of optical fiber**

Fiber optic communication relies on light signals traveling through glass or plastic fibers, utilizing key properties such as total internal reflection (TIR), refraction, scattering, and attenuation to ensure efficient data transmission. TIR keeps light inside the fiber by reflecting it between the core and cladding, minimizing signal loss. Refraction helps guide light through the fiber, even around bends. Scattering, particularly Rayleigh scattering, causes attenuation, with single-mode fibers having lower signal loss than multimode fibers. Dispersion, which distorts signals, can be reduced with single-mode fibers and advanced designs. While optical fibers don't emit light, diffraction can occur at imperfections, and absorption due to impurities in the fiber material results in signal degradation over long distances.[9][10]

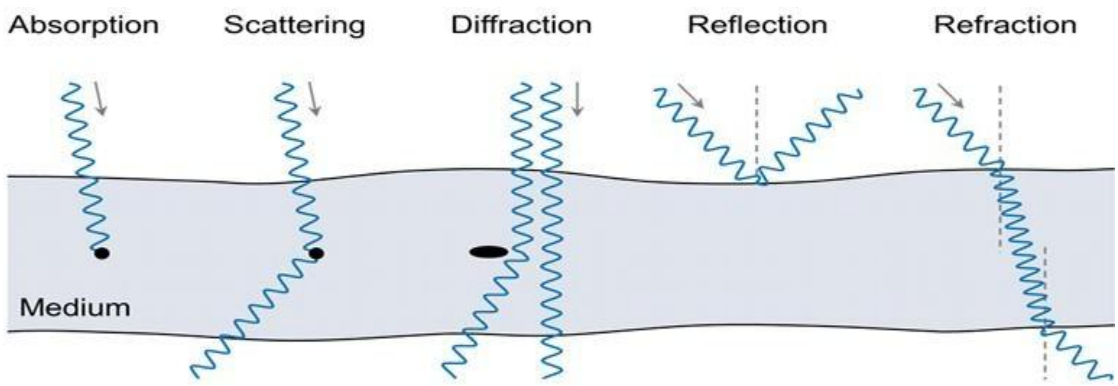


Figure 6: Characteristics of optical fiber [10].

I.2.2.2 Line amplifier

Its function is to amplify the signal after traveling a specific distance, enabling it to cover more distance. It needs a low noise level and substantial gain.[3]

I.2.3 Receiver

The role of the receiver block is to detect and demodulate a light signal transmitted over a fiber and convert the optical signal into an electrical signal, it is made up of:

I.2.3.1 Preamplifier

Positioned right before the receiving module, it ensures the signal's strength is adequate for correct identification. It's designed to boost the desirable signal, which has become weak and gathered much interference. Thus, the noise factor should be kept as low as possible.

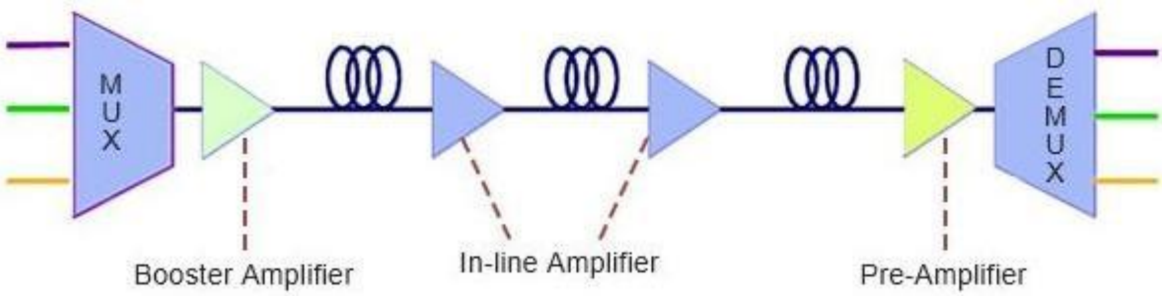


Figure 7: MUX, DEMUX and amplifiers in optical system.[11]

I.2.3.2 Photodiode

A photodetector, or optical receiver, transforms the light signal from the optical fiber into an electrical one. Following this, the signal often goes through an amplification stage, which might be built in like an amplifier. [3] There are two main kinds of photodiodes: the APD (Avalanche

Photo Diode) and the PIN (Positive Intrinsic Negative).

I.2.3.3 Demultiplexer

demultiplexer separates a combined optical signal into individual channels or wavelengths at the receiving end. It uses wavelength-selective filters like fiber Bragg or arrayed waveguide gratings to distinguish the different wavelengths.

The demultiplexer then directs each separated signal to the appropriate receiver for further processing, ensuring efficient handling of multiple signals in high- speed optical transmission systems.

I.3 Transmission technologies Evolution

Transmission technologies are essential for transporting data, voice, and video over long distances. Early systems like PDH enabled digital communication using time- division multiplexing but faced issues with synchronization. This led to the development of SDH, which offered better scalability and international standardization. To meet modern high-speed demands, WDM emerged, allowing multiple data signals to be sent simultaneously over a single optical fiber using different wavelengths. These technologies reflect the ongoing evolution toward faster and more efficient communication networks.

I.3.1. PDH (plesiochronous Digital Hierarchy) Technology

PDH, or Plesiochronous Digital Hierarchy, is a telecommunications standard that was created in the 1960s to facilitate the transmission of substantial volumes of voice and data traffic over both copper and fiber-optic networks. The term "plesiochronous" denotes that PDH operates with nearly synchronized timing between data streams, but it also permits minor fluctuations in timing. PDH is distinguished from more contemporary systems such as SDH (Synchronous Digital Hierarchy) and SONET (Synchronous Optical Networking) by this characteristic, which operate with entirely synchronized timing. PDH was a foundational technology for data transmission and was extensively used in telecom networks for many years, particularly for voice communications. However, it was primarily replaced by SDH and SONET. PDH is no longer frequently employed in contemporary high-capacity networks due to the fact that these newer standards provide enhanced synchronization, increased bandwidth, and increased efficiency in network management. PDH was instrumental in the early development of digital communication systems and facilitated the widespread adoption of fiber-optic networks, despite being supplanted by technologies that are more sophisticated. [12]

I.3.2. SDH/SONET Technology

At the end of the 1980s, the Synchronous Digital Hierarchy (SDH) emerged, based on the Synchronous Optical Network (SONET), and provided an international standard for high-speed telecommunications over optical networks. SDH uses Time Division Multiplexing (TDM) to support various services like voice, data, and video at high speeds and can be deployed across access, metropolitan, and core networks, primarily using fiber optic infrastructure. Unlike the Plesiochronous Digital Hierarchy (PDH), SDH synchronizes clocks at all network levels, reducing discrepancies. It encapsulates signals in containers with overheads for management, and the first levels of SONET (STS-1 at 51.84 Mbps) and SDH (STM-1 at 155.52 Mbps) correspond to one another. SONET is an American standard, while SDH is international; both use similar frame structures, but SDH was designed for global compatibility, offering greater flexibility and easier interconnection. Both systems ensure clock synchronization, but SDH is better suited for international use, enabling seamless interconnection and management across different regions. [4][12]

I.3.3 Moving from SDH to WDM

SDH (Synchronous Digital Hierarchy) and optical fiber address the growing bandwidth demand, but SDH's use of a single wavelength doesn't fully utilize the fiber's capacity. To improve this, Wavelength Division Multiplexing (WDM) technology multiplexes multiple wavelengths (8, 16, 32, or 64) within a single fiber, significantly increasing transmission capacity. This allows operators to transmit multiple SDH streams, achieving terabit-per-second speeds. WDM has been used for transoceanic networks and is now expanding to terrestrial SDH networks, offering cost savings by reducing the need for additional optical fibers. It introduces a new optical layer, enabling the creation of all-optical mesh networks.

National, regional, departmental, and metropolitan networks utilize SDH and WDM technologies based on required transmission capacities. WDM is also used for transatlantic and transpacific communication, with modern systems offering up to 3200 Gbps capacity. The increasing demand for data, driven by voice and internet traffic, is leading to WDM replacing SDH. WDM and Dense Wavelength Division Multiplexing (DWDM) technologies optimize transmission capacity and cost-efficiency, allowing integration with newer systems. The future of optical networks will rely on an optical transport layer, reducing the need for specific transport protocols, thus enhancing global network efficiency.

I.4 Advantages and Challenges of Optical Transmission System

I.4.1 Advantages of Optical Transmission Systems

- *High Bandwidth and Data Rates*: Optical fibers support gigabit and terabit data rates, making them ideal for high-demand applications like broadband internet and data centers.
- *Low Signal Attenuation*: Optical fibers experience minimal signal loss over long distances, making them perfect for long-haul communications without frequent repeaters.
- *Immunity to Electromagnetic Interference (EMI):* Optical fibers are unaffected by electrical interference, ensuring stable and clear signals even in noisy environments.
- *Security and Privacy*: Fiber-optic communication is more secure than copper lines, making it harder to tap into and providing enhanced privacy.
- *Lightweight and Flexible*: Optical fibers are lighter and more flexible than copper cables, making installation easier, especially in challenging locations.
- *Longer Transmission Distance*: Optical fibers allow for long transmission distances with fewer signal quality losses, ideal for connecting distant locations.
- *Low Power Consumption*: Optical fiber systems consume less power for data transmission, offering energy efficiency and cost savings.
- *Scalability*: Optical fiber networks can be upgraded using WDM and DWDM technologies to carry multiple data streams, improving capacity without physical infrastructure changes.

I.4.2 Challenges of Optical Transmission Systems

- High Initial Cost: The cost of fiber-optic infrastructure, including installation and equipment, is high compared to copper systems, limiting adoption, especially in remote or developing areas.
- Complex Installation and Maintenance: Installing and maintaining fiber- optic cables, especially in difficult environments like underground or underwater, requires specialized skills and can be expensive.
- Signal Dispersion and Attenuation: Despite low attenuation, signal dispersion (chromatic and modal) can degrade performance over long distances, requiring advanced techniques for compensation and amplification.

- Physical Fragility: Optical fibers are more fragile than copper cables, making them prone to damage from bending, pulling, or crushing, especially in harsh environments.
- Limited Bandwidth Over Long Distances Without Repeaters: Fiber-optic capacity can be limited over long distances without repeaters or amplifiers, which are costly and require maintenance.
- Fiber Aging and Environmental Impact: Environmental factors such as extreme temperatures, moisture, and UV radiation can degrade optical fibers over time, reducing their performance and requiring maintenance or replacement.
- Need for Specialized Equipment: Fiber-optic systems require expensive, specialized equipment (e.g., lasers, modulators), which can be more complex to operate than traditional electrical systems.
- Infrastructure Limitations in Rural and Developing Regions: Laying fiber-optic cables in rural or developing areas can be difficult and costly due to geographic barriers and lack of existing infrastructure, leading to potential inequalities in network access.
- Interoperability Issues: Different optical fiber standards (e.g., SONET/SDH, WDM/DWDM) can cause compatibility problems between network operators and legacy systems, leading to higher costs for upgrades and ensuring cross-compatibility.

I.5 Application of Optical Transmission System

- Telecommunications: Optical fiber enables high-speed internet, phone services, and long-distance data transmission, forming the backbone of modern communication networks with reliable, high-bandwidth connectivity.
- Broadband Internet: Optical fiber delivers faster, more stable broadband internet speeds, supporting applications like streaming, gaming, and cloud services, outpacing traditional copper-based systems.
- Data Centers: Data centers rely on optical fiber for high-speed data transfer between servers and storage devices, ensuring efficient cloud computing and large-scale enterprise network operations.
- Television Broadcasting: Optical fiber transmits high-definition (HD) and ultra-high-definition (UHD) video signals for television broadcasting, especially in remote locations and between stations, minimizing signal loss.
- Medical Applications: Optical fibers are used in medical devices like endoscopes for

minimally invasive procedures, as well as for transmitting high-resolution images in diagnostic tools for real-time monitoring and surgery.

- Military and Defense: Optical fiber provides secure, interference-resistant communication for military operations and is used in surveillance and monitoring systems, ensuring continuous, protected communication.
- Underwater and Submarine Communication: Fiber-optic submarine cables provide high-speed, long-distance communication across oceans, facilitating global data exchange with minimal signal attenuation.
- Smart Grids and Power Systems: In smart grids, optical fiber helps manage energy distribution by transmitting data from sensors and meters, enabling real-time monitoring, control, and efficient energy management.
- Industrial Automation and Control Systems: Optical fiber transmits data in industrial systems, ensuring reliable communication between machines and sensors in harsh environments due to its immunity to electromagnetic interference.
- Scientific Research: Optical fibers are used in scientific applications like telecommunications research, quantum computing, and particle physics, enabling precise data collection and analysis in laboratory instruments.

I.6 Conclusion

In conclusion, optical transmission systems have become a cornerstone of modern telecommunications, providing high-speed, secure, and efficient data transfer over long distances. Integrating optical fibers into communication networks offers numerous advantages, including immunity to electromagnetic interference, low signal attenuation, and a high bandwidth.

It is ideal for a wide range of applications, from telecommunications to industrial automation. Despite the challenges, such as high initial costs, installation complexities, and potential signal degradation over long distances, the ongoing advancements in technologies like Wavelength Division Multiplexing (WDM) and Dense Wavelength Division Multiplexing (DWDM) have significantly enhanced the capabilities of optical transmission systems. As the demand for faster and more reliable data transmission continues to grow, optical fiber networks will remain integral to the development of next-generation communication infrastructures. With continuous research and innovation, the potential of optical fiber technology is vast, paving the way for more advanced and scalable communication solutions in the future.

Chapter II: Study of DWDM System

II.1.introduction

The evolution of fiber optic communication has been greatly enhanced through the introduction of Wavelength Division Multiplexing (WDM). This method enables the parallel transmission of numerous data channels via a single optical fiber, where each channel is assigned a unique wavelength of light. As a result, WDM delivers both high-speed performance and substantial bandwidth. This technology is primarily divided into two categories: Coarse Wavelength Division Multiplexing (CWDM) and Dense Wavelength Division Multiplexing (DWDM), each designed for particular use cases based on distance and capacity demands. As a foundational element in contemporary communication systems, WDM plays a pivotal role in supporting internet backbone infrastructure, large-scale data centers, and cloud computing operations. This chapter explores the key concepts, classifications, advantages, and applications of WDM in modern optical networks.

II.2. Fundamental Concepts of WDM

Wavelength Division Multiplexing (WDM) represents a major leap in the development of optical fiber communication systems. It functions by merging several light signals—each assigned a distinct wavelength—and transmitting them concurrently over a single optical fiber. At the receiving end, these signals are demultiplexed—meaning they are separated by wavelength—and directed to their respective terminals for processing. This technique allows for efficient and high-capacity data transfer through a single transmission medium. The underlying concept of WDM systems is depicted in Figure 1 [13].

