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Study and simulation of XG-PON and NG-PON architectures for the FTTH optical network.

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Dedication

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AYA

Dedication

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ISMAIL

Abstract

Fiber-to-the-Home (FTTH) networks have emerged as the standard for high-speed broadband access. This research explores the performance of different PON architectures, namely BPON, GPON, XG-PON, XGS-PON, and Next-generation WDM-PON, in FTTH networks through simulation using OptiSystem software. The study assesses the quality of service by varying fiber length, attenuation, and bit rate.

Simulation results demonstrate that XG-PON, XGS-PON, and Next-generation WDM-PON exhibit superior signal quality retention over longer distances and outperform BPON and GPON in terms of bit rate capacity. Notably, Next-generation WDM-PON shows the highest transmission rate and longer distance coverage.

The findings emphasize the potential of next-generation PON architectures for enhanced performance and future network upgrades, addressing the increasing bandwidth demands, particularly during the COVID-19 pandemic.

Keywords: Optical fiber, FTTH, OptiSystem, QoS, XG-PON, NG-PON, WDM-PON.

Résumé

Les réseaux Fiber-to-the-Home (FTTH) se sont imposés comme la norme pour l'accès haut débit. Cette recherche explore les performances de différentes architectures PON, à savoir BPON, GPON, XG-PON, XGS-PON et WDM-PON de nouvelle génération (NG-PON2), pour les réseaux FTTH en utilisant des simulations réalisées avec le logiciel OptiSystem. L'étude évalue la qualité de service en variant la longueur de la fibre, l'atténuation et le débit.

Les résultats de simulation démontrent que XG-PON, XGS-PON et WDM-PON présentent une meilleure rétention de la qualité du signal sur de plus longues distances et surpassent BPON et GPON en termes de débit. Notamment, WDM-PON de nouvelle génération présente le débit de transmission le plus élevé et une couverture sur de plus longues distances.

Ces résultats soulignent le potentiel des architectures NG-PON2 pour des performances améliorées et des mises à niveau futures du réseau, répondant ainsi à l'augmentation de la demande de bande passante, notamment pendant la pandémie de COVID-19.

Mots clés: Optical fiber, FTTH, OptiSystem, QoS, XG-PON, NG-PON, WDM-PON.

الملخص

اصبحت شبكات الألياف إلى المنزل (FTTH) المعيار الأساسي للنفاذ عالي السرعة ذو النطاق العريض لخدمات الانترنت.

يستكشف هذا البحث أداء مختلف بنيات شبكة الالياف الضوئية PON المستخدمة في FTTH ، مثل BPON و GPONو XG-PON و XGS-PON والجيل التالي من WDM-PON ، و ذلك عبر محاكاة باستخدام برنامج OptiSystem.

تقيم الدراسة جودة الخدمة من خلال ملاحظة تأثير الاختلافات في طول الألياف والتوهين ومعدل البت.

تُظهر نتائج المحاكاة أن XG-PON و XGS-PON والجيل التالي من WDM-PON يظهرون احتفاظًا بجودة الإشارة الفائقة عبر مسافات أطول ويتفوقون على BPON و GPON من حيث سعة معدل البت. والجدير بالذكر أن الجيل التالي من WDM-PON يُظهر أعلى معدل نقل وتغطية أطول للمسافات.

تؤكد النتائج على إمكانات الجيل التالي من تقنيات PON لتحسين الأداء وترقيات الشبكة في المستقبل ، مما يلبي الزيادة في متطلبات النطاق الترددي ، خاصة خلال جائحة COVID-19 .

Glossary

AES: Advanced Encryption Standard

APD: Avalanche Photodiode

AON: Active Optical Network

ATM: Asynchronous Transfer Mode

AWG: Arrayed Waveguide Grating

BER: Bit Error Rate

BPON: Broadband PON

CO: Central Office

CWDM: Coarse Wavelength Division Multiplexing

DBA: Dynamic Bandwidth Allocation

DBS: Direct Broadcast by Satellite

DCF: Dispersion Compensation Fiber

DWDM: Dense Wavelength Division Multiplexing

EDFA: Erbium-Doped Fiber Amplifier

EPON: Ethernet PON

FC: Face Contact connector

FTTH: Fiber to the Home

FTTX: Fiber to the x

GEM: GPON Encapsulation Method

GPON: Gigabit PON

GUI: Graphical User Interface

HDTV: High-Definition Television

IEEE: Institute of Electrical and Electronic Engineers

ITU: International Telecommunications Union

LAN: Local Area Networks

LC: Lucent Connector

LED: Light-Emitting Diode

LT: Line Termination

MAC: Media Access Controller

MAN: Metropolitan Area Network

MDUs: Multiple Dwelling Units

MPEG: Moving Picture Experts Group

NG-PON1: Next Generation PON 1

NT: Network Termination

ODN: Optical Distribution Network

OBD: Optical Distribution Box

ODF: Optical Distribution Frame

OLT: Optical Line Terminal

ONU: Optical Network Unit

OFDM: Orthogonal Frequency Division Multiplexing

O-E-O: Optical-Electrical-Optical

PCB: Printed Circuit Board

P2MP: Point-to-Multipoint

P2P: Point-to-Point

PIN: Photodiode that converts optical signals into electrical signals

PoE: Power over Ethernet

PON: Passive Optical Network

PSTN: Public Switched Telephone Network

QPSK: Quadrature Phase Shift Keying

QoS: Quality of Service

RE: Reed-Solomon Encoding

RF: The high-frequency RF modulation signal

SC: Subscriber Connector

SOA: Semiconductor Optical Amplifier

ST: Straight Tip connector

T-CONT: Transmission Container

TDM: Time Division Multiplexing

VDSL: Very high bit rate DSL

VoIP: Voice over Internet Protocol

WAN: Wide Area Network

WDM: Wavelength Division Multiplexing

WWDM: Wide Wavelength Division Multiplexing

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General introduction

Fiber-to-the-Home (FTTH) networks are considered the ultimate level of access bandwidth. Their deployment has gained significant momentum, with countries like South Korea, Japan, and several European nations leading the way in terms of penetration and coverage. Today, FTTH networks have become the gold standard for high-speed, reliable broadband access, providing the necessary infrastructure to support emerging technologies such as 5G, Internet of Things (IoT), cloud computing, and immersive multimedia experiences.

Fiber-to-the-Home (FTTH) technology has a rich history that spans several decades, characterized by significant milestones and technological advancements, it originated in the 1970s when researchers recognized the potential of fiber optic cables for high-speed data delivery to homes. In the 1980s, initial experiments and trials were conducted to test residential broadband connections using fiber optics. A turning point occurred in 1988 with the first commercial deployment of FTTH in the United States, connecting neighborhoods in Ithaca, New York.

Throughout the 1990s, foundational fiber optics technologies like FDDI and SONET laid the groundwork for FTTH networks. The introduction of the ATM protocol in the 1990s played a vital role in enabling high-speed data transmission over fiber optics. In the early 2000s, the emergence of GE-PON, capable of delivering data rates of up to 1 Gbps, marked a significant milestone. The ITU's development of GPON standards in 2003 accelerated FTTH deployment globally. The introduction of XG-PON in 2009 offered symmetrical data rates of 10 Gbps, addressing increasing bandwidth demands. EPON technology gained popularity, particularly in Asia, for its compatibility and support for higher split ratios.

The integration of WDM technology into PON architectures in the early 2010s led to the development of WDM-PONs, significantly increasing network capacity by transmitting multiple wavelengths over a single fiber. The release of NG-PON2 in 2015, using WDM technology and multiple wavelengths, achieved even higher data rates of up to 50 Gbps. TWDM and Hybrid-PON architectures further expanded the capabilities of FTTH networks.

The current focus revolves around next-generation NG-PON standards such as XG-PON, NG-PON2, and beyond, providing enhanced performance, flexibility, and support for future network upgrades. However, the exponential increase in bandwidth demand, especially during the COVID-19 pandemic, led to the standardization of 50-GPON in September 2021 and planned for even higher data rates to meet evolving needs.

The purpose of this work is to investigate the performance of various PON architectures for FTTH networks using OptiSystem software, a powerful tool used for simulation, designing and analyzing optical communication systems. In this study, we focus on five different PON architectures: BPON, GPON, XG-PON, XGS-PON, and Next-generation WDM-PON which differ in terms of their bandwidth capacity, coverage, and cost. This work is divided into the following chapters:

The first chapter aims to provide a detailed understanding of the fundamental concepts and principles of optical transmission, which are essential for the design and optimization of Passive Optical Network architectures. The chapter provides a comprehensive review of the state-of-the-art optical transmission technologies, it discusses the basic principles of optical communication systems, starting with the principles of light transmission, different types of fibers, and cabling, it also includes a description of the optical link transmission chain, encompassing components such as light sources, optical receivers, and complementary elements like optical amplifiers. Additionally, this chapter introduces attenuation and dispersion as limiting factors in optical networks that need to be overcome. and finally, concludes by presenting the advantages and disadvantages of optical fiber, along with some of its applications in various fields of technology.

In the second chapter, main wired access network technologies including xDSL and FTTx are thoroughly discussed focusing on different FTTx types, as well as the operation of passive optical networks (PONs) with their various components such as OLTs (Optical Line Terminations), ONUs (Optical Network Units), and splitters. as well as the development of their standards architectures along with their technical specifications and implementation requirements and the deployment of PON based FTTH.

The third chapter focuses on the planning and simulation of different PON architectures for FTTH network, it starts by presenting the software of OptiSystem, and it covers the simulation methodology, including the setup of the simulation environment and the performance metrics used to evaluate the five different architectures BPON, GPON, XG-PON, XGS-PON, and Next-generation WDM-PON. The simulation results focus mainly on performance evaluation of PONs at different parameters as fiber length, bite rate, and attenuation, by analizyng Q-factor, BER and Eye Diagram. these quality of service (QOS) metrics offer valuable insights into the performance of the different architectures, which can help telecommunication companies in selecting the most suitable architecture for their specific needs.