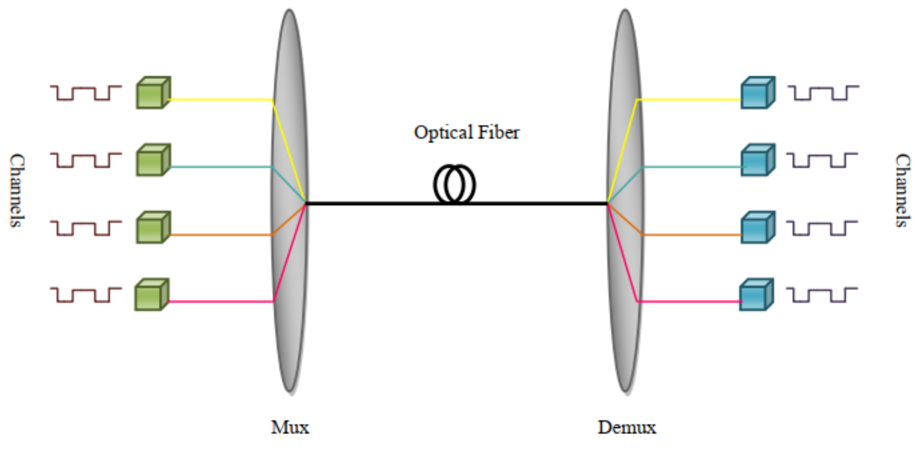


Figure II .1: Principle of Wavelength-division multiplexing WDM [13].

II.3. Different **technology of WDM**

II.3.1. Coarse Wavelength Division Multiplexing (CWDM):

CWDM refers to a multiplexing system that utilizes fewer than eight active wavelengths per fiber. Designed for short-distance communications, CWDM operates over a broad frequency spectrum, with wide spacing between wavelengths. Due to the thermal variations in laser performance, standardized channel spacing helps accommodate wavelength shifts. CWDM is an efficient and compact choice when spectral efficiency is not a primary concern, offering a cost-effective solution for moderate capacity needs [14].

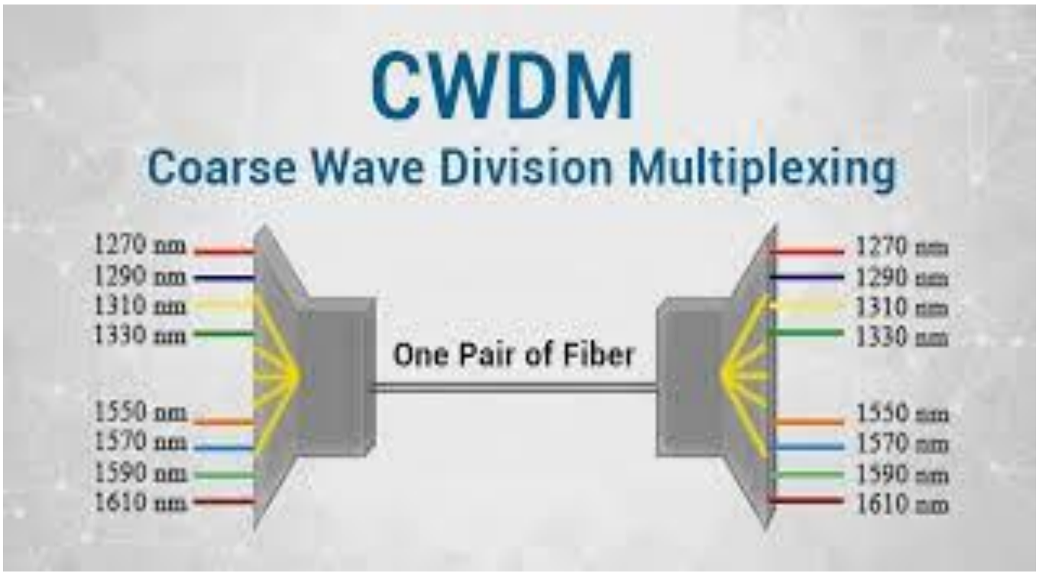


Figure II.2: Multiplexage CWDM [15]

II.3.1.1. Benefits of CWDM

- Capable of spanning distances up to 80 km without requiring amplification
- Provides reliable transmission with minimal signal loss
- Straightforward setup and operation

II.3.2. Dense Wavelength Division Multiplexing (DWDM):

DWDM, a more advanced version of WDM, is engineered to increase bandwidth by allowing more tightly packed wavelength channels. It is ideal for establishing transport links that cover medium to long distances, offering enhanced scalability over existing fiber infrastructure [14].

II.3.2.1. Benefits of DWDM

- Maximized bandwidth usage with high channel density.
- Compatible with optical amplifiers (such as EDFA) for extensive reach.
- Suitable for cost-efficient long-haul communication.

II.4. Comparison between Technologies of WDM

The taking after table summarizes the contrasts between WDM multiplexing frameworks:

Multiplexing type	Wavelength Spacing(nm)	Number of channels	Band signals in (nm)
WDM	8	32	1530 - 1565
CWDM	20	8 - 18	1270 - 1610
DWDM	0,8	80-160	1525 - 1565

Table 01: Comparison of multiplexing technologies [16]

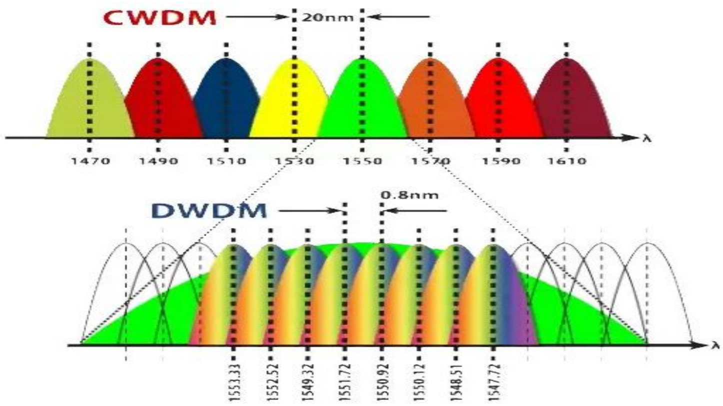


Figure II.3: Difference between DWDM and CWDM multiplexer techniques band [17]

II.5.DWDM network

II.5.1. principle and architecture:

The emergence of Dense Wavelength Division Multiplexing (DWDM) marks a major leap forward in fiber optic transmission technologies. This section briefly outlines the progression of optical fiber communication and the essential role of DWDM within it. A detailed analysis follows, focusing on the structure and functions of a DWDM system, including the technologies that enable it. The section concludes with an overview of how DWDM systems operate in practical deployments.

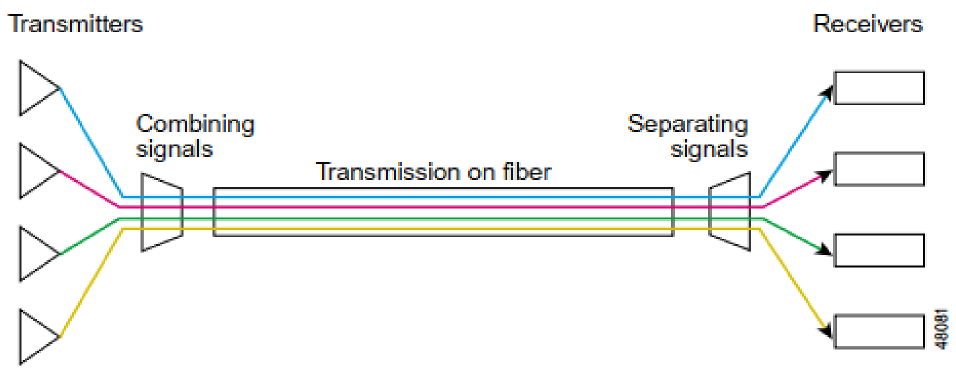


Figure II.4: DWDM Functional Schematic [**18**]

II.5.2. Different components of a DWDM system

The functionality of a WDM system relies on several integrated components that collectively handle the transmission and reception of multiple data channels. These components ensure reliable, long-distance data delivery with minimal signal degradation and high efficiency. Among the most vital elements are optical transceivers, amplifiers, filters, fibers, and receivers [**19**].

II.5.2.1. Optical Signal Transmitters and Receivers

In DWDM systems, transmitters are responsible for producing the initial signals to be multiplexed. These sources of light—most commonly lasers—transform electrical input into optical pulses, with each pulse representing a distinct wavelength, typically measured in nanometers. In simple terms, a "1" is represented by a light pulse and a "0" by its absence. These light pulses are transmitted through fiber using total internal reflection.

The receiving end includes photodetectors (such as photodiodes), which transform the optical signals into their corresponding electrical form. Generally, two fibers are used—one for transmitting and one for receiving signals—connecting a pair of transmission and reception devices [**19**].

II.5.2.2. DWDM mux/demux filters

DWDM multiplexers integrate multiple light signals, each operating at a unique wavelength, into a single optical fiber for transmission. These are often passive optical filters operating in the 1550 nm window. The resulting composite signal travels over the fiber. At the destination, demultiplexers separate the signal back into its constituent wavelengths, each routed to a specific receiver.

Typically, a single unit contains both the multiplexer and demultiplexer. These optical devices function passively, requiring no electrical power. A typical DWDM system uses two fibers—one for upstream and one for downstream traffic [**19**]

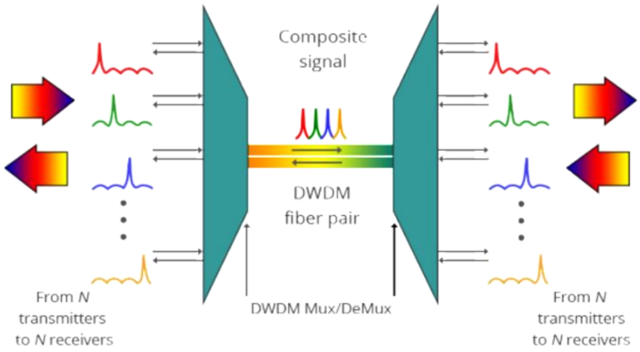


Fig II.5: Mux/demux (transmit/receive) components [**19**]

II.5.2.3. Optical add/drop multiplexers (OADMs)

OADMs selectively remove or add signals with specific wavelengths from the DWDM stream. For instance, if a red signal is dropped, it is diverted to a local receiver. A new signal with the same wavelength can then be added to replace it. The modified stream continues along the fiber path. This process allows for flexible traffic management in DWDM networks [**19**].

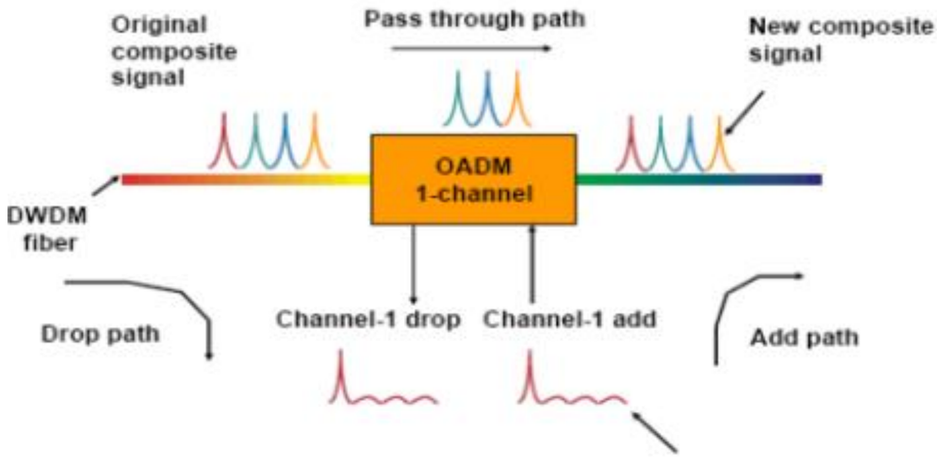


Figure II.6: OADM's [**19**]

II.5.2.4. Optical amplifiers

Optical amplifiers boost signal strength without converting light to electricity. These in-fiber devices energize signal photons directly and work over a wide range of wavelengths. The most common type is the Erbium-Doped Fiber Amplifier (EDFA), which plays a crucial role in preserving signal integrity across extended transmission distances. In DWDM systems [**19**].

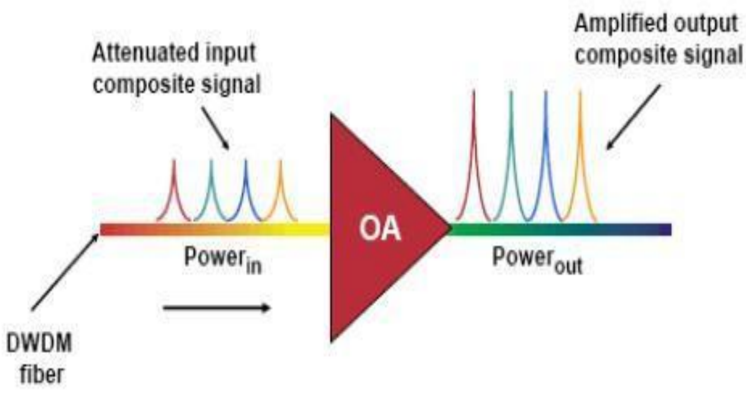


Figure II.7: Optical amplifiers [**19**]

II.5.2.5. Transponders (wavelength converters)

Transponders are responsible for changing the wavelength of optical signals. They perform an Optical-Electrical-Optical (O-E-O) conversion: the optical signal is converted into electrical form, regenerated (reamplified, reshaped, and optionally retimed), and re-emitted on a new wavelength compatible with the DWDM grid.

In practice, transponders serve as intermediaries between client equipment and the DWDM system. They also operate bidirectionally, converting incoming and outgoing signals to the appropriate wavelengths for transmission or delivery [**19**].

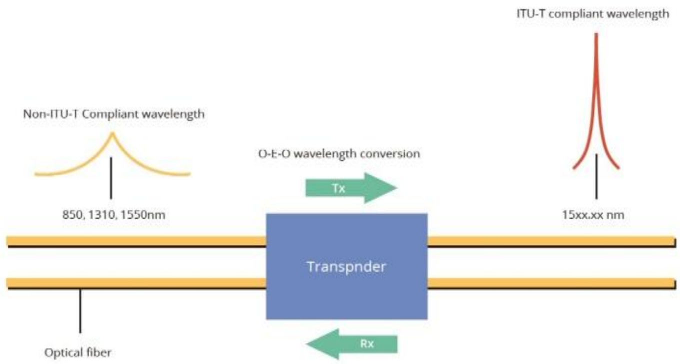


Figure II.8: Transponder [**19**]

II.5.3. DWDM SYSTEM

The following steps describe the block diagram shown below [**19**]

- The system starts at the client side, where signals are sent to the optical system.
- The signals are converted into **DWDM**-compatible wavelengths and combined using a multiplexer (**Mux**).
- These combined signals travel through optical fiber over long distances.
- Optical amplifiers (**EDFA**) boost the signal strength during transmission.