Chapter 1

Generalities of optical transmission

1.1. Introduction

Optical fiber communication is a method for carrying information at a distance in the form of light. Initially introduced in the mid-1970s, fiber optics played a pivotal role in revolutionizing the telecommunications industry. The tremendous surge in information traffic driven by the Internet, e-commerce, computer networks, multimedia, voice, data, and video necessitated a transmission medium capable of accommodating such vast volumes of data.

Optical fibers have become a critical component and a major building block in modern communication networks. Its remarkable attributes, including high bandwidth capacity and minimal signal loss, make it exceptionally suitable for ultra-fast gigabit transmission and beyond. This chapter covers fiber optic overview, including its composition, principle characteristics, and types. Then it describes the optical transmission system and its related problems and last a presentation of fiber optics advantages and main applications.

1.2. Definition and design of optical fiber

A type of communication medium that uses thin, flexible strands of glass or plastic to transmit light signals over long distances with minimal signal loss.

The fiber consists of a high-purity, low-loss core usually made of pure silicon dioxide (SiO2), which is surrounded by a cladding layer with a lower refractive index to ensure total internal reflection. The core and cladding are typically coated with a protective layer to prevent damage and maintain optical performance (as shown in fig 1.1) [1].

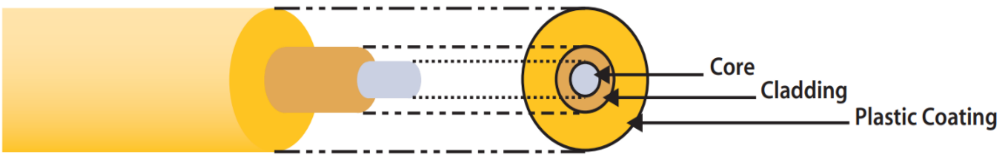


Fig 1.1 : The composition of optical fiber [1].

1.3. Transmission principles

When a ray of light enters a fiber at an angle α, the ability of the fiber cable to transmit light through its core is determined by a characteristic called the numerical aperture (NA). The numerical aperture can be calculated using the equation:

$$NA = \sin \alpha_0 = \sqrt{{n_1}^2 - {n_2}^2} \qquad \textbf{(Eq.1.1)}$$

Here, α_0 represents the maximum angle of acceptance, which defines the boundary between reflection and refraction. The refractive index of the core is denoted by n_1, while n_2 refers to the refractive index of the cladding [1].

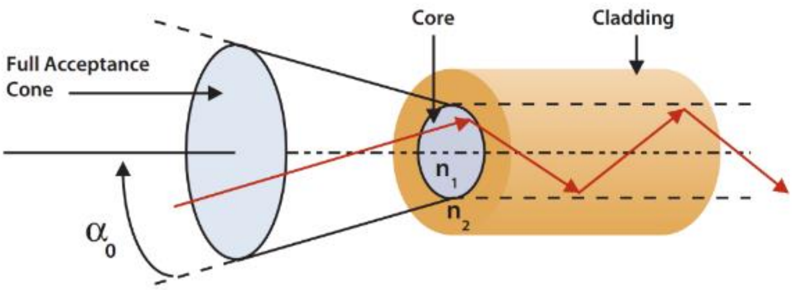


Fig.1.2: The injection of light into a fiber [1].

1.3.1. Light propagation

The transmission of a light ray within an optical fiber adheres to Snell-Descartes' law. When light is introduced into the fiber within the complete acceptance cone, a portion of it is guided through the optical fiber.

A. Refraction

Refraction is the bending of a ray of light at an interface between two areas one with refraction index n_1 and another with refractive index n_2 . If $\alpha > \alpha_0$, then the ray is fully refracted and is not captured by the core.

$$n_1 sin\,\alpha_i = n_2 sin\,\alpha_r \quad \textbf{(Eq.1.2)}$$

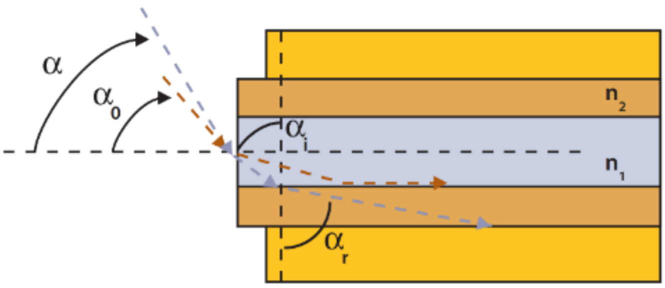


Fig.1.3: Refraction of light [1].

B. Reflection

Reflection occurs when a light ray undergoes a sudden change in direction at the boundary between two different transmitting materials. In this case, the light ray returns to the media from which it originated. If $\alpha < \alpha_0$, then the ray is reflected and remains in the core: $\alpha_i = \alpha_r$

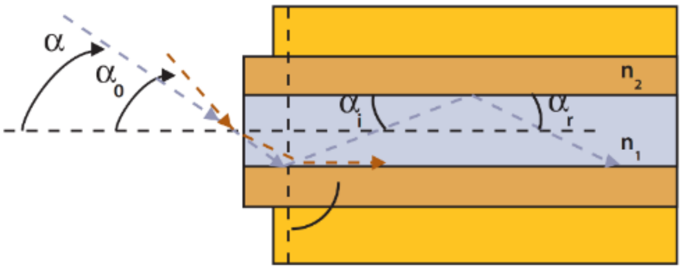


Fig.1.4: Reflection of light [1].

C. The propagation principle

When light rays enter an optical fiber, they can take various paths depending on the angle at which they enter. Rays that enter the center of the fiber core at a low angle follow a more direct path through the center of the fiber. In contrast, rays that enter at a high angle or near the outer edge of the core take a longer, less direct path and travel slower through the fiber. Each path corresponds to a mode, which is affected to some extent as it propagates along the fiber. This attenuation varies depending on the angle of incidence and the entry point [1].

1.3.2. Velocity

Light speed is determined by the refractive index (n) of the transmission medium, which represents the ratio of light velocity in a vacuum to its velocity in the medium [1].

$$n\ (Index\ of\ Refraction) = \frac{c\ (Speed\ of\ light\ in\ vacuum)}{v\ (Speed\ of\ light\ in\ a\ material)} \qquad \textbf{(Eq.1.3)}$$

- $\boldsymbol{n}$**:** is the refractive index of the transmission medium
- $\boldsymbol{c}$**:** is the speed of light in a vacuum (2.99792458 × 10^8 m/s)
- $\boldsymbol{v}$**:** is the speed of light in the transmission medium.

Typical values of *n* for glass, such as optical fiber, are between 1.45 and 1.55. As a rule, the higher the refractive index, the slower the speed in the transmission medium.

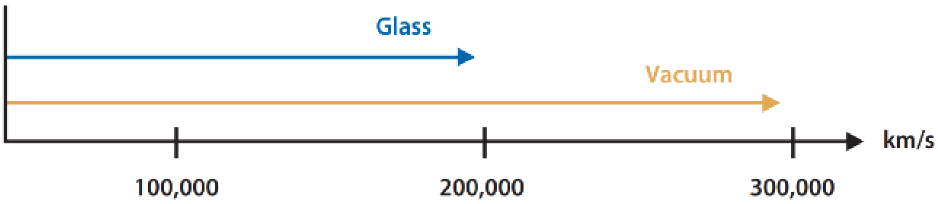


Fig.1.5: Comparing the speed of light through different transmission [1].

1.3.3. Bandwidth

Bandwidth refers to the frequency range width that an optical fiber can transmit. It plays a crucial role in determining the maximum capacity of information that can be carried over a specific distance through the fiber. Bandwidth is typically measured in MHz/Km units.

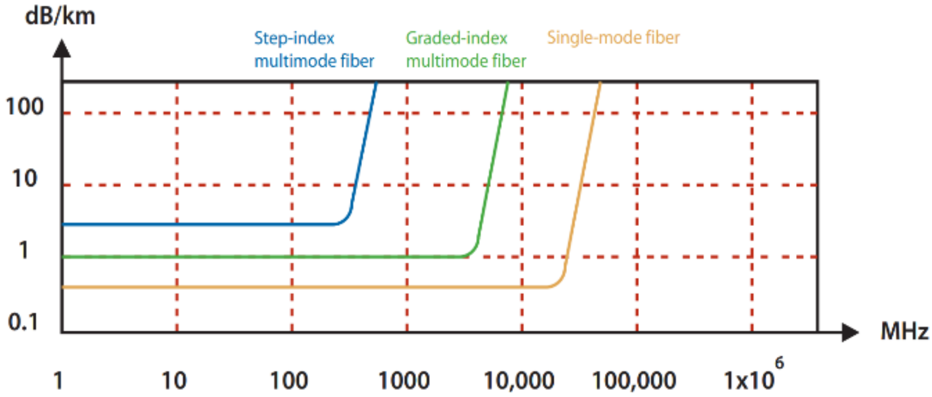


Fig.1.6: Typical bandwidths for different types of fiber [1].

In multimode fiber, bandwidth is mainly limited by modal dispersion, whereas almost no limitation exists for bandwidth in single-mode fiber [1] .

The attenuation is constant regardless of frequency. Only light dispersion limits the bandwidth width.

1.4. Types of fiber

The fiber type is closely related to the diameter of the core and cladding and how light travels through it, based on these variations the Fiber is classified as either single-mode or multimode

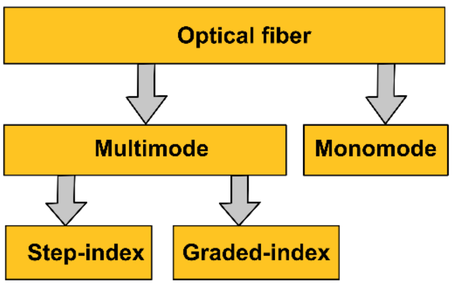


Fig.1.7: Types of fiber.

1.4.1. Single-mode optical fiber

Single-mode fibers have a small core diameter of 8-10 micrometers, they are designed to carry only one mode of light to propagate through them, which results in a lower dispersion of the signal. This high bandwidth and low attenuation, make single-mode fibers ideal for applications that require high-speed data transmission over long distances [2] [3].

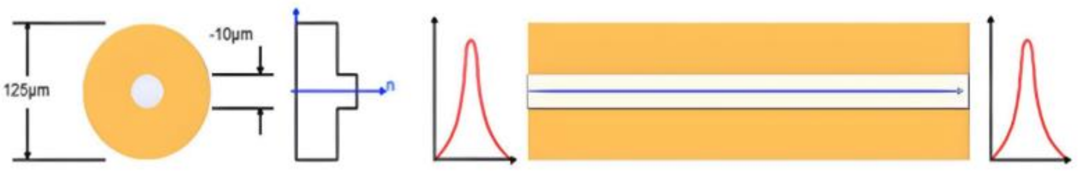


Fig.1.8: The composition of single-mode fiber [6]

1.4.2. Multimode optical fiber

Multi-mode fibers have a core diameter of around 50-62.5 micrometers and a cladding diameter of around 125 micrometers (as shown in fig 1.9). Allowing for the transmission of light using different paths simultaneously. This results in a higher dispersion of the signal as the different modes travel at slightly different speeds, causing the signal to spread out over time.

Multimode fiber optic cables offer a lower bandwidth and higher attenuation compared to single-mode fiber optic cables; they are better suited for shorter distances and lower-bandwidth applications such as local area networks (LANs) and data centers [4].

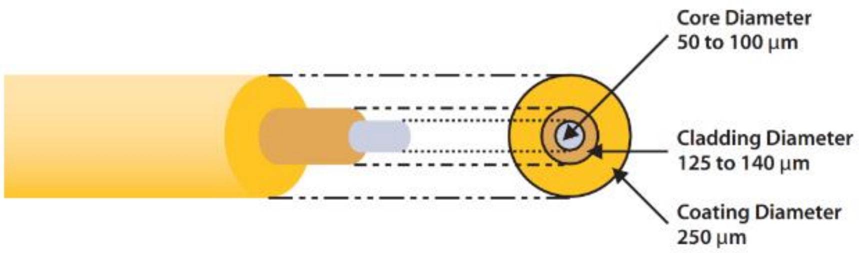


Fig.1.9: The composition of multimode fiber [1].

A. Step-Index multimode fiber

The refractive index of the core remains constant and undergoes an abrupt change (or step) at the cladding boundary, resulting in the light traveling in straight paths through the fiber.

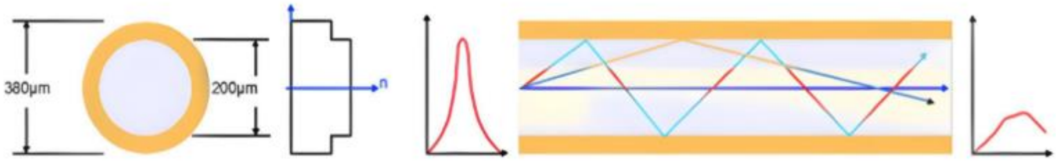


Fig.1.10: Light propagation through SI multimode fiber [6].

B. Graded-Index multimode fiber

The refractive index of the core is made to vary as a function of the radial distance from the center of the fiber, it gradually decreases from the central axis to the cladding. This index variation of the core forces the rays of light to progress through the fiber in a sinusoidal manner.

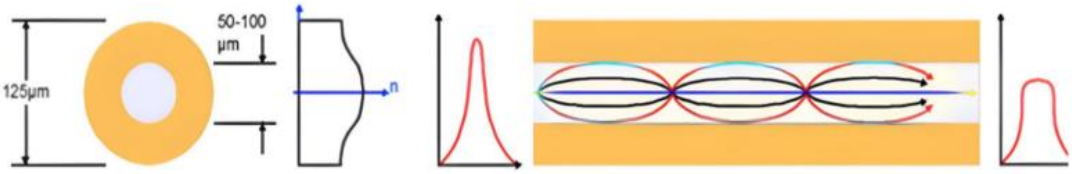


Fig.1.11: Light propagation through GI multimode fiber [6]

1.5. Optical fiber cabling

1.5.1. Design of fiber optic cables

To ensure that optical fibers can withstand the challenges of handling, transportation, and installation, they are commonly integrated into cable structures. There are two primary types of fiber optic cable designs: tight-buffered fiber cables and loose-tube cables(as shown in fig 1.12).

Tight-buffered fiber cables consist of multiple fibers surrounded by a closely fitting buffer coating. These cables are typically used in indoor settings where they are shielded from harsh weather conditions. On the other hand, loose-tube cables contain multiple fibers enclosed within a protective outer jacket, providing additional durability and safeguarding against moisture, temperature changes, and physical stress. Due to their resilience, loose-tube cables are commonly employed in outdoor applications such as long-distance telecommunications and industrial installations [4].

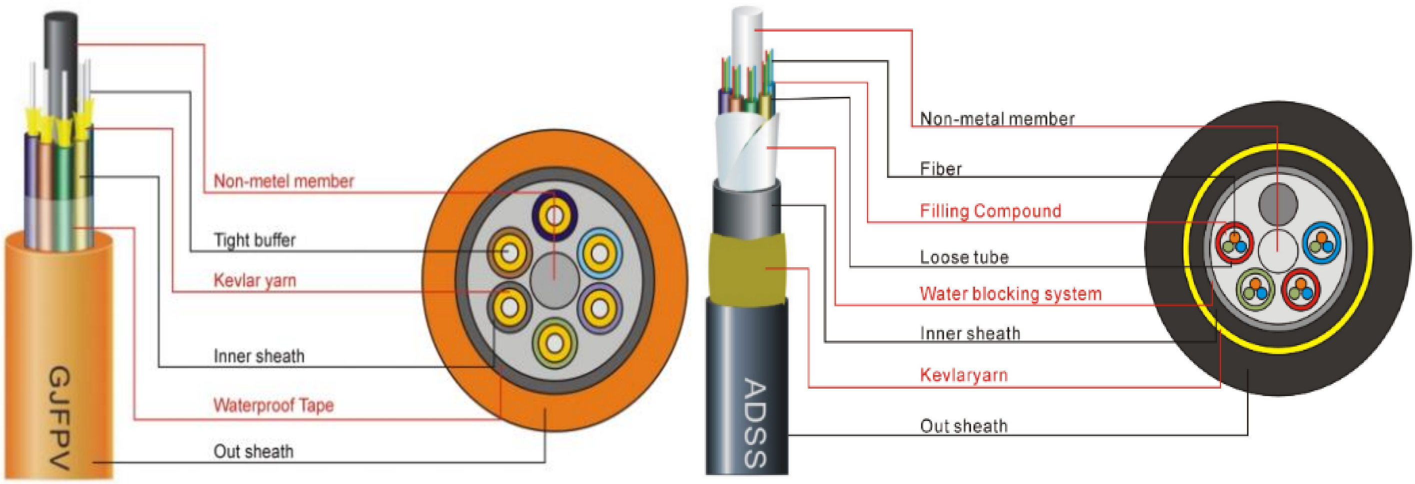


Fig.1.12: The tight-buffered fiber cable design and the loose-tube cable configuration [26] [27].

1.5.2 Fiber-Optic connection

Proper connection is a critical aspect of fiber optic network deployment, and the potential risks associated with improper connection techniques must be carefully considered.

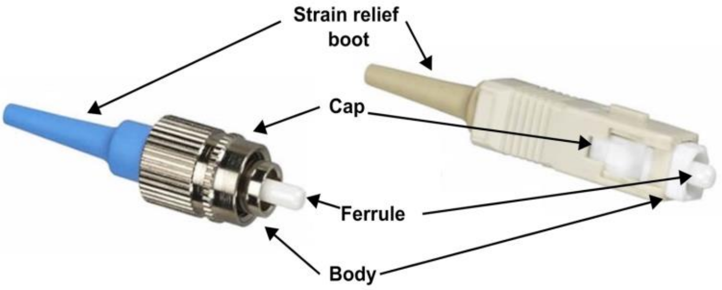


Fig.1.13: Connector components.

A. Connectors

A connector is a device that protects the end of the optical fiber while reliably joining it to equipment or other optical fibers. Connectors can be useful when network assignments must be changed, when equipment must be removed/replaced, or when expansion is anticipated.

Although there are several different types of connectors recognized by industry standards, they all contain common components, shown in Figure 1.13 [5]

Some of the most commonly used connectors are listed in the following table [5]:

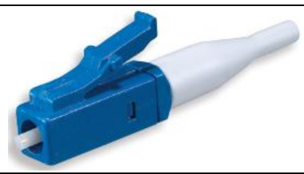
The SC (subscriber) connector: is among the most widely used connectors. It has a standard is squared shape and a snap-in connection with a 2.5mm sized ferrule	
The ST (straight tip) connector: round shaped with a 2.5mm ferrule and a metal connector cap that must be twisted to lock into place. It is considered a legacy connector, as it has been around for quite some time and can still be found in many installations today.	
The FC (face contact) connector: a rugged metal cylindrical connector with a screw-on connector cap and a 2.5mm ferrule. It is used in connections where proper polarization must be maintained.	
The LC (Lucent) connector: a square Push-in connector of 1.25mm ferrule that is considered to be a smaller version of the SC (half the size of it)	

Table 1.1: Characteristics of some commonly used connectors.