- An Optical Add-Drop Multiplexer (**OADM**) can add or remove specific wavelengths as needed.
- Finally, the signals are separated, converted back to their original form, and delivered to the client.

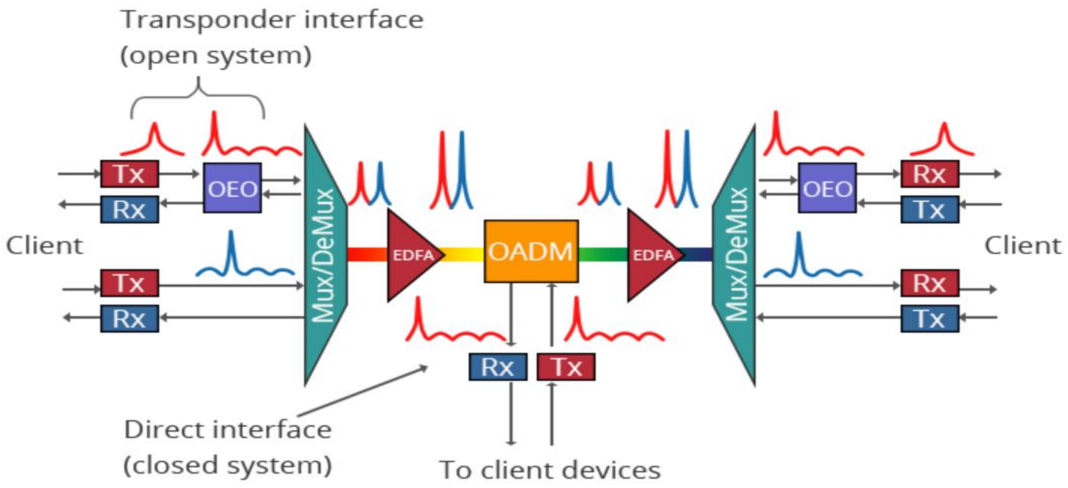


Figure II.9: Description of system DWDM [**19**]

II.5.4. DWDM transmission technology

II.5.4.1. Coherent detection

This technique uses a local oscillator to generate a reference signal. By combining it with the incoming optical signal, both amplitude and phase information can be retrieved. Coherent detection improves signal interpretation and extends transmission range, making it ideal for long-haul, high-capacity networks [**1**].

II.5.4.2. Optical modulation format

Modulation formats determine how data is encoded into optical signals. Common methods include Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), and Phase Shift Keying (PSK). The choice depends on factors like distance, data rate, and optical hardware capabilities [**1**]

II.5.4.3. Dispersion compensation

Dispersion compensation corrects the spreading of light pulses caused by fiber properties. By using fibers with tailored dispersion characteristics, signal clarity is preserved, and transmission range is extended. The specific needs of the network—such as capacity, distance, and signal type—guide the choice of dispersion management methods [**1**].

II.5.5. advantages and disadvantages of DWDM technology [21]

II.5.5.1. The advantage of DWDM:

- **High Bandwidth**: Enables the transmission of multiple data channels on a single fiber.

- **Scalability**: Easily accommodates network growth by adding more wavelengths.
- **Long-Distance Capability**: Supports extended communication links with minimal loss.
- **Cost-Efficiency**: Offers long-term operational savings despite initial investment.

II.5.5.2. Disadvantages of DWDM:

- **High Setup Costs**: Requires expensive equipment and infrastructure.
- **Power Demand**: Components like amplifiers and transponders consume significant energy.
- **Compatibility Constraints**: Specialized hardware can limit vendor flexibility.
- **Fiber Quality Dependency**: Optimal performance depends on high-grade optical fiber.

II.5.6. DWDM technology applications [20]

- **5G** and Mobile Networks: Supports high-capacity mobile backhaul.
- Government and Military Communications: Enables secure, high-speed data exchange.
- Cloud Services and Data Centers: Facilitates fast, reliable inter-server connectivity.
- Broadcast and Media: Delivers high-definition video and live content transmission

II.6.Conclusion

This chapter has detailed the key aspects of Wavelength Division Multiplexing (WDM), focusing on its two primary variants—CWDM and DWDM. By enabling multiple optical signals to travel over a single fiber, WDM significantly boosts data transmission capabilities.

CWDM provides a cost-effective solution for shorter links, while DWDM excels in handling long-distance, high-capacity communications. This overview covered DWDM's principles, components, and advantages, emphasizing its vital role in today has advanced communication systems, including cloud infrastructure and high-speed networks

Chapter III: Simulations and Discussion of Results

III.1. Introduction

We studied the operation and application of Dense Wavelength Division Multiplexing (DWDM), a critical technology in contemporary optical communications, during the practical segment of this experiment. By utilizing distinct wavelengths (or channels) of light, DWDM enables the simultaneous transmission of multiple data streams across a single optical cable. The practical was designed to investigate the effects of channel spacing and wavelength distribution, evaluate critical performance metrics, including signal loss, and comprehend the processes of multiplexing and demultiplexing multiple signals. We acquired substantial insights into high-capacity optical networking systems through practical experiments with DWDM components.

III.2. Presentation Optisystem

The complexity of optical communication systems is increasing on a daily basis. The design and analysis of these systems, which typically involve nonlinear devices and non-Gaussian noise sources, are both highly complex and time-consuming. Consequently, these duties can only be executed efficiently and effectively with the assistance of sophisticated, new software tools.

OptiSystem is a cutting-edge optical communication system simulation program that is capable of designing, testing, and optimizing virtually any form of optical link in the physical layer of a wide range of optical networks, including intercontinental backbones and analog video broadcasting systems.

OptiSystem is a self-contained product that does not depend on any other simulation frameworks. Based on the realistic modeling of fiber-optic communication systems, it is a system-level simulator. It has a genuinely hierarchical definition of components and systems, as well as a potent new simulation environment. Its capabilities can be effortlessly expanded by incorporating user components and can be seamlessly integrated with a diverse array of tools [**21**]

III.3. Key features of Optisystem software [16]

The primary features of the software are:

- virtual components in the library that can replicate the desired behavior and effects based on the selected accuracy, thereby mirroring the efficiency of actual components. The component library enables the input of parameters that can be quantified from actual devices. Testing and measuring apparatus from a variety of vendors can be integrated with these components.

- Auditory signals, ocular diagrams, and polarization statuses are all provided by advanced visualization techniques.
- Indefinitely many monitors may be connected to a single port.

III.4. OptiSystem-Interface

The interface is intended to be user-friendly and intuitive, allowing users to efficiently configure and develop their optical systems. There are numerous components in the central window.

- Component Library window
- Project Browser window
- Project layout window
- Description Layout

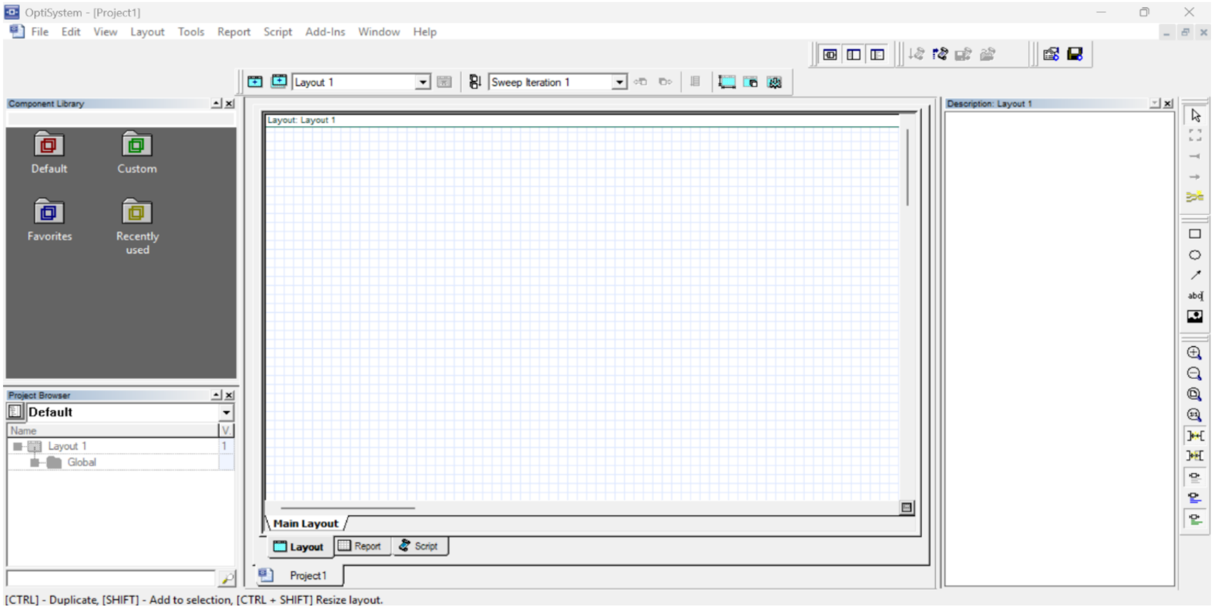


Figure III.1: OptiSystem graphical user interface (GUI)

III.4.1. Library window

OptiSystem, a comprehensive software solution for the design of optical communication networks, employs a variety of components and simulation tools from the OptiSystem Library. Enabling users to model, simulate, and evaluate fiber-optic communication systems, it comprises a diverse selection of optical, electrical, and signal processing components.

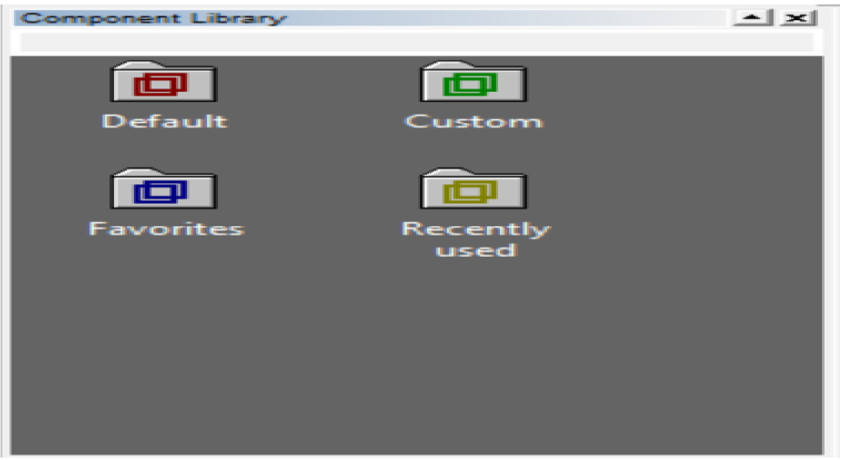


Figure III.2: Component Library window

III.4.2. Project Browser window

The Project Viewer in OptiSystem serves as a navigation tool that organizes and displays all components, subsystems, and simulation configurations of an optical system design. It offers a hierarchical perspective on the project, enabling users to effectively manage configurations, modify settings and access a variety of modules within the system.

This instrument facilitates the development, modification, and evaluation of optical systems for communication.

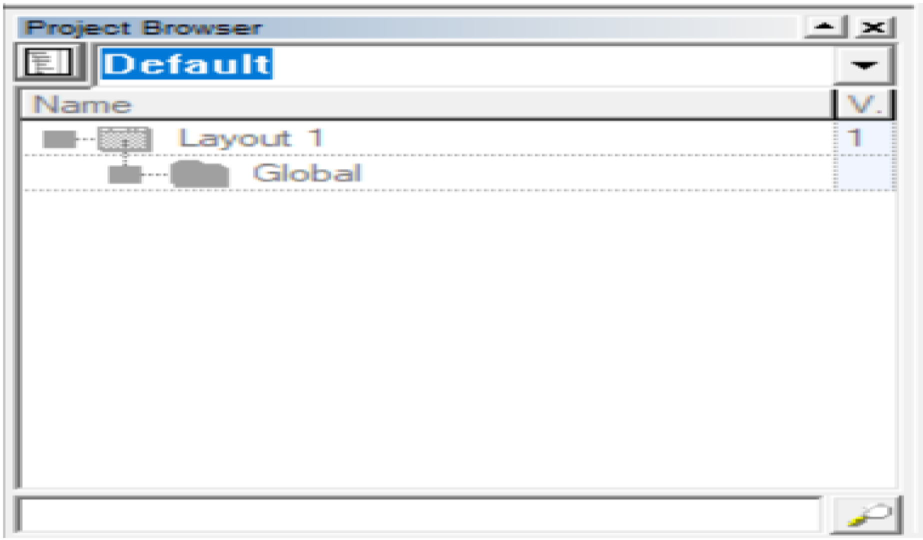


Figure III.3: Project Browser window

III.4.3 Layout window

The primary workspace where you place components into the design, modify components, and establish connections between them [**21**].

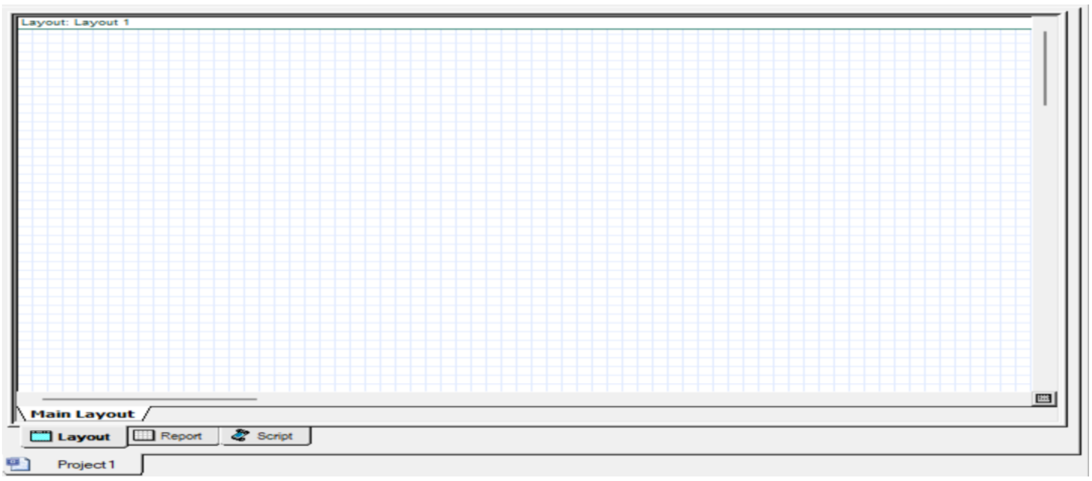


Figure III.4: Project layout window [**21**].