B. Splicing

Splicing is a permanent method used to join optical fibers, similar to connectors. It serves purposes such as cable repair, cable length extension, or connecting different cable types [5]. Two splicing techniques can be used:

- ❖ **Mechanical splicing**

By aligning two optical fibers and holding them in place with a splice sleeve.

The index-matching gel inside the mechanical splice reduces or eliminates Fresnel reflections

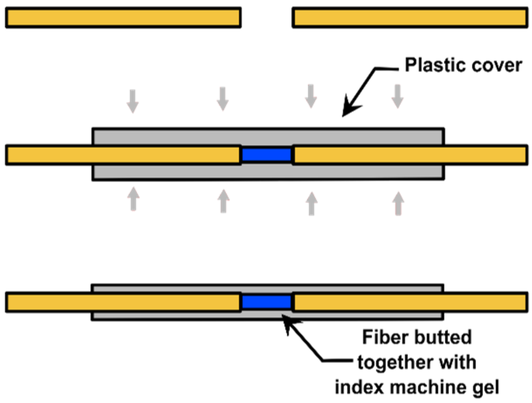


Fig.1.14: Mechanical splicer.

- ❖ **Fusion splicing**

Involves the use of a fusion splicer by melting the optical fiber end faces to one another with an electric arc between two electrodes. The fusion splice is then enclosed in heat-shrink tubing.

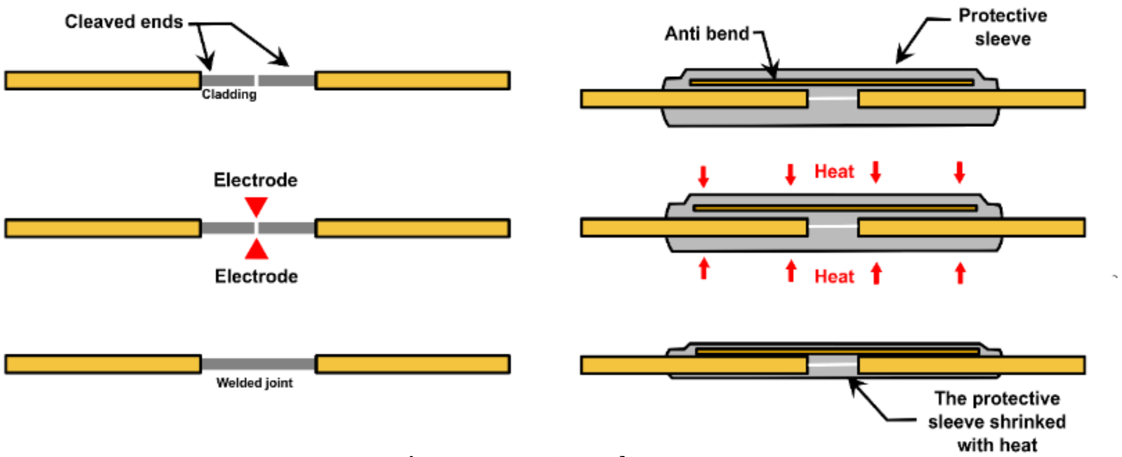


Fig.1.15: Fusion splicer.

Fusion splicers are more expensive than the assembly tool required for a mechanical splice. However, they provide the lowest-loss splice possible. In addition, fusion splices do not produce Fresnel reflections.

The choice of connection technique should be based on the specific requirements of the network, equipment, and infrastructure. To ensure the reliable transmission of data and the sustainability of the network [5].

1.6. Description of the optical fiber transmission chain

The principle in optical communications is to transport information in light from one point to another through a dielectric guide. The information to be transmitted is converted from an electrical signal to an optical signal by a transmitter, then injected into an optical fiber. At the reception, the signal will undergo the reverse treatment i.e., the optical-electrical conversion thanks to a receiver [6].

Overall, an optical link is composed of a transmitter and a receiver connected by an optical fiber.

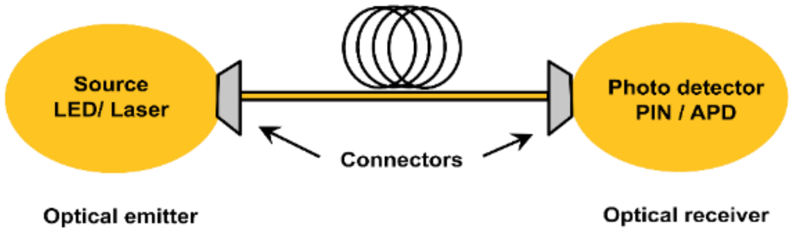


Fig.1.16: Synoptic diagram of an optical transmission system.

1.6.1. Optical transmitter

The transmission part of an optical link is made up of several elements, in particular the optical source, the modulator, and the pilot. Its objective is to provide the transmission medium with an optical signal carrying the data to be transmitted.

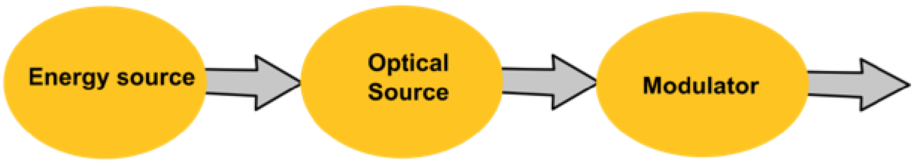


Fig.1.17: Structure of an optical transmitter.

1.6.2. Optical sources

They are active components used in optical fiber communications. Their main function is to convert electrical energy into optical energy, which is called electro-optical conversion. In optical telecommunications, the need to use increasingly wide bandwidths makes it necessary to use reduced spectrum sources such as DL laser diodes and LEDs. Both of these sources are made from directly polarized PN junctions, and their emission principle is due to the recombination of electron-hole pairs [6].

1.6.2.1. Light-Emitting diodes (LEDs)

LEDs serve as light emitters through the process of spontaneous emission. They emit incoherent light with a relatively wide spectrum, which is attributed to their compact size, extended lifespan, and cost-effectiveness. Typically, the light output of LEDs falls within the range of 30 – 60 nm, leading to suboptimal beam focus and incoherent radiation.

Consequently, this can impose limitations on the transmission distances achievable for data.

Fig.1.18: Light Emitting Diodes.

1.6.2.2. Laser diodes

Lasers emit light by amplifying radiation through stimulated emission, a process known as "Light Amplification by Stimulated Emission." Compared to LEDs, lasers typically have higher output power, with laser diodes capable of emitting light at around 100 mW. This makes lasers suitable for transmitting information over long distances. Additionally, lasers have a narrower spectral width and can carry a larger bandwidth, making them ideal light sources for long-haul fiber optic links [7].

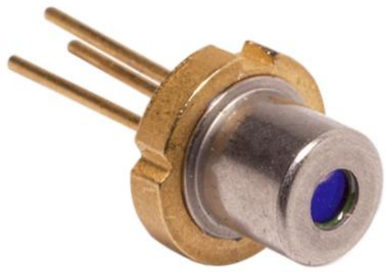


Fig.1.19: Laser diode.

1.6.3. Modulation

Lasers and LEDs used in telecommunication applications are modulated using one of two methods: direct modulation or external modulation. In order to transmit information in optical digital systems, it must be printed on the signal to be sent in the fiber, this is called modulation, which is an essential function of any transmission system.

1.6.3.1. Direct modulation

It is the modification of the current in the light emitting diode (LED) or in the laser diode (DL) that requires low power and a reduced voltage (2 to 3 volts). The modification of the current which passes by the laser leads directly to the modulation of the light emitted by this one, this method is called "direct modulation", it is the simplest and less expensive it causes a dynamic change of the diagram of radiation and the spectrum due to amplitude-frequency conversion.

In this modulation type, the output power of the device depends directly on the input drive current. This means light is emitted from the device when "1 (binary one)" is being transmitted and no light is emitted when "0 (binary zero) " is being transmitted [7].

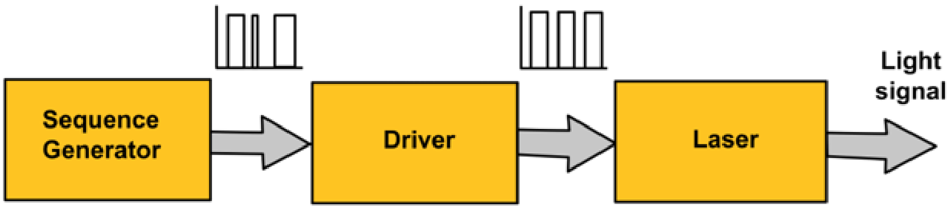


Fig.1.20: Laser diode used as optical direct modulation.

1.6.3.2. External modulation

In external modulation (see Figure 1.21), an external device is used to modulate the intensity or phase of the light source. While the light source remains active, the external modulator functions akin to a controllable "shutter," influenced by the information being transmitted. External modulation finds widespread usage in high-speed applications such as long-haul telecommunication or cable TV headends.

External modulation offers several advantages, including its ability to operate at faster speeds and its compatibility with higher-power laser sources. However, this approach comes with certain drawbacks, such as increased cost and the need for complex circuitry to handle high-frequency RF modulation signals [7].

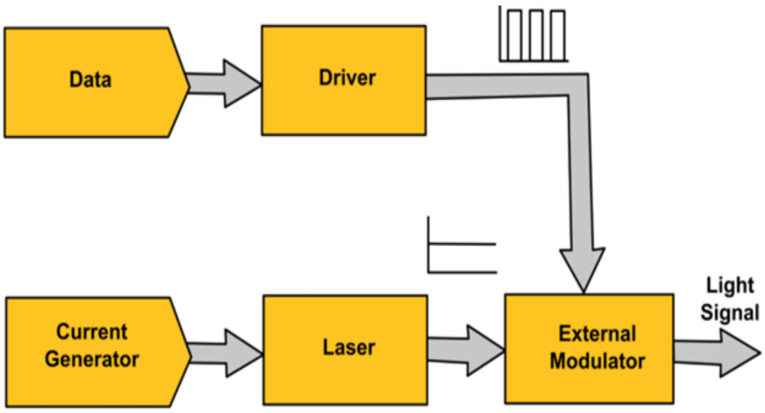


Fig.1.21: Laser diode used as optical external modulation

1.6.4. Optical receiver

The photodetector is an indispensable component in fiber optic communications. Its role is to translate the optical signal sent by the optical fiber into an electrical signal, which will be processed by electronic devices. The most used photodetectors in fiber optic transmission systems are the positive intrinsic negative (PIN) diode and the avalanche photodiode (APD).