III.4.4 Description Layout window

The Description Layout in OptiSystem allows users to establish and record their simulation parameters. It offers a structured environment for the inclusion of pertinent information, comments, and descriptions regarding the optical communication system that is currently being developed. This architecture aids users in comprehending the simulation's objectives, components, and anticipated results. It is advantageous for record-keeping, problem-solving, and cooperation within the OptiSystem framework.

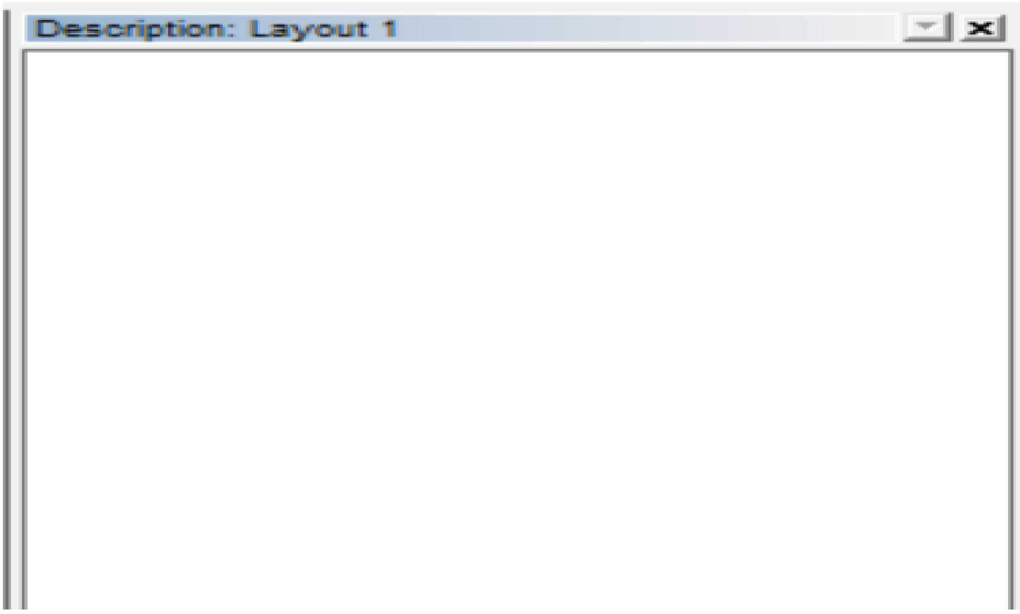


Figure III.5: Description Layout window

- **III.4.5 OptiSystem Calculations window**

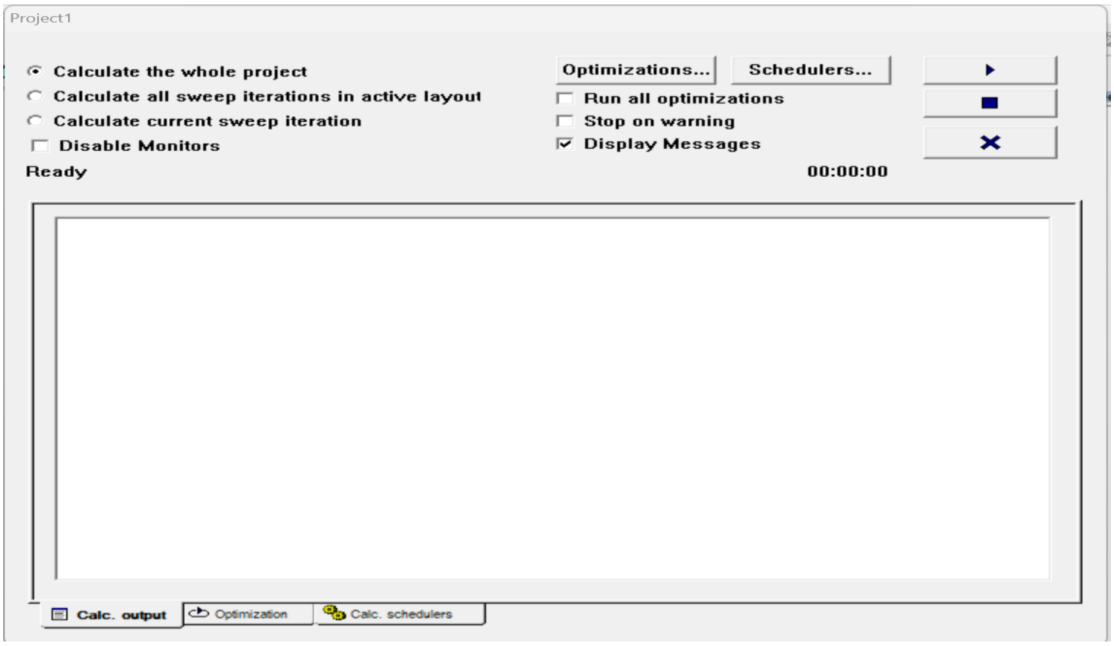


Figure III.6: OptiSystem Calculations window [**21**].

The Calculation Output window displays the results. The simulation results are depicted below the components involved in the simulation, with the computation output displayed in this window [**21**].

III.5 Displaying and Representing Signals [16].

III.5.1 Displaying results from a device

To display the graphics and results generated by the simulation, double-click on the viewer in the project structure.

- **Optical Spectrum Analyzer**: affiche le signal optique modulé dans le domaine fréquentiel.
- **Optical time-domain viewer**: displays the modulated optical signal in the time domain.
- **Oscilloscope**: displays the electrical signal after the PIN code in the time domain.
- **BER analyzer (BET):** measures system performance as a function of the signal before and after propagation.

III.5.2 Optisystem signal representation [16]

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

Different levels of abstraction imply different signal representations. The signal representation must be as complete as possible to enable efficient simulation. There are five signal types in the software library, all color-coded.

- **Electrical signals**

Electrical signals are generated by components such as pulse generators in the transmitter library and photodetectors in the receiver library. Electrical signals consist of the waveform signal sampled in the time domain. The main properties of the electrical signal are signal noise variances in the time domain and noise power spectral densities in the frequency domain.

- **Binary signals**

Binary signals are generated by components such as bit sequence generators. Pulse generators in the transmitter 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 a binary signal is its bit rate.

- **Optical signals**

Optical signals are generated by components such as lasers in the transmitter library. optical signals allow different signal representations:

  - sampled signals
  - parameterized signals

- **M-ary signals:**

M-ary signals are multi-level signals used for special types of coding, such as PAM, QAM, PSK, and DPSK. M-ary signals are similar to binary signals. However, M-Ary signals can have any level instead of just the high (1) and low (0) levels, or marks and spaces.

III.6 Applications and benefits of the optisystem.

III.6.1 Applications of optisystem software [21]

OptiSystem allows for the design automation of virtually any type of optical link in the physical layer, and the analysis of a broad spectrum of optical networks, from longhaul systems to MANs and LANs.

- ***OptiSystem's wide range of applications include:***
  - optical communication system design from component to system level at the physical layer.
  - Passive optical networks (***PON***) based ***FTTx***.
  - ***SONET***/***SDH*** ring design.

- Transmitter, channel, amplifier, and receiver design.
- Amplified system ***BER*** and link budget calculations.

III.6.2 Benefits of optisystem software [21].

- Rapid, low-cost prototyping.
- Global insight into system performance.
- Straightforward access to extensive sets of system characterization data.
- Automatic parameter scanning and optimization.
- Assessment of parameter sensitivities aiding design tolerance specifications.
- Dramatic reduction of investment risk and time-to-market.
- Visual representation of design options and scenarios to present to prospective customers.

III.7 Simulation modes [16].

Optisystem software offers three different simulation modes.

1. *Normal mode*: simply enter the value of the desired parameter
2. *Sweep mode:* where the parameter value varies according to a given curve.
3. *Script mode:* where the parameter is evaluated as an arithmetic expression.

III.8: Transmission quality criteria

To characterize the quality of an optical transmission, diverse criteria exist. The three fundamental quality criteria of a transmitted signal are:

Bit error rate (BER), the eye diagram, the quality factor *(Q)*

- **Bit error rate**: The bit error rate (**BER**) is the ratio of incorrectly received bits to the total number of bits transmitted in a communication system. It assesses the transmission's precision and may be affected by factors such as signal intensity, interference, and noise. Superior transmission quality is indicated by a reduced **BER.**

$$\boldsymbol{BER = \frac{number\ of erroneous\ bits}{number\ of\ bits\ transmitted}} \ldots.. \textbf{(III.1)}$$

- **The eye diagram:** An eye diagram is a graphical tool that is used in signal analysis to assess the integrity of digital signals during transmission. It is produced by superimposing multiple signal waveforms within a single period, resulting in a pattern that resembles an eye.

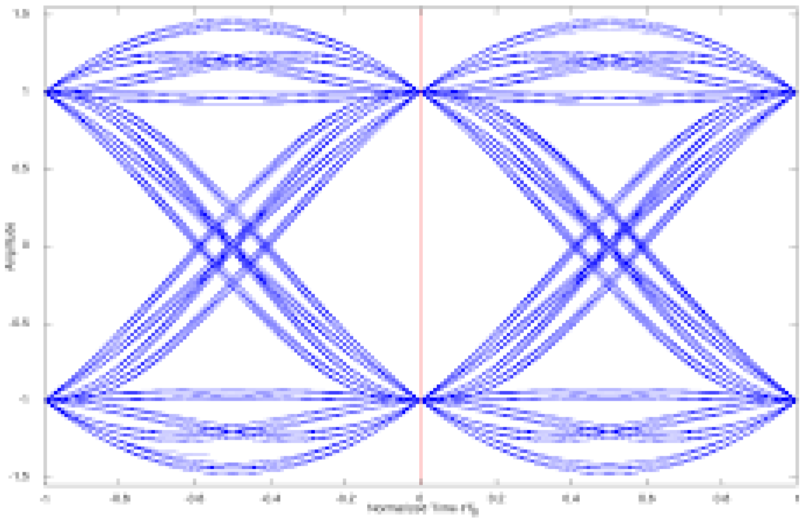


Figure III.7: example of eye diagram

- **The quality factor:**

The efficiency and efficacy of a transmission system, particularly in analog and digital communications, are indicated by the quality factor (Q-factor). It evaluates the effectiveness of a system in preserving signal integrity by taking into account factors such as distortion, bit error rate (BER), and signal-to-noise ratio (SNR). A higher Q-factor suggests that the transmission quality has been improved, as evidenced by a reduction in noise and errors.

$$Q = \frac{I1 - I2}{\delta 1 - \delta 2} \ldots\ldots \text{ (III.2)}$$

Where I1 and I2 are the mean values representing the useful signal, δ1 and δ2 are the standard deviations of the probability densities of the symbols 1 and 0

III.9 Threshold

Threshold plays a critical role in the efficacy of transmission systems, especially in digital and optical communications. It refers to the minimum signal level at which a receiver can reliably distinguish between binary values, such as ‘0’ and ‘1’. This threshold ensures accurate signal detection and affects the system’s performance in terms of bit error rate (BER) and signal integrity. When the signal falls below the threshold, the likelihood of detection errors increases, potentially degrading communication quality. In digital communication, the threshold marks the decision point for bit recognition; in error detection, it defines the limit beyond which corrective measures are needed; and in terms of signal strength, it represents the lowest acceptable power level for reliable reception. Setting an appropriate threshold is essential to avoid data loss and maintain system reliability [**1**].

III.10 Decision instant

A decision instant is the precise moment at which a receiver in a digital communication system sample an incoming signal to determine its communicated value (e.g., a binary 0 or 1) [**1**].

This is crucial for the prevention of bit errors and the assurance of precise data recovery:

- Sampling is conducted at the optimal moment when the signal is most stable, which is guaranteed by the proper synchronization of the transmitter and receiver. Inter-symbol interference (**ISI**) and elevated bit error rates (**BER**) may result from timing errors during critical decision points**.**

III.11 Simulation Description

We simulated, with each channel operating at a data rate of 10 Gbps, over a total transmission distance of 300 km. The simulation incorporated both Return-to-Zero (RZ) and Non-Return-to-Zero (NRZ) modulation formats to evaluate their performance. The transmitter consisted of 32 DWDM channels spaced at 100 GHz, multiplexed and transmitted over an optical link composed of two Optical Amplifiers, a 10 km Dispersion Compensation Fiber (DCF), and a 50 km single-mode fiber (SMF). This structure was repeated five times to simulate long-distance transmission using a loop control mechanism. At the receiver side, a 32-channel DWDM demultiplexer and a Bit Error Rate (BER) analyzer were utilized to assess signal quality and performance across all channels, our simulation will follow the algorithm shown below:

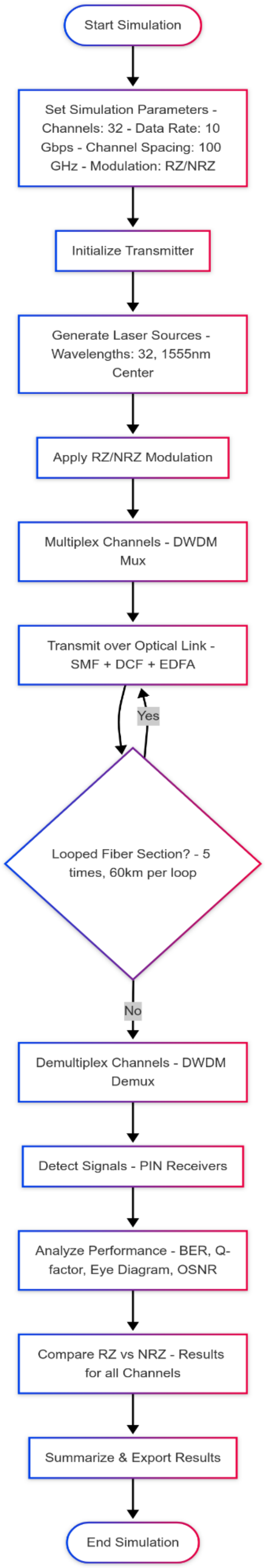


Figure III.8: simulation algorithm.