1.6.4.1. Positive Intrinsic Negative (PIN)

To allow operation at longer wavelengths where the light penetrates more deeply into the semiconductor material, a wider depletion region is necessary.

To achieve this, the n-type material is doped so lightly that it can be considered intrinsic, and to make low resistance contact a highly doped n-type (n+) layer is added. This creates a PIN structure, as may be seen in figure.1.23 where all absorption takes place in the depletion region.PIN- type photo-detectors are naturally limited in sensitivity to a received power of the order of -30dBm [8]

Fig.1.22: PIN Photodiode.

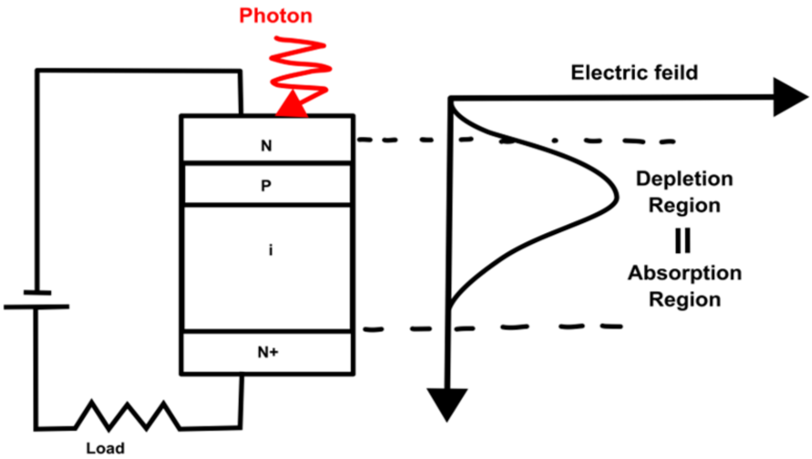


Fig.1.23: PIN photodiode showing combined absorption and depletion [8]

1.6.4.2. Avalanche Photodiode (APD)

The second major type of optical communications detector is the avalanche photodiode (APD). This has a more sophisticated structure than the PIN photodiode, the creation of an extremely high electric field region, as depicted in Figure 1.25, involves various aspects. Alongside the depletion region where photon absorption and primary carrier pairs are generated, there exists a high-field region where electrons and holes acquire sufficient energy to trigger the excitation of new electron-hole pairs. This phenomenon, known as impact ionization, is responsible for

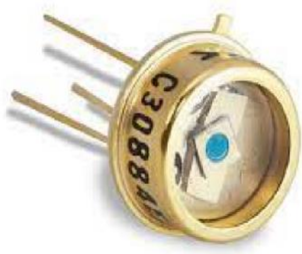


Fig.1.24 : Avalanche photodiode.

the avalanche breakdown observed in reverse biased-diodes. Typically, impact ionization requires the application of high reverse bias voltages, ranging from 50 to 400 volts [8].

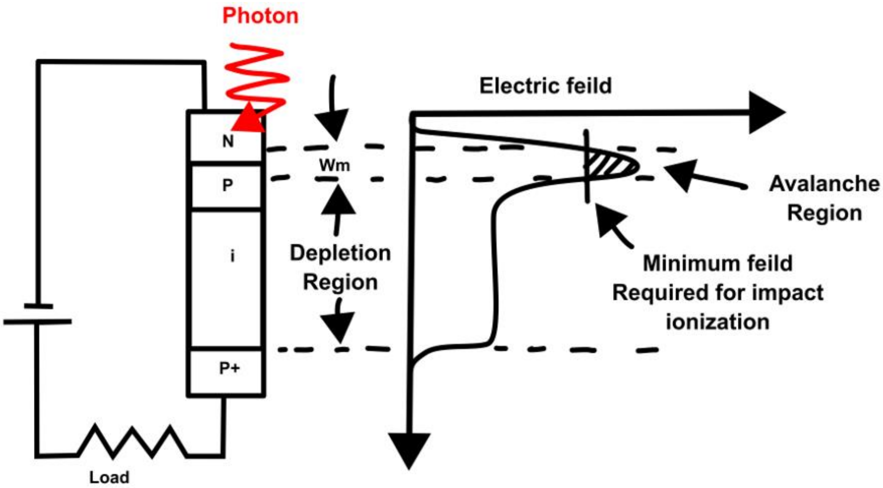


Fig.1.25: Avalanche photodiode showing high electric field region [8].

1.7. Problems of optical fiber transmission

As seen above, Light transmission in optical fiber uses three basic elements: a transmitter, a receiver, and a transmission medium that passes the signal from one to the other. The use of optical fiber introduces some factors that affect the performance of the system:

1.7.1. Attenuation

As the light signal propagates through the fiber, it decreases in power level. The decrease in power level is expressed in decibels (dB) or as a rate of loss per unit distance (dB/km) [1].

$$A[dB] = 10 \log \left(\frac{P_i}{P_o}\right) \qquad \textbf{(Eq.1.4)}$$

Where: Pi : Input Power, Po: Output Power, A is attenuation constant.

Attenuation is caused by various factors, and it can be divided into two main categories: intrinsic attenuation and extrinsic attenuation.

A. Intrinsic attenuations

Occur due to the inherent properties of the fiber and are caused by the absorption and scattering of light energy by the fiber material itself [9].

- **Attenuation by absorption**

The fiber material absorbs light, converting its energy to heat through molecular resonance and the presence of wavelength impurities. This absorption is most often expressed as attenuation, where the wave propagating in a fiber along the z-axis has an amplitude term in exp(-αz). If P_e is the power injected at the input of a fiber of length L.

$$P_l = P_e \; exp(-\alpha l) \qquad \textbf{(Eq.1.5)}$$

For example, hydrogen and hydroxide resonance occurs at approximately 1244 and 1383 nm.

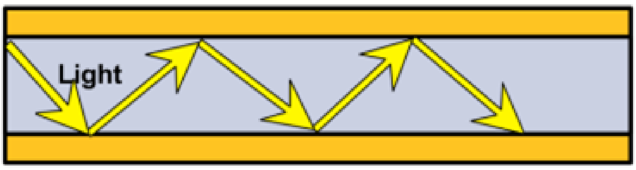


Fig.1.26: Light Absorption in optic fiber.

- **Attenuation by scattering**

One of the primary causes of dispersion in optical fibers is Rayleigh scattering, which leads to the scattering of light energy in various directions. As a result, some of the light escapes from the core of the fiber. A fraction of this light energy is reflected through the core, known as backscattering [1].

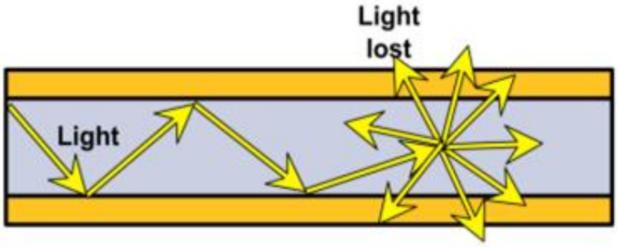


Fig.1.27: Rayleigh scattering.

Forward light scattering (Raman scattering) and backward light scattering (Brillouin scattering) are two additional scattering phenomena that can occur in optical materials under high power conditions [1].

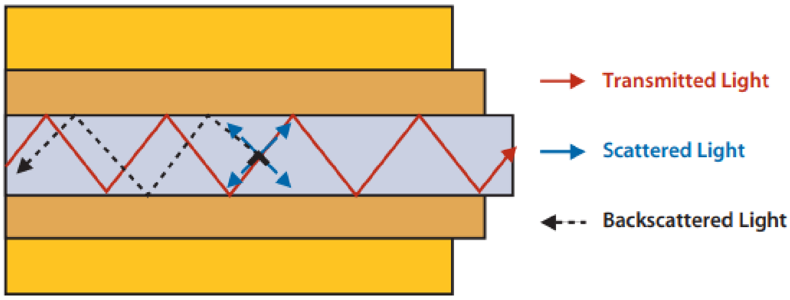


Fig.1.28: Backscattering effects of light transmission [1].

B. Extrinsic attenuation

It lies in the way the links are implemented as well as the connections between two ends of the fiber.

❖ **Attenuation due to micro-bending**

Micro bending refers to the occurrence when the fiber core deviates from its axis. This phenomenon can arise due to manufacturing defects, mechanical constraints encountered during the fiber laying process, and environmental variations (temperature, humidity, or pressure) during the fiber's lifetime. The trace "μc" refers to a fiber having micro bending [1]

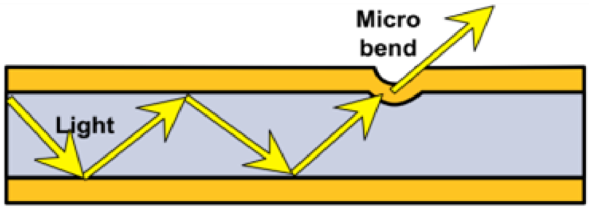


Fig.1.29: micro-bending

❖ **Attenuation due to macro-bending**

Macro bending refers to a large bend in the fiber (with more than a 2 mm radius).