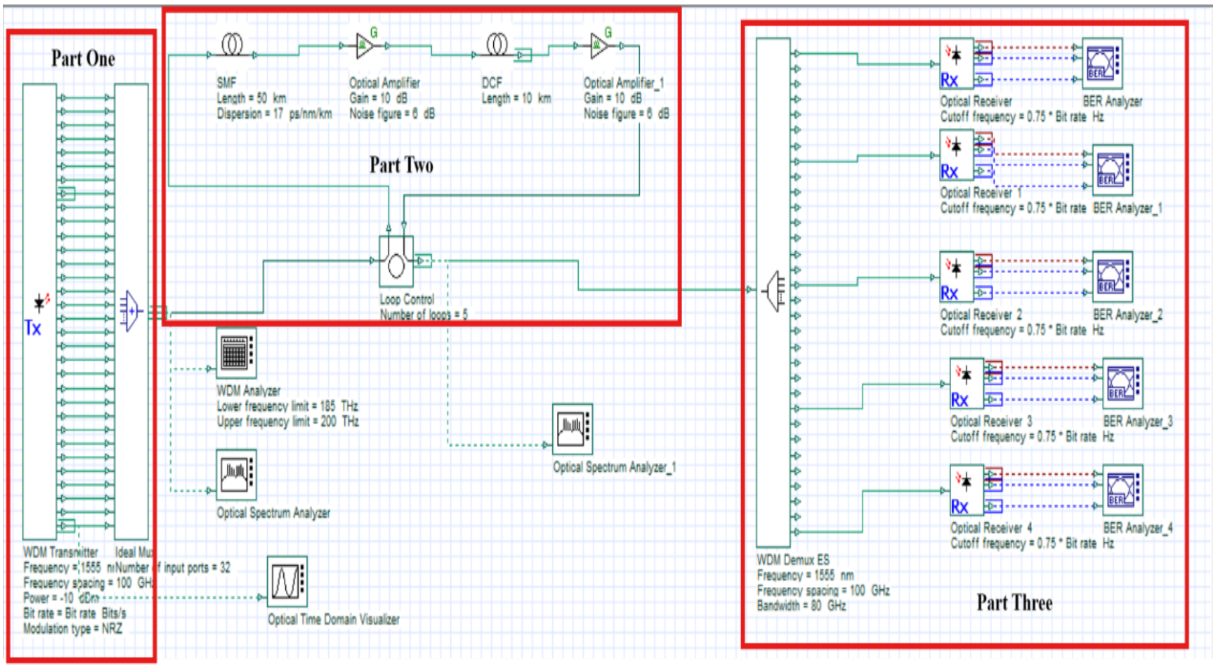


Figure III.8: DWDM communication system diagram.

The entire project is split into three segments: the DWDM transmitter, the fiber optic connection, and the DWDM receiver.

Part one:

The DWDM transmitter utilizes a laser source with a wavelength of 1555nm, which reduces attenuation at 1550nm and enables high-speed connections. Channel separation is 100 GHz, and thirty-two channels are broadcast. The data rate that is employed is 10 Gbit/s. RZ and NRZ are the modulation formats that are implemented. A multiplexer aggregates and multiplexes signals from all channels. A single fiber is used to consolidate and aggregate all channel signals.

Part two:

The second section of the system consists of a fiber optic link used to transmit the signal from the transmitter to the receiver over a long distance. This link utilizes Single-Mode Fiber (SMF) with a core diameter of 6 micrometers, a numerical aperture of 0.1, and a V-number of approximately 2.4 at a wavelength of 1545 nm, which ensures single-mode operation. However, this type of fiber suffers from relatively high chromatic dispersion, measured at 17 ps/nm/km, which can degrade signal quality—particularly at high data rates such as 10 Gbit/s per channel. The SMF used in this setup spans 50 kilometers, after which the signal is amplified using an Erbium-Doped Fiber Amplifier (EDFA) providing a gain of 10 dB and a noise figure of 6 dB. These amplifiers are well-suited for DWDM applications due to their compatibility with multiple wavelengths, low coupling loss, and stable performance under polarization variations.

To mitigate the dispersion effects introduced by the SMF, the signal then passes through a 10-kilometer Dispersion Compensation Fiber (DCF), which helps restore pulse shape and reduce intersymbol interference. An additional optical amplifier with the same specifications is used to re-amplify the signal. To simulate long-distance transmission without manually duplicating system components, the loop control feature is employed, repeating the entire segment (SMF + DCF + EDFA) five times, representing a total transmission distance of 300 km. Finally, the signal exiting the loop is directed to the input of the WDM demultiplexer for channel separation and performance analysis at the receiver end.

Part three:

The third part of the system consists of a WDM demultiplexer, which separates the multi-channel optical signals and sends each channel to an independent receiver. This system uses a 100 GHz frequency separation between the channels, while the bandwidth of each filter within the demux device is approximately 80 GHz. This means that each channel passes through a filter that allows signals within a range of ±40 GHz around the center frequency, leaving a 20 GHz guard band between the channels to reduce spectral overlap and improve separation accuracy.

The separated channels are then sent to PIN optical receivers, which are essentially semiconductor detectors consisting of a weakly doped intrinsic layer separating the p- and n-band regions and operating under a reverse bias voltage. This type of receiver is capable of operating within a wavelength range of 1100 nm to 1600 nm, with quantum efficiencies ranging from 30% to 95%, depending on operating conditions. The signals coming out of the receivers are then sent to bit error rate analyzers (BER analyzers) to evaluate the signal quality and determine the transmission accuracy.

III.12 Materials utilized in Optical Transmission

- **WDM transmitter**

We utilize a WDM transmitter to combine several optical signals into one optical fiber, enabling high-capacity data transmission; it merges and modulates various wavelengths of light to transmit multiple data streams at the same time.

Disp	Name	Value	Units	Mode
☐	Number of output ports	32		Normal
☑	Frequency	1555	nm	Normal
☑	Frequency spacing	100	GHz	Normal
☑	Power	-10	dBm	Sweep

Figure III.9: WDM Parameter

- **Ideal mux**

  The basic cycle is to combine several light signals (different channels at different wavelengths) into a single laser or optical fiber.

- ***SMF:***

  SMF refers to "Single Mode Fiber," a category of fiber that carries light in just a single mode, which minimizes dispersion and allows the signal to travel over extensive distances.

Disp	Name	Value	Units	Mode
☐	User defined reference wavelength	☑		Normal
☐	Reference wavelength	1555	nm	Normal
☑	Length	50	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.2	dB/km	Normal
☐	Attenuation vs. wavelength	Attenuation.dat		Normal

Figure III.10: SMF parameter

- **Optical Fiber (DCF)**

The purpose of DCF is to reduce the impact of dispersion in optical communication systems, thereby enhancing signal quality and allowing for extended transmission distances.

Disp	Name	Value	Units	Mode
☐	User defined reference wavelength	☑		Normal
☐	Reference wavelength	1555	nm	Normal
☑	Length	10	km	Normal
☐	Attenuation effect	☑		Normal
☐	Attenuation data type	Constant		Normal
☐	Attenuation	0.5	dB/km	Normal
☐	Attenuation vs. wavelength	Attenuation.dat		Normal

Figure III.11: DCF parameter

- **Optical amplifier**

The optical amplifier within Optisystem is utilized to boost optical signals in fiber optic communication networks and deliver high-power amplification for extended transmission distances without converting between electrical and optical signals.

Disp	Name	Value	Units	Mode
☐	Operation mode	Gain Control		Normal
☑	Gain	10	dB	Normal
☐	Power	10	dBm	Normal
☐	Saturation power	10	dBm	Normal
☐	Saturation port	Output		Normal
☐	Include noise	☑		Normal
☑	Noise figure	6	dB	Normal

Figure III.12: Optical amplifier parameter

- **Loop Control**

A component designed to replicate multiple stages of optical signal transmission through fibers and devices (like optical amplifier and DCF) without the need to recreate the same components repeatedly. Streamline the design (conserve space and avoid manual duplication of components). Testing performance over long distances.

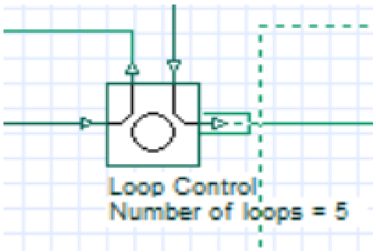


Figure III.13: Loop control

- **WDM Demux ES**

It is a device designed to divide the multi-wavelength optical signals (channels) transmitted through the optical fiber after being combined in the Mux at the transmitter. Once the signal arrives at the receiver, it's necessary to isolate these channels into distinct outputs. This is the role of the demux, which separates them based on their wavelengths.

Disp	Name	Value	Units	Mode
☐	Number of output ports	32		Normal
☑	Frequency	1555	nm	Normal
☑	Frequency spacing	100	GHz	Normal
☑	Bandwidth	80	GHz	Normal

Figure III.14: WDM Demux ES parameter

- **Optical Receiver**

It converts the light signal into an electrical signal that can be analyzed and processed. In other words, it transforms light into comprehensible data for electronic devices. To determine the Q-factor, assess the BER (bit error rate) and evaluate the signal using a BER analyzer or optical power meter.

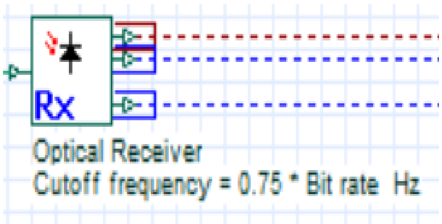


Figure III.15 : Optical Receiver

- **BER analyzer**

It functions as an analytical instrument within simulation applications such as OptiSystem to assess the fidelity of a digital signal following its traversal through the optical system.

Additionally, it evaluates the bit error rate (BER), which is the ratio of wrongly received bits to the overall number of bits transmitted.

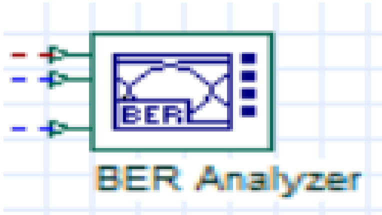


Figure III.16: BER Analyzer

- **Optical Spectrum Analyzer**

The Optical Spectrum Analyzer (OSA) plays a crucial role in an optical communication system by displaying the distribution of optical signals over different wavelengths and identifying any interference between channels or undesired signals.

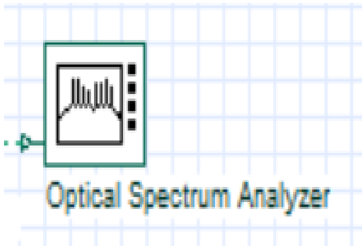


Figure III.17: Optical spectrum analyzer

- **WDM Analyzer**

An analysis tool in a fiber optic system simulator (like Optisystem) that is utilized to observe and examine several signals in WDM (wavelength division multiplexing) systems. Its main purpose is to evaluate the Optical Spectrum of the signal after it travels through the network sections.

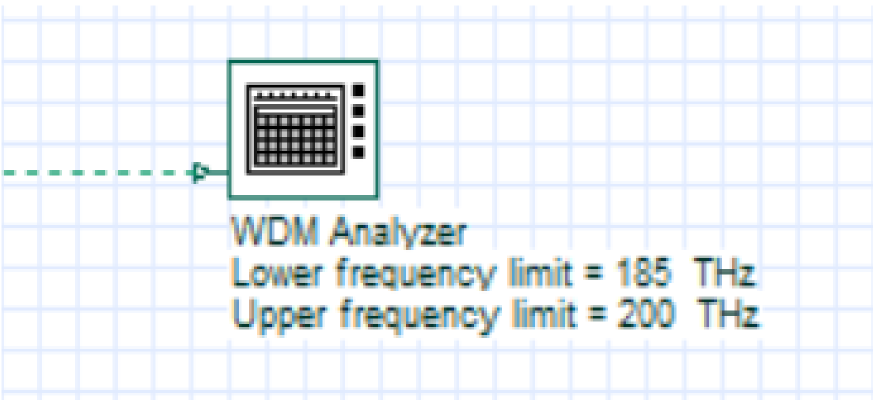


Figure III.18: WDM analyzer

- **Optical Time Domain Visualizer**

  It is a feature within simulation software (like OptiSystem) that allows for the visualization of an optical signal in the time domain. Its primary purpose is to help identify signal distortion, interference, scattering, or any disruptions caused by fibers or components.

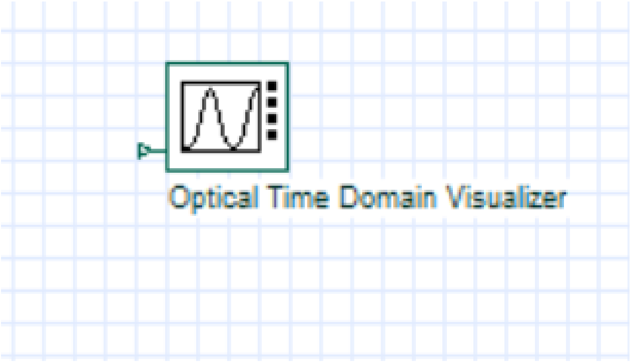


Figure III.19: OTDV

Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
192.79258	-18.232576	-43.200747	24.968171
192.89258	-18.359014	-41.414946	23.055931
192.99258	-18.291434	-41.386327	23.094892
193.09258	-18.335512	-41.404085	23.068573
193.19258	-18.315289	-41.301048	22.985759
193.29258	-18.36031	-41.302059	22.941748
193.39258	-18.374918	-41.308949	22.93403
193.49258	-18.314418	-41.237084	22.922666
193.59258	-18.390256	-41.268527	22.878272
193.69258	-18.377388	-41.374641	22.997253
193.79258	-18.349072	-41.411354	23.062282
193.89258	-18.299254	-41.504447	23.205192
193.99258	-18.394485	-41.502654	23.108169
194.09258	-18.362668	-41.70082	23.338152
194.19258	-18.400213	-41.321165	22.920953
194.29258	-18.314078	-41.368705	23.054628
194.39258	-18.320199	-41.403802	23.083603
194.49258	-18.355296	-41.488741	23.133445
194.59258	-18.363499	-41.579593	23.216094
194.69258	-18.394194	-41.566848	23.172654
194.79258	-18.426863	-41.466036	23.039173
194.89258	-18.317909	-41.35409	23.036181
194.99258	-18.308239	-41.342088	23.033849
195.09258	-18.419532	-41.310823	22.89129
195.19258	-18.387808	-41.52737	23.139562
195.29258	-18.369487	-41.297122	22.927634
195.39258	-18.367367	-41.596051	23.228684
195.49258	-18.382683	-41.346458	22.963775
195.59258	-18.32076	-41.437154	23.116393
195.69258	-18.327026	-41.44756	23.120534
195.79258	-18.349524	-41.466698	23.117174
195.89258	-18.194667	-43.15242	24.957753

Frequency (THz)	Signal Power (dBm)	Noise Power (dBm)	OSNR (dB)
192.79258	-13.289617	-42.053431	28.763813
192.89258	-13.391869	-39.871144	26.479276
192.99258	-13.305108	-39.792281	26.487172
193.09258	-13.319899	-39.88163	26.561731
193.19258	-13.313066	-39.761519	26.448453
193.29258	-13.390239	-39.796848	26.406608
193.39258	-13.382009	-39.89044	26.508431
193.49258	-13.322224	-39.669709	26.347485
193.59258	-13.399898	-39.701065	26.301166
193.69258	-13.382649	-39.751347	26.368698
193.79258	-13.325828	-39.881866	26.556037
193.89258	-13.306581	-39.933626	26.627045
193.99258	-13.380589	-39.912526	26.531937
194.09258	-13.380279	-39.933024	26.552745
194.19258	-13.391954	-39.805292	26.413338
194.29258	-13.311894	-40.144654	26.83276
194.39258	-13.314709	-39.944423	26.629714
194.49258	-13.366176	-39.905666	26.53949
194.59258	-13.378703	-40.057968	26.679265
194.69258	-13.379022	-40.01732	26.638298
194.79258	-13.387009	-39.959284	26.572275
194.89258	-13.315181	-39.866757	26.551576
194.99258	-13.311205	-39.898514	26.587309
195.09258	-13.385988	-39.842749	26.456761
195.19258	-13.387057	-39.940049	26.552992
195.29258	-13.383052	-39.834292	26.45124
195.39258	-13.379617	-39.86411	26.484493
195.49258	-13.385769	-39.895352	26.509583
195.59258	-13.314553	-39.980762	26.66621
195.69258	-13.357223	-39.855339	26.498116
195.79258	-13.387319	-39.944196	26.556877
195.89258	-13.273599	-42.058649	28.78505

Figure III.20: WDM analyzer for RZ and NRZ modulation formats

III.13 Results and discussions

This image illustrates a table that compares the results of a WDM analyzer's evaluation of RZ and NRZ modulation formats. The table assesses the signal power, noise power, and optical signal-to-noise ratio (OSNR) of all 32-channel frequencies in the WDM network.