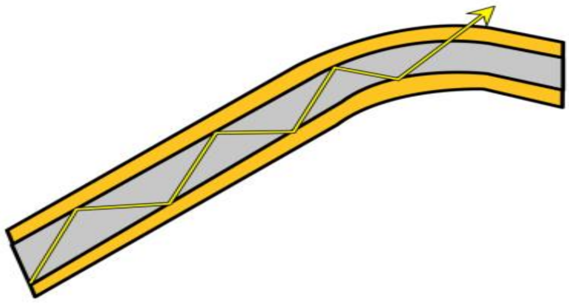


Fig.1.30: Macro-bending

The graph in fig 1.31 shows the influence of the bend radius (*R*) on signal loss as a function of the wavelength.

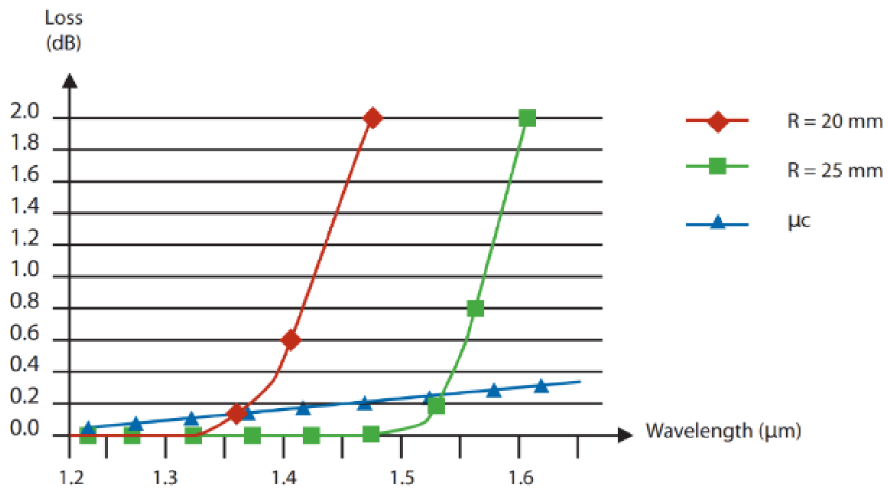


Fig.1.31: The effects of micro and macro bending on a fiber [1].

For example, the signal loss for a fiber that has a 25 mm macro bend radius will be 2 dB at 1625 nm, but only 0.4 dB at 1550 nm [1].

❖ Attenuation due to connections

The two ways of connecting optical fibers (splicing and connectors) also cause light transmission losses by multiple mechanisms, for example [9] [5] .

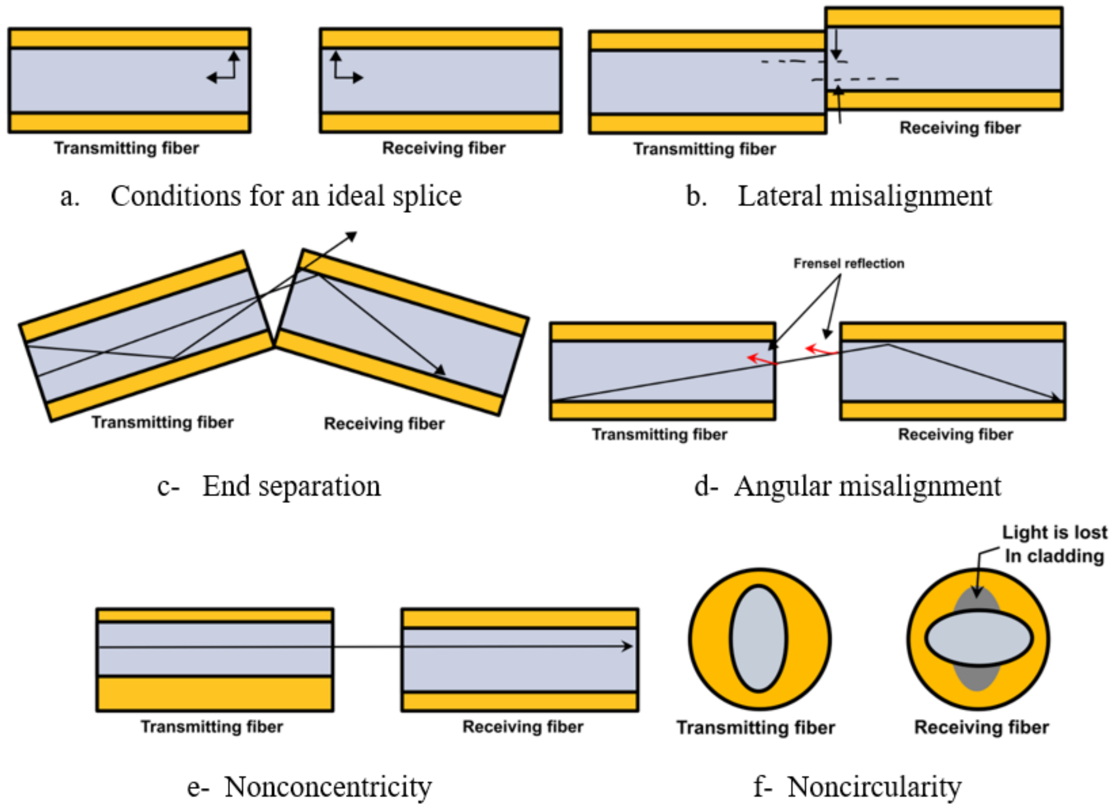


Fig.1.32: Fiber Optic Connection.

❖ Link loss mechanisms

For a fiber optic span, the effects of passive components and connection losses must be added to the inherent attenuation of the fiber to obtain the total signal attenuation. This attenuation (or loss), for a given wavelength, is defined as the ratio between the input power and the output power of [1].

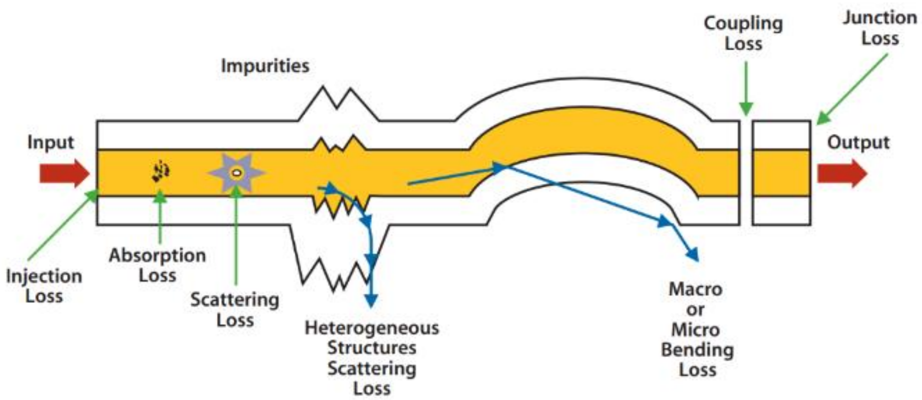


Fig.1.33: Light attenuation mechanisms in optical fiber

1.7.2. Dispersion

Another factor that affects the signal during transmission is dispersion, which is the spreading of the optical signal over time due to the different propagation velocities of different wavelengths of light. It reduces the effective bandwidth available for transmission [1].

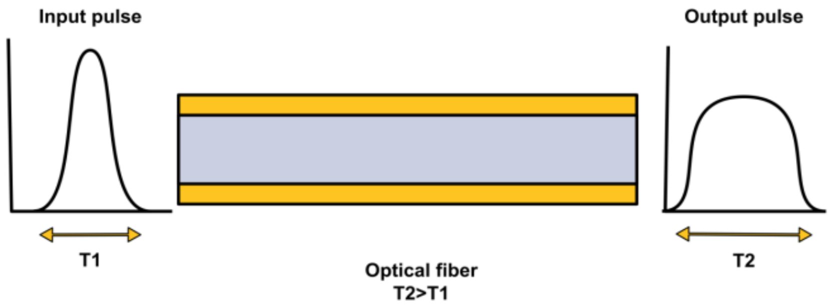


Fig.1.34: Fiber dispersion.

The scheme below shows the three main types of dispersion:

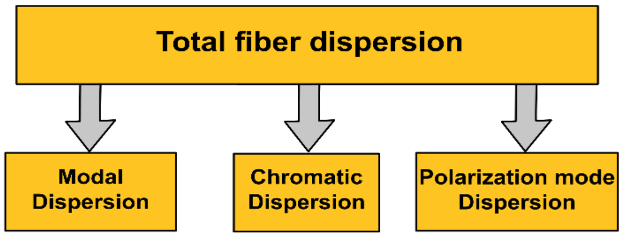


Fig.1.35: Types of fiber dispersion.

A. Modal dispersion

Modal dispersion is typically observed in multimode fiber. When a brief light pulse is introduced into the fiber within the numerical aperture, not all of the energy reaches the fiber's end simultaneously. The energy is carried by different oscillation modes, each following paths of varying lengths. As a consequence, transmission distances are reduced due to the disparities in arrival times [1].

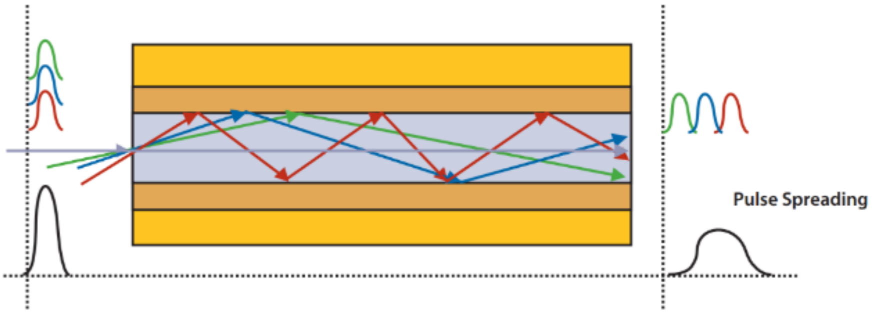


Fig.1.36: Modal dispersion in SI multimode fiber [1].

B. Chromatic dispersion

(CD) occurs because a light pulse is made up of different wavelengths, each traveling at different speeds down the fiber. These different propagation speeds broaden the light pulse when it arrives at the receiver, reducing the signal-to-noise ratio (SNR) and increasing bit errors [1].

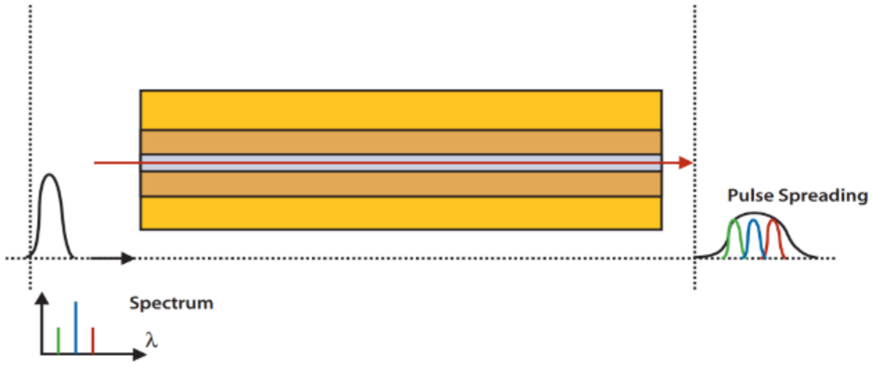


Fig.1.37: CD caused by different wavelengths in a light source [1].

C. Polarization Mode Dispersion (PMD)

Single-mode fiber possesses a fundamental characteristic that impacts the transmission rate's magnitude. This characteristic, known as polarization mode dispersion (PMD), arises due to variations in the propagation speeds of energy at a particular wavelength. The energy is split into two polarization axes that are perpendicular to each other, as depicted in the accompanying diagram.

The primary factors contributing to PMD are non-circularities in the fiber's design and external stresses exerted on the fiber, such as macro bending, micro bending, twisting, and temperature fluctuations [1].

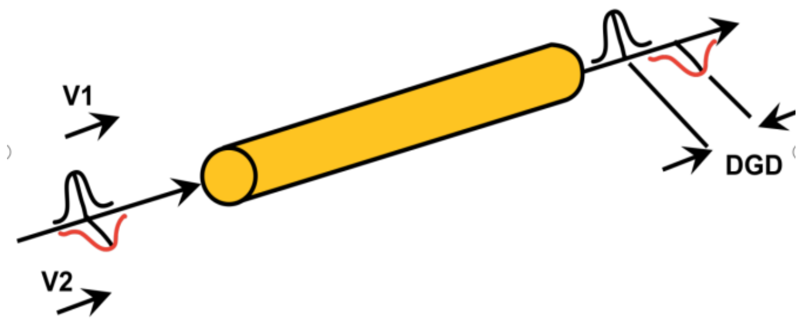


Fig.1.38: PMD (or differential group delay) effects on a fiber.

The PMD causes the transmission pulse to broaden when it is transmitted along the fiber. This phenomenon generates distortion, increasing the bit error rate (BER) of the optical system and leading to significant impairments in high-speed communication systems.

Overall, in an optical fiber transmitting system, attenuation causes an increase in the power requirements of the transmitter to compensate for the power needed by the receiver.

1.8. Optical fiber amplifiers

The transmission loss of the light passing through the optical fiber is a very small value of less than 0.2 dB per km with a light wavelength in the 1,550 nm band. However, when the optical fiber spans distances of 10 km or 100 km, the impact of this transmission loss becomes significant. In such cases, the weakening of the light signal over long distances necessitates the usage of optical amplifiers to amplify the light signal directly, without the need for converting it into an electrical signal. This makes optical amplifiers a vital component for maintaining the integrity and effectiveness of long-distance optical communication systems. The major types of optical amplifiers include EDFA, RA, and SOA [10].

1.8.1. Erbium-Doped Fiber Amplifiers EDFA

In all existing optical fiber projects, Erbium-Doped Fiber Amplifiers (EDFAs) are commonly employed, making it crucial to understand their characteristics. Several commercially available types can be considered, each with its key specifications [10]:

- The first type is designed with gain flattening for small signals (SSG) ranging from 16-32 dB. It offers a saturated output power (SOP) between 12-24 dBm, a noise figure (NF) of 4.5 dB, and a bandwidth (BW) of 35 nm.
- The second type is an In-Line amplifier featuring an SSG of 43 dB, an SOP of 14-20 dBm, an NF of 3.6 dB, and a BW of 37 nm.

Currently, repeater spacing in optical fiber projects is typically around 80-100 km for a transmission speed of 10 Gb/s.

1.8.2. Raman amplifier

Raman scattering is a phenomenon observed in silica glass, wherein the injection of an optical beam (referred to as the pump) into an optical fiber leads to signal amplification if the frequency of the signal aligns with the shifted frequency of the pump. This frequency shift, known as the Stokes shift, is approximately 13 GHz (equivalent to around 100 nm) from the frequency of the propagating pump beam, assuming a wavelength of 1450 nm. Consequently, a signal with a wavelength of 1550 nm would experience amplification.

Raman amplifiers leverage this phenomenon and are categorized into two main types: distributed and discrete (or lumped) amplifiers, similar to EDFA's. In distributed Raman amplifiers, amplification occurs throughout the entire fiber span between two stations. The pump can be placed near the transmitter (known as forward pumping) or near the receiver (known as backward pumping). The advantage of distributed Raman amplification lies in the fiber itself acting as the amplifier. Additionally, an exciting aspect of Raman amplifiers is the use of Dispersion Compensation Fiber (DCF) to counteract chromatic dispersion and loss this can be achieved by increasing the pump power [10].

1.8.3. Semiconductor optical amplifier

In-line optical amplifiers, optical burst, and packet systems, as well as all-optical regeneration and reshaping (2R), require the capability of accepting a wide range of input power and delivering constant output power. This necessitates the use of semiconductor optical amplifiers (SOAs). SOAs are suitable for this purpose due to their short carrier lifetimes, ranging from several tenths to several hundreds of picoseconds, in contrast to the several hundred microseconds to several milliseconds found in EDFA [10].

To regulate the output level of SOAs, an external light injection can be employed. Remarkably, it has been observed that even with a varying input signal level of 13.5-18.5 dB at wavelengths between 1530-1560 nm, modulated at a rate of 10 Gb/s, the output level of the SOA remains constant at +10 dBm. This method of output level control finds application in photonic networks [10]

1.9. Advantages and disadvantages of the optical fiber link

1.9.1. Advantages

Optical communications through glass or plastic fibers offer several advantages over conventional metallic transmission media, which are briefly described below:

- **Higher data rates**

Optical fiber transmission can provide higher data rates compared to traditional copper cables. This is due to the high bandwidth capacity of optical fiber, which allows for more data to be transmitted simultaneously. Optical fiber transmission can support data rates of up to terabits per second [2].

- **Lower latency**

Optical fiber transmission has lower latency compared to traditional copper cables. This is since optical fiber signals travel at the speed of light, which is faster than the speed of electrons in copper cables. This makes optical fiber transmission ideal for real-time applications such as video conferencing and online gaming. Optical fiber transmission can reduce latency by up to 50% compared to copper cables.

❖ **Longer transmission distance**

Optical fiber transmission can support longer transmission distances compared to traditional copper cables. This is due to the low attenuation of optical fiber, which enables the signal to travel further without significant signal degradation. Optical fiber can support transmission distances of up to several thousand kilometers [4].

❖ **Better signal quality**

Optical fiber transmission provides better signal quality compared to traditional copper cables. This is due to the fact that optical fiber is immune to electromagnetic interference and signal loss due to attenuation. Optical fiber transmission can provide a signal-to-noise ratio of up to 40 decibels, which is significantly higher than copper cables.

❖ **Greater reliability**

Optical fiber transmission provides greater reliability compared to traditional copper cables. This is because optical fiber is less vulnerable to physical damage and environmental factors such as temperature and moisture. "Optical Fiber Communications," optical fiber transmission has a higher mean time between failures compared to copper cables [3].

❖ **Security**

Optical fiber transmission provides greater security compared to traditional copper cables. This is because optical fibers do not radiate signals and are difficult to tap, making it harder for potential eavesdroppers to intercept communication. Optical fibers can also be used in conjunction with encryption techniques to provide an additional layer of security. Optical fiber transmission is considered to be one of the most secure methods of communication available.

1.9.2. Disadvantages

❖ **High installation cost**

Optical fiber transmission requires specialized equipment and skilled technicians, which can result in high installation costs. The cost of laying fiber optic cables is also higher than that of traditional copper cables, which can make it difficult for small businesses and startups to adopt the technology [2].

❖ **Vulnerability to physical damage**

Optical fiber cables are vulnerable to physical damage, which can result in the loss of signal or a complete failure of the system. The cables can be damaged by excavation, drilling, or other construction activities, which can result in expensive repairs and downtime [2].

- **Need for special equipment**

Optical fiber transmission requires special equipment, such as repeaters, amplifiers, and transceivers. This can result in higher maintenance costs and more complex systems, which can be difficult to manage for small businesses and startups [2].

1.10. Applications of optical fiber

Fiber optics is a versatile technology that has found applications in various fields including [2]:

1.10.1. Telecommunications

Fiber optics is the backbone of modern telecommunications networks, providing high-speed data transmission over long distances. In recent years, the demand for bandwidth has increased exponentially, with the rise of video streaming, cloud computing, and other data-intensive applications. Fiber optic technology has enabled the development of high-speed internet, making it possible to transfer data at speeds up to 100 Gbps over long distances. This technology has also been used for intercontinental communications, such as the undersea cables that connect continents.