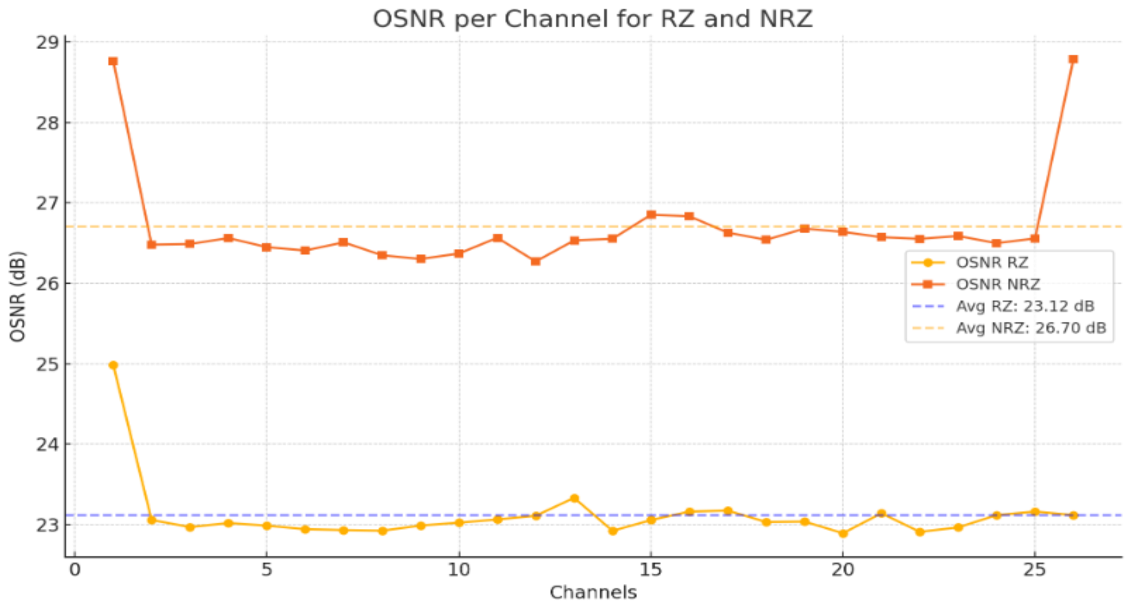


Figure III.21: OSNR per channel for RZ and NRZ

NRZ shows higher and more stable OSNR values (≈26.70 dB) compared to RZ (≈23.12 dB), indicating better signal quality. The broader spectrum of RZ pulses may cause greater sensitivity to dispersion and inter-channel interference.

III.14 Results of Optical Spectrum

- **Before transmission**

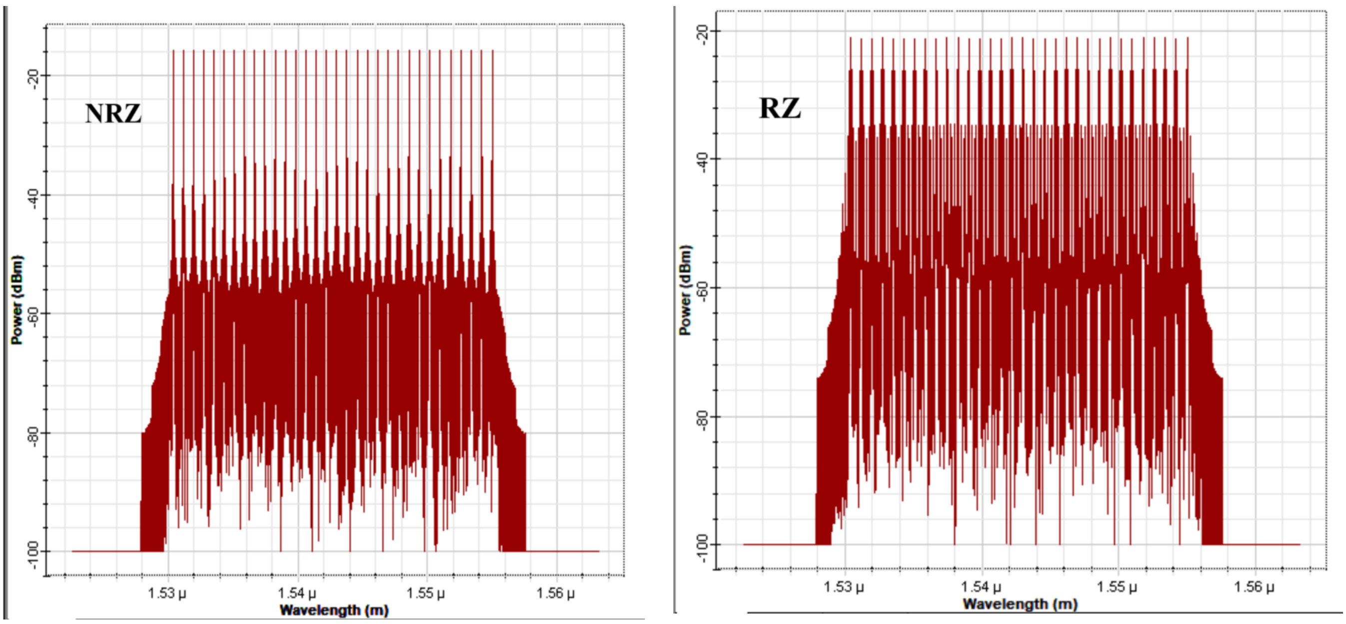


Figure III.22: Results before transmission

- **After transmission**

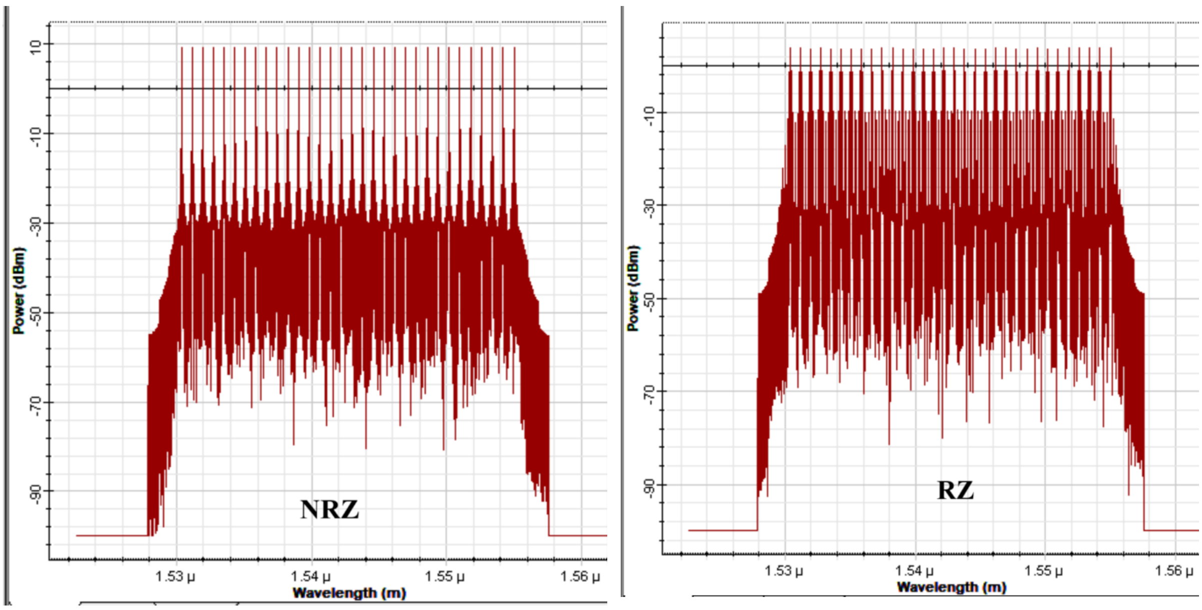


Figure III.23: Results after transmission

Examine the frequency spectrum of the signal prior to and following its transmission through the optical link.

The spectrum of two optical signals was analyzed using the NRZ (Non-Return-to-Zero) and RZ (Return-to-Zero) modulation methods. The following was observed:

- **First: Before sending:** NRZ signal: Defined by a comparatively narrower spectral bandwidth, featuring a consistent power distribution throughout the spectrum. Elevated peaks signify strong, concentrated power.
- **RZ signal:** demonstrated a broader spectrum due to the modulation characteristics, featuring sharper and more closely spaced spectral peaks, which reveal high-frequency components resulting from the quick return to zero.
  - **Secondly: After sending**
    - NRZ signal: A noticeable drop in power level (around -20 to -25 dBm).
    - **RZ signal:** There was a slight reduction in power, yet the spectrum exhibited improved coherence and consistency**.**

RZ modulation demonstrates significant advantages in overcoming spectral distortions caused by transmission, which makes it the preferred option for long-distance or high-speed transmission systems.

In contrast, NRZ modulation is more susceptible to dispersion and noise, requiring extra measures like optical amplification or spectral filters for support.

Comparative examination of eye diagrams

- **For channel 1**

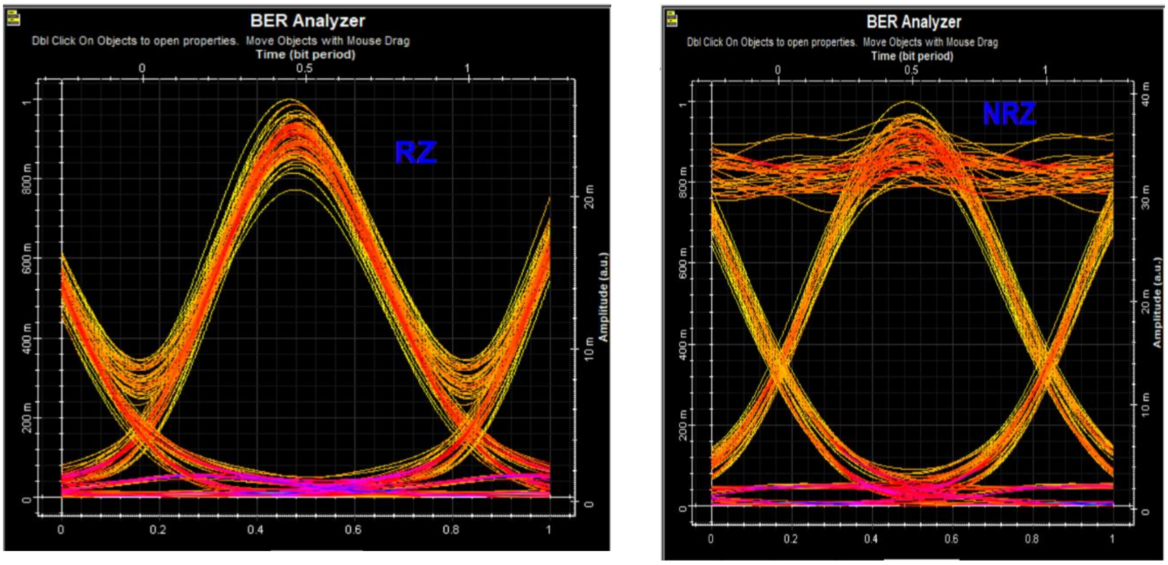


Figure III.24: Q factors of RZ and NRZ modulation channel 1

	RZ	NRZ
Q FACTOR	**15.7762**	**13.3252**
Min BER	**1.95658 e-56**	**8.13644 e-41**
EYE HEIGHT	**0.0185894**	**0.0248289**
THRESHOLD	**0.00607155**	**0.0147621**
DECISION INST	**0.509766**	**0.623047**

Table: Comparison between RZ & NRZ for Channel 1

❖ **For channel 8**

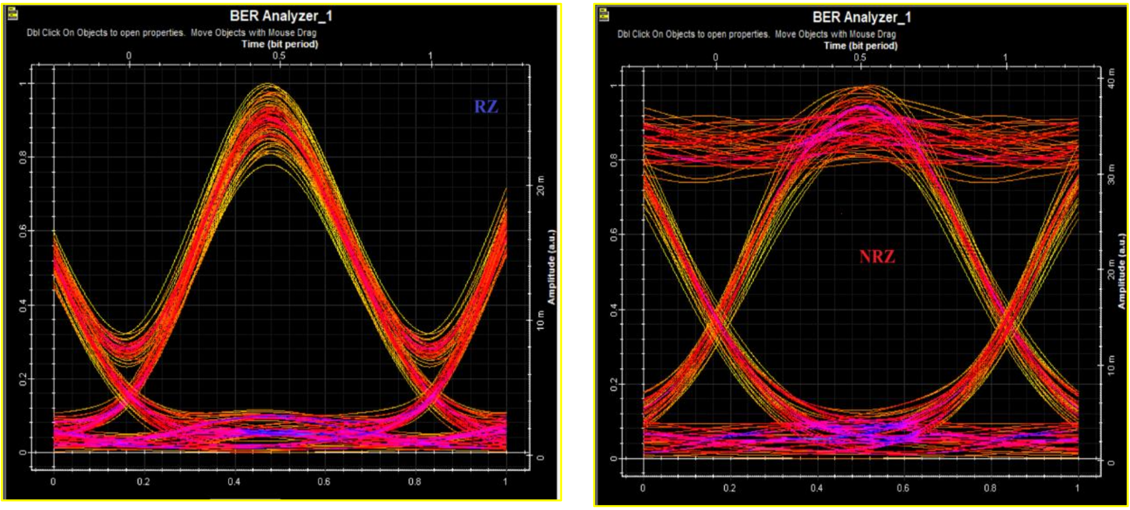


Figure III.25: Q factors of RZ and NRZ modulation channel 8

	RZ	**NRZ**
Q FACTOR	**10.6042**	**10.6302**
Min BER	**1.389 e-26**	**1.306754 e-26**
EYE HEIGHT	**0.164904**	**0.23103**
THRESHOLD	**0.0105418**	**0.0164606**
DECISION INST	**0.515625**	**0.619141**

Table: Comparison between RZ & NRZ for Channel 8

- **For channel 16**

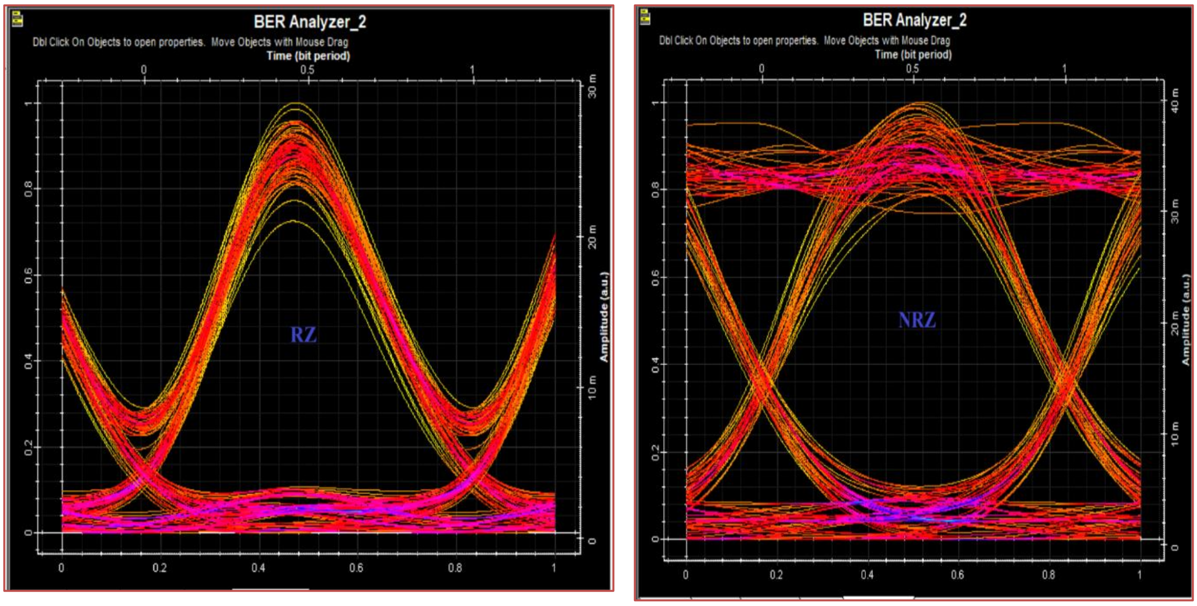
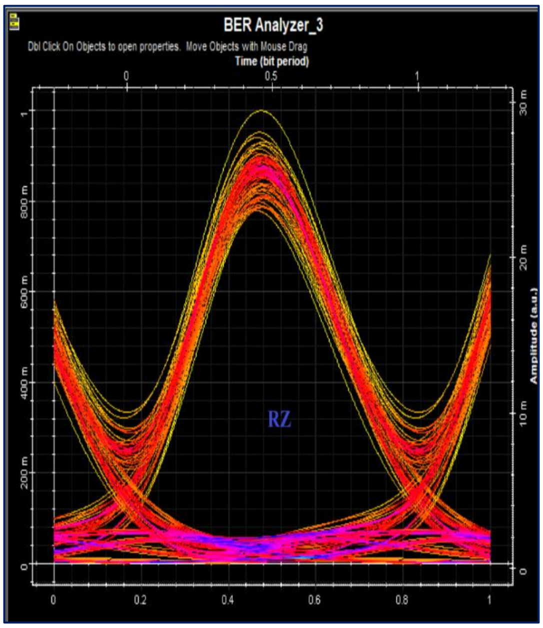


Figure III.26: Q factors of RZ and NRZ modulation channel 16

	RZ	**NRZ**
Q FACTOR	**10.4002**	**9.55307**
Min BER	**1.20475 e-25**	**6.19764e-22**
EYE HEIGHT	**0.0168611**	**0.0218606**
THRESHOLD	**0.0108054**	**0.0155815**
DECISION INST	**0.458984**	**0.625**

Table: Comparison between RZ & NRZ for Channel 16

- **For channel 24**



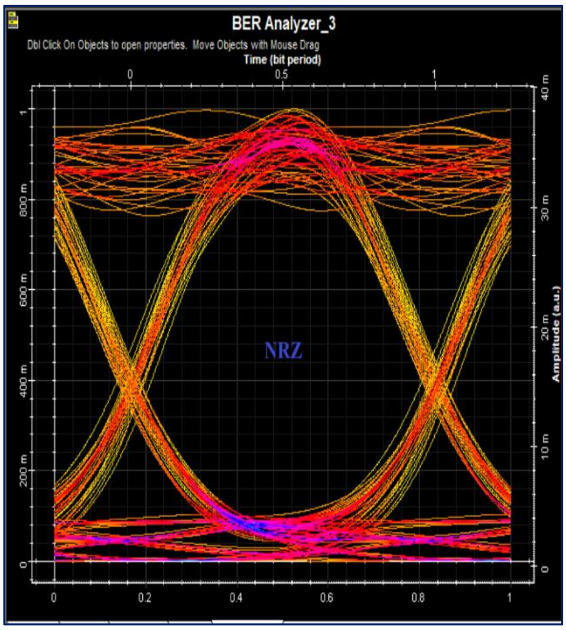


Figure III.27 : Q factors of RZ and NRZ modulation channel 24

	RZ	NRZ
Q FACTOR	**13.9203**	**11.7554**
Min BER	**2.12155 e-44**	**3.25193 e-32**
EYE HEIGHT	**0.0189906**	**0.0240093**
THRESHOLD	**0.00765852**	**0.0154715**
DECISION INST	**0.457031**	**0.431641**

Table: Comparison between RZ & NRZ for Channel 24

- **For channel 32**

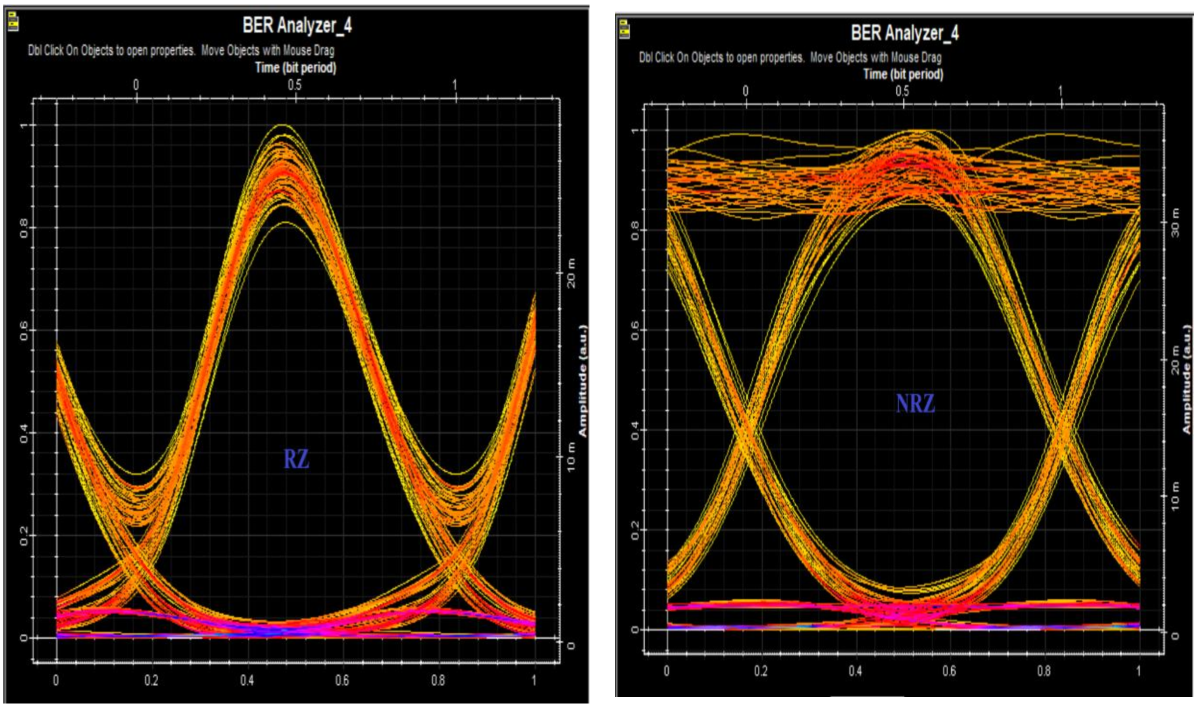


Figure III.28: Q factors of RZ and NRZ modulation channel 32

	RZ	NRZ
Q FACTOR	19.8269	15.6371
Min BER	6.89687 e-88	1.92783 e-55
EYE HEIGHT	0.0210416	0.0262085
THRESHOLD	0.00488208	0.0124721
DECISION INST	0.453125	0.466797

Table: Comparison between RZ & NRZ for Channel 32

We plotted the Q Factor against channel numbers for both NRZ and RZ modulation formats. The results show that while both formats exhibit variations across the channels, RZ consistently achieves higher Q Factor values than NRZ, particularly in channels 1, 16, 24, and 32. This indicates that RZ offers better signal quality, especially as the channel number increases. In contrast, NRZ shows greater fluctuations and generally lower Q values, suggesting a higher sensitivity to dispersion and nonlinear effects in multi-channel optical transmission systems.

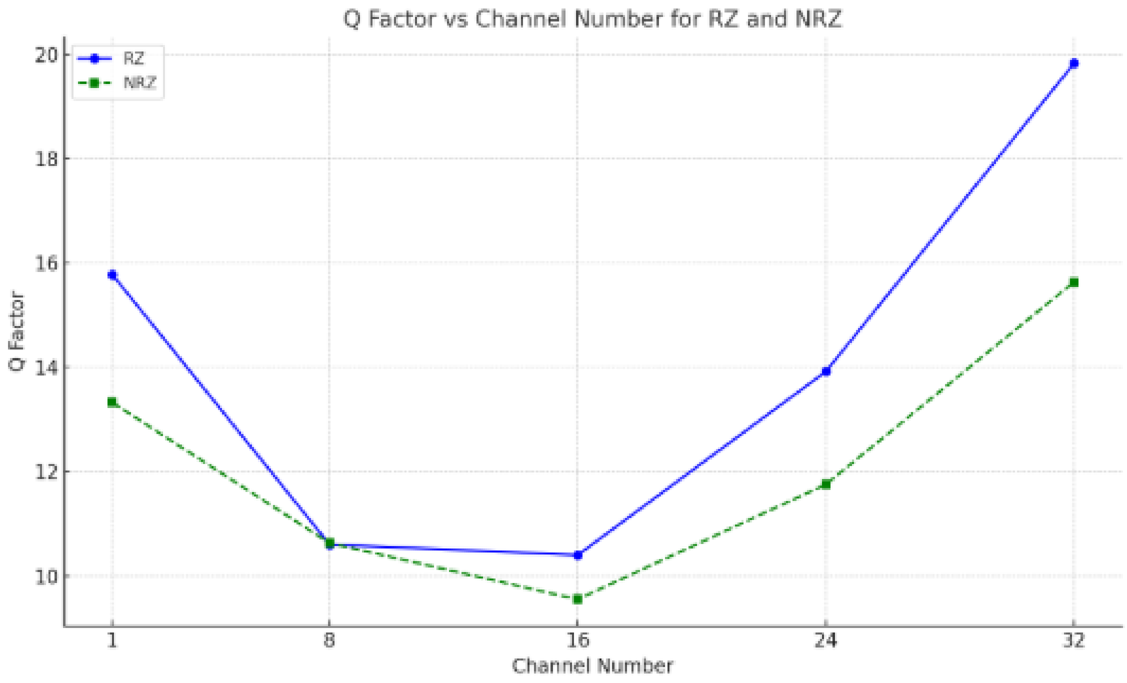


Figure III.29: Q factor Comparison between RZ and NRZ Modulation

Note: The close Q Factor values observed in channel 8 do not indicate uniform performance across the entire system; instead, they suggest that the specific conditions of this channel minimize the typical performance advantages that RZ usually holds over NRZ.

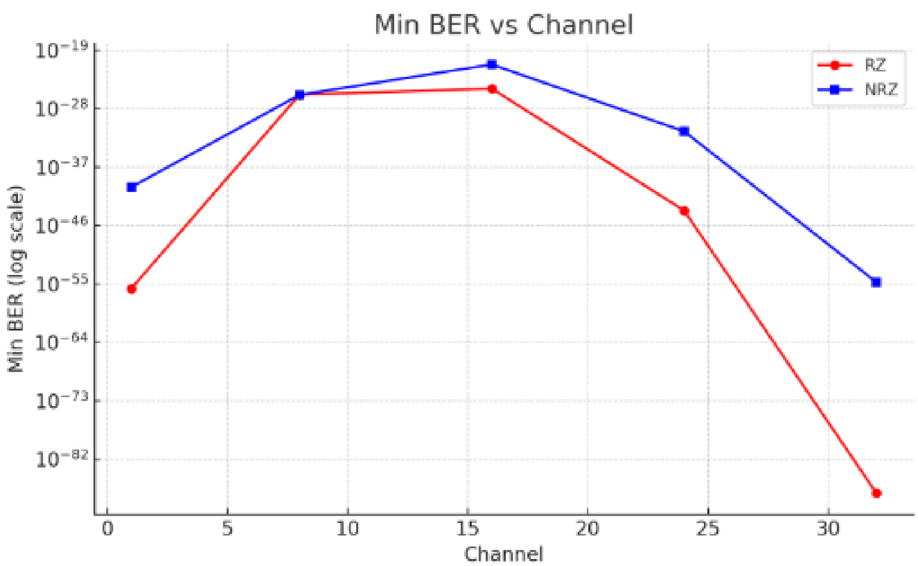


Figure III.30: Min BER Comparison between RZ and NRZ Modulation

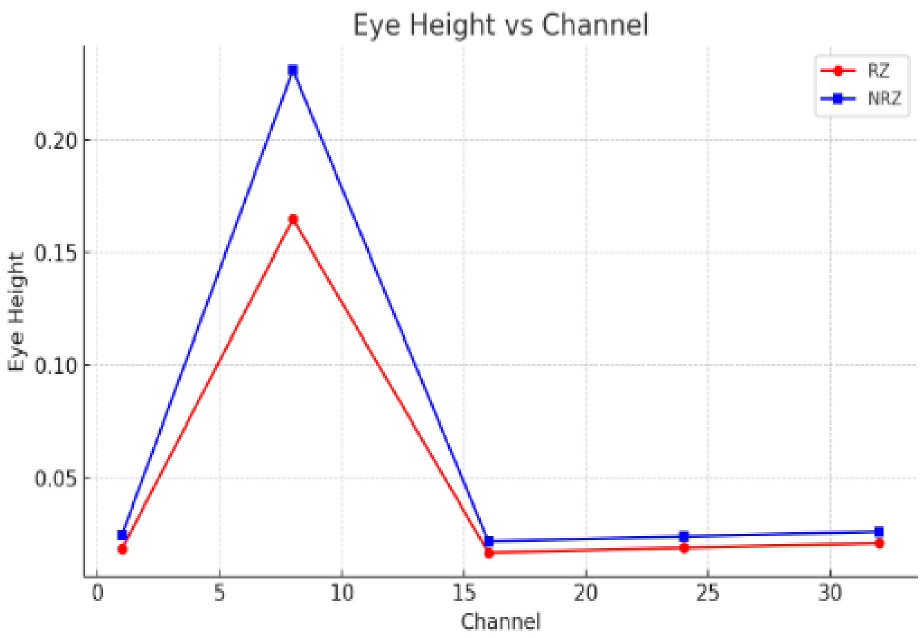


Figure III.31: Eye height Comparison between RZ and NRZ Modulation

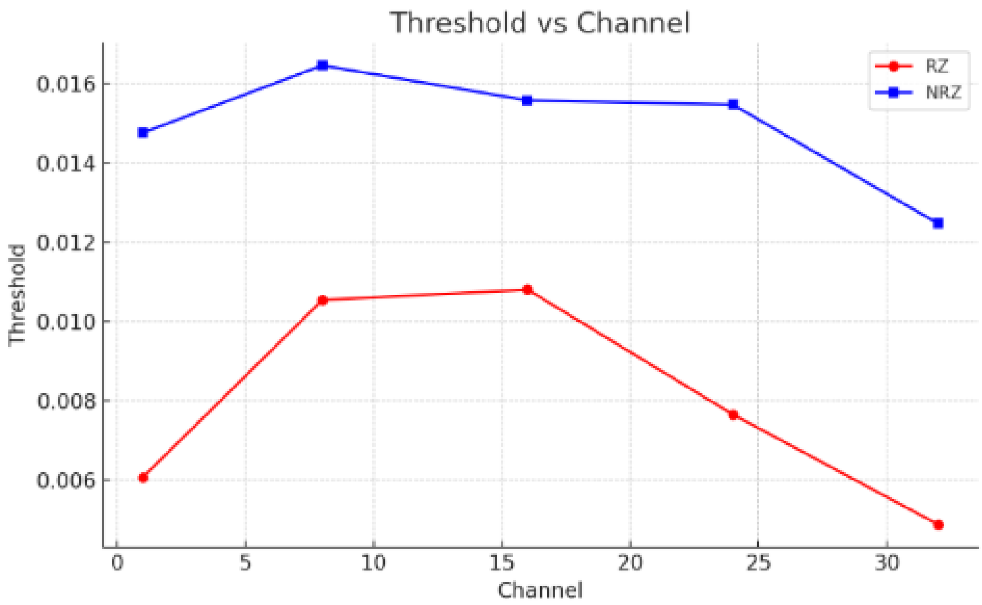


Figure III.32: Threshold Comparison between RZ and NRZ Modulation

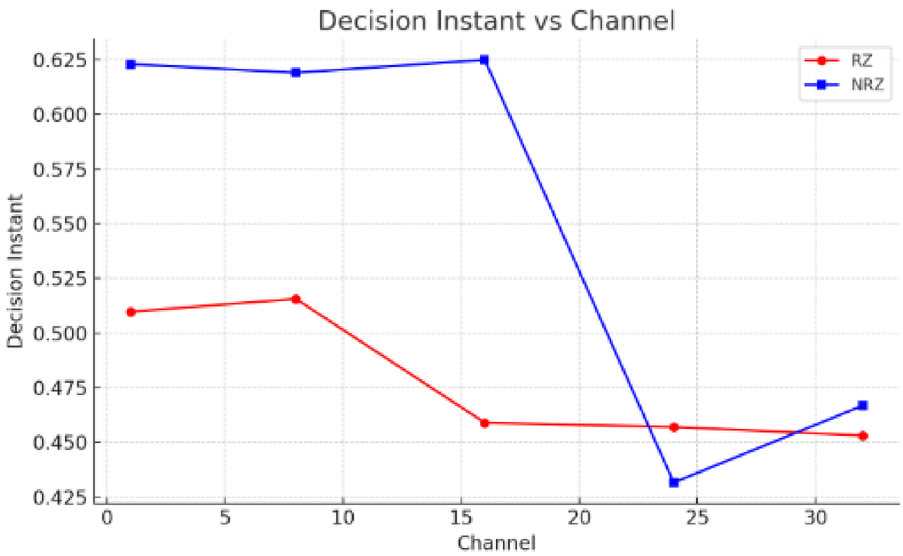


Figure III.33: Decision instant Comparison between RZ and NRZ Modulation

Interpreting study results

The graph illustrates the varying performance of RZ and NRZ across four critical parameters that influence signal quality in an optical communication system:

1. **Min BER**

   Both RZ and NRZ techniques demonstrate excellent performance with very low BER values**.** The Min BER curve shows that the RZ system achieves significantly lower bit error rates compared to the NRZ system across most channels, indicating its superior performance in minimizing errors. Channel 32 stands out, where RZ records an extremely low BER (~6.89687 e-88), demonstrating exceptional performance in that case. These results support the conclusion that RZ is more resilient to noise and interference in certain environments.

2. **Eye height**

   The height of the eye diagram serves as a visual measure of the clarity of the signal at the receiver:

   From the Eye Height curve analysis, it is evident that NRZ has a consistently higher eye opening across all channels compared to RZ. A larger eye height indicates better signal clarity and facilitates more accurate bit detection. Channel 8 shows a significant advantage for NRZ, suggesting superior visual signal clarity. Thus, NRZ provides more stable signals with enhanced optical quality.

3. **Threshold**

The Threshold curve indicates that NRZ generally requires higher threshold levels compared to RZ. Conversely, RZ utilizes lower thresholds, likely due to its pulsed nature that reduces intersymbol interference. This makes RZ more adaptable to signal variations, while NRZ demonstrates greater consistency in determining the optimal decision threshold.

4. **Decision instant**

In the Decision Instant curve, NRZ tends to make decisions at relatively later time instances (around 0.62), whereas RZ makes decisions closer to the midpoint or earlier within the bit period. This difference arises from NRZ relying on the full shape of the signal, while RZ is based on a limited pulse portion. As a result, RZ is quicker in making decisions, which is beneficial in systems prone to signal delay or timing jitter.

Summary of Simulation Results:

In summary, the simulation study provides compelling evidence of the strengths and trade-offs associated with each modulation format:

- RZ modulation offers superior performance in terms of lower bit error rates, higher Q factors, more flexible threshold adaptation, and generally faster decision timing. These characteristics make RZ particularly well-suited for applications requiring exceptional accuracy and robustness against channel impairments.
- NRZ modulation demonstrates consistently larger eye heights, supporting enhanced signal clarity and straightforward bit discrimination. Its simplicity and reliable eye opening make it advantageous for systems prioritizing ease of implementation and strong optical signal distinction.
- The obtained results are significant, with clear eye diagram openings, excellent Q factors, and bit error rates exceeding the industry standards for optical telecommunications. All measured BER values are more than 1.31×10^{-32}, which is significantly lower than the accepted threshold (BER = 1×10^{-12}). This confirms the effectiveness and reliability of the designed DWDM system using both modulation schemes.

In conclusion, the RZ modulation format is ideal for high-performance, interference-prone optical systems, while NRZ remains a practical choice where implementation simplicity and signal clarity are the main priorities. The insights gained from this study provide a valuable reference for selecting the appropriate modulation strategy in future optical communication network designs.

Conclusion

The results of the modeling of a DWDM optical fiber transmission system using OptiSystem software are summarized in this chapter. Variables such as Q-factor, BER, eye diagram clarity, and other significant signal quality metrics were used to evaluate the performance. The system exhibited exceptional dependability, as evidenced by its minimal error rates and distinct signal differentiation in both RZ and NRZ modulation formats. The efficacy of the system architecture and its suitability for high-capacity, long-distance optical communication.

General conclusion

General conclusion

The continuous growth in global data traffic and the increasing demand for high-speed communications have led to the development of optical transmission technologies. This work explores the theoretical foundations and practical implementation of dense wavelength division multiplexing (DWDM) systems, which play a pivotal role in meeting modern bandwidth requirements. Through a detailed study of optical fiber systems and multiplexing techniques, we examine how DWDM improves the transmission capacity and efficiency of optical networks.

The first part of this thesis provided an in-depth overview of the structure, components, and principles of optical transmission systems. It also paved the way for understanding the limitations of conventional multiplexing methods and the advantages offered by WDM technology and its variants. The second part focused on DWDM technology as an advanced and scalable solution for long-range, high-capacity communications. We analyzed its key components, such as multiplexers, demultiplexers, optical amplifiers, dispersion-compensating fibers, and transceivers, as well as their benefits and limitations in practical applications.

The practical part of this work was conducted using OptiSystem simulation software, where we designed and simulated a 32-channel DWDM transmission system. The simulation tested different modulation modes (RZ and NRZ) and evaluated key performance parameters such as Q factor, bit error rate (BER), eye diagram, and signal strength over a transmission distance of 300 km. The results confirmed the effectiveness of dispersion management techniques and the role of optical amplification in maintaining signal quality over long distances. We obtained the following results:

- **Very low BER values (up to 6.89e-88 with RZ modulation)**.
- **high Q coefficients (up to 19.82)**.
- **stable eye diagrams across most channels.**

The simulation results were highly satisfactory. Using both RZ and NRZ modulation modes, the system achieved the following:

These values are indicators of exceptional transmission quality, minimal signal degradation, and an efficient system design. The use of dispersion-compensating fibers (DCFs) and EDFAs significantly improved performance compared to scenarios without dispersion compensation. Moreover, the received signal power remained well above the sensitivity threshold of the photodetectors, confirming the integrity of the signal at the receiving end.

In short, the project successfully achieved its objectives. The DWDM system demonstrated robust performance over long distances and at high capacity, substantiating the theoretical analysis with practical evidence. These results not only confirm the reliability of DWDM under challenging transmission conditions but also reinforce its importance as a core technology for next-generation optical communications networks. Its ability to support high-speed, scalable, and energy-efficient data transmission makes it suitable for future integration into cloud services, 5G networks, and large-scale data infrastructures, looking ahead, several directions can be explored to further enhance WDM-based systems:

1. *Use of advanced simulation tools*: It is proposed to develop work using newer versions of simulation software, such as OptiSystem 2024, which offers broader capabilities to simulate complex optical systems at higher resolution and greater integration with modern analysis and programming tools.
2. *AI-based Spectrum Management*: Future research could explore the use of artificial intelligence, particularly machine learning algorithms, for dynamic wavelength allocation in WDM systems. This approach can improve spectral efficiency and adapt to real-time network demands.
3. *WDM Performance in Harsh Environments*: It is important to evaluate the performance of WDM technology in challenging environments, such as undersea cables or extreme temperature regions, to develop more robust and reliable optical networks.

References

References

- [1] Ayache, A., & Boudiaf, K. (2023). *Implementation and simulation of DWDM technology* (Master's dissertation). University of Akli Mohand Oulhaj - Bouira.
- [2] https://www.meetoptics.com/light-sources/incoherent-sources-and-single-emitters/light-emitting.diodes?Emission+Wavelength__u_nm__t_r=1000%2C1700
- [3] Berrouane, W. (2018). *Design study of a very high-speed optical transmission chain based on III-Nitride semiconductors* [Doctoral dissertation, Djillali Liabès University, Faculty of Electrical Engineering].
- [4] G. Keiser, *Optical Communications Essentials*. New York, NY, USA: McGraw-Hill, 2007.
- [5] G. P. Agrawal, *Fiber-Optic Communication Systems*, 3rd ed. Hoboken, NJ, USA: John Wiley & Sons, 2002.
- [6] K. Fidanboylu, *Fiber Optic Sensors and Their Applications*. 2015.
- [7] I. Haddouche and S. Boubekeur, *La Fibre Optique et les Transmissions DWDM et SDH*, 2020.
- [8] A. Kapoor, *Modeling, Design and Applications of Optical Amplifiers and Long Period Gratings*. 2010.
- [9] N. Boudrioua, *Étude et optimisation d'une chaîne de transmission numérique par voie optique : vers une compensation électronique des effets de la PMD*, Université Paul Verlaine-Metz, 2007.
- [10] D. Soliman, *Augmented Microscopy: Development and Application of High-Resolution Optoacoustic and Multimodal Imaging Techniques for Label-Free Biological Observation*, Oct. 2016.
- [11] https://www.gophotonics.com/community/what-is-an-in-line-optical-amplifier
- [12] Olabenjo, B., & Mbarouk, S. (2014). A review of Plesiochronous Digital Hierarchy (PDH) and Synchronous Digital Hierarchy (SDH). *International Journal of Scientific Research Engineering & Technology (IJSRET)*, *3*(3), 399–402. ISSN 2278–0882.
- [13] Martil, K. (2021). *La question de l'identité dans « La Boîte à merveilles » d'Ahmed Sefrioui*. Revue Marocaine des Sciences de l'Éducation, 7, 174–185
- [14] Kaur, R., & Singh, M. (2016). *Design and comparison of symmetric compensation method for DWDM system*. International Journal of Engineering Sciences & Research Technology, 5(5), 383–388.
- [15] https://www.omnitron-systems.com/blog/understanding-cwdm-boosting-bandwidth-with-coarse-wave-division-multiplexing

- [16] Gaouat, I. (2020). *Conception et analyse d'un système de communication optique WDWM* [Mémoire de master, Université Mohamed Khider de Biskra].
- [17] https://www.fibermall.com/fr/blog/cwdm-vs-dwdm.htm
- [18] Cisco Systems, Inc. (2000). *Introduction to DWDM Technology* (Text Part Number: OL-0884-01). Cisco Systems.
- [19] Antil, R., Pinki, & Beniwal, S. (2012). *An overview of DWDM technology & network*. *International Journal of Scientific & Technology Research*, *1*(11), 43–46.
- [20] Agrawal, G. P. (2010). *Fiber-optic communication systems* (4th Ed.). Wiley.
- [21] Optiwave. (2006). *OptiSystem: Getting started (Version 5.0)*. Optiwave Corporation.