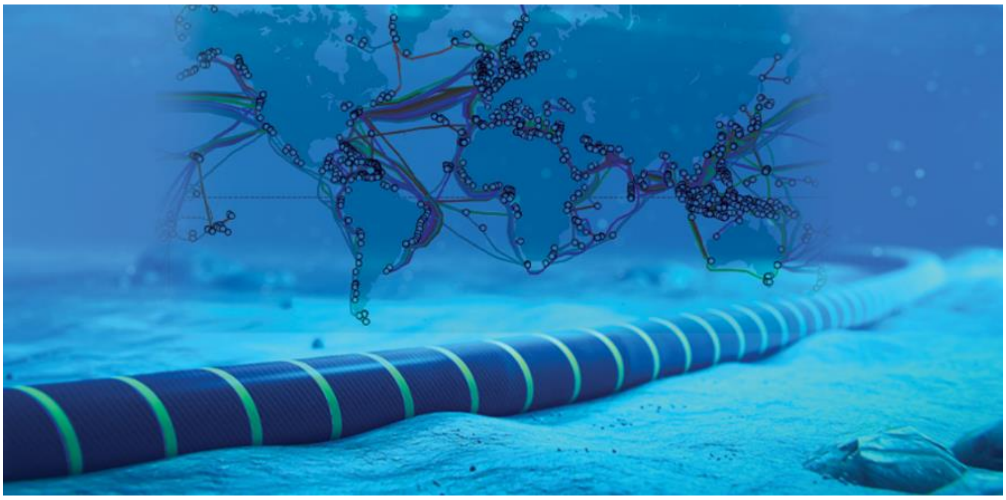


Fig.1.39: Under-sea cables that connect continents [28].

1.10.2. Healthcare

Fiber optics has made significant contributions to the field of medicine, particularly in diagnostic imaging. Fiber optic cables are used to create endoscopes, which allow doctors to view the inside of the body without invasive surgery. This technology has revolutionized the diagnosis and treatment of various medical conditions, from cancer to gastrointestinal disorders. Fiber optic sensors have also been used to monitor vital signs, such as blood pressure and oxygen saturation, in real-time.

Fig.1.40: Endoscopes [33]

1.10.3. Defense technologies

Fiber optics technology has been utilized by the defense industry for various applications. For instance, fiber optic sensors can be used for detecting seismic activity or monitoring the structural integrity of buildings and bridges. They can also be used for remote sensing, such as detecting chemical and biological agents, or for detecting and tracking enemy movements. In addition, fiber optic cables are used for secure communications, as they are more difficult to intercept than traditional copper cables.

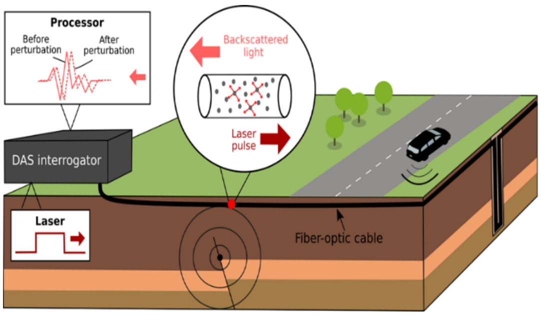


Fig.1.41. a: Fiber optic in seismic-arrays [29].

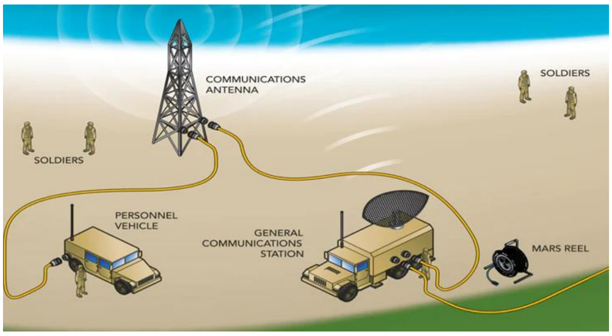


Fig.1.42. b: Military-fiber-optic [30].

1.11.4. Industrial applications

Fiber optics has found applications in various industrial sectors, such as manufacturing, transportation, and energy. For instance, fiber optic sensors can be used to monitor temperature, pressure, and other variables in industrial processes, improving efficiency and reducing downtime. In the transportation sector, fiber optics is used for signaling and control systems in railways and traffic lights. In the energy sector, fiber optic cables are used for monitoring and controlling the distribution of power.

Fig.1.43. a: RF over fiber [32].

Fig.1.44. b: optical fiber in robotics [31] .

1.11. Conclusion

Optical fiber is a dielectric waveguide that utilizes the principle of total internal reflection to propagate an optical signal over long distances with minimal signal loss. The fiber consists of a high-purity, low-loss core made of glass or plastic, which is surrounded by a cladding layer with a lower refractive index. Which provide the desired optical properties, such as high bandwidth, low attenuation, controlled dispersion, and immunity to electromagnetic interference. These properties made optical fibers widely used in telecommunications, data communications, and sensing applications.

In the next chapter, we will cover a detailed study of FTTH, or Fiber-to-the-Home, which is a type of broadband network architecture that uses fiber optic cables to deliver high-speed Internet and other communication services directly to individual residences or buildings.

Chapter 2

Study of the FTTH network

2.1. Introduction

The main driving force behind the development of new access technologies is the growing demand for high-speed internet, which has made telecommunication operators consider optical-fiber-based access networks as means of achieving true broadband. Legacy copper networks are being phased out in favor of optical fiber networks, as the latter can provide faster and more reliable connections. In this context, fiber to the home (FTTH) is emerging as the preferred choice for achieving long-term broadband objectives, as it allows for easy scalability in terms of bandwidth.

FTTH is specifically designed to accommodate data-intensive applications like video on demand, online gaming, HD TV, and VoIP (voice over internet protocol). Passive optical networks (PON) are a popular implementation of FTTH, as they use unpowered optical splitters to allow a single optical fiber to serve multiple premises in a point-to-multipoint network architecture.

In this chapter, we will thoroughly discuss the main wired access network technologies including XDSL and FTTx as we will focus on passive optical networks and the development of their standard architectures and the deployment of PON-based FTTH.

2.2. Main access network technologies

An access network encompasses connections that extend from a central communication switching facility (called the central office) to individual businesses, organizations, and homes. This network establishes the connection between subscribers and a specific service provider, allowing them to access various networks, including the Internet, through the carrier network. Initially, the access networks were constructed using copper infrastructure, commonly known as the Switched Telephone Network (PSTN).

Currently, other technologies like fiber optics allow a huge increase in access bandwidth [7].

Technologies for access network Wired:

- Digital Subscriber line XDSL.
- Optical Access Network FTTx.

Technologies for access network Wireless:

- Satellite Systems: For Direct broadcast by satellite (DBS) this technology uses satellite communication to provide internet connectivity, making it useful in remote areas where wired connections are not available.
- Cellular networks: This technology uses radio waves to provide mobile phone connectivity and data services, allowing for wireless communication and data transfer.

2.3. XDSL networks

DSL, short for Digital Subscriber Line, is a term used to describe a type of subscriber line that enables the transmission of data. The letter 'x' preceding DSL denotes the specific type of modem being used. XDSL technologies leverage the copper pairs within the public telephone network to offer high-speed data services. Ongoing efforts are focused on developing and defining various XDSL technologies to ensure they align with desired services and enhance achievable speeds.

The classification of XDSL technologies can be based on their transmission modes, which can be either symmetrical or asymmetrical. Symmetrical connections are established when the upstream and downstream links operate at the same speed, whereas asymmetrical connections involve a lower speed for the upstream link compared to the downstream link.

To establish an XDSL connection, a point-to-point link is created using a telephone line between the network termination (NT) at the user's location and the Line Termination (LT) installed at the service provider's end. Multiple XDSL technologies exist, each offering distinct features and intended applications [11].

2.3.1. HDSL (High Bit Rate DSL)

HDSL was among the initial DSL technologies introduced and finds primary usage in the infrastructure of telecommunications companies. This particular symmetric technology represents the most widely adopted form of XDSL technology. HDSL employs three twisted pairs of cables to facilitate data transmission, achieving a bidirectional speed of 2 Mbps [12].

For the transmission of data, HDSL requires two twisted pair lines, enabling data flow in both directions upstream (from the subscriber to the network) and downstream (from the network to the subscriber) at a rate of 1.544 Mbps. An alternative version of HDSL technology utilizes three twisted-pair copper lines, allowing for data transmission at a capacity of 2.048 Mbps [13].

Although HDSL ensures the continuous availability of the line, it does not concurrently support the simultaneous use of a telephone channel [11].

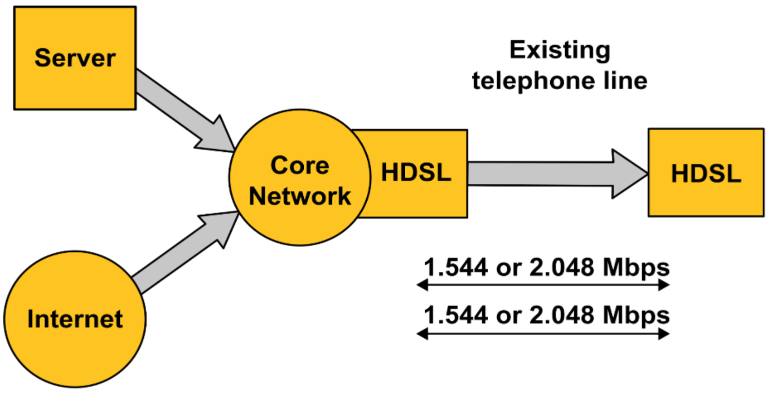


Fig 2.1: HDSL Architecture.

2.3.2. SDSL (Single Pair DSL)

In SDSL technology, digital data is transferred at the same speed as HDSL, requiring only one twisted-pair copper wire [13], this symmetric technology was developed to offer high-speed internet on a single twisted-pair cable.

SDSL served as the basis for the development of the HDSL2 standard, which offers the same benefits as the HDSL standard but on a single twisted pair cable. In the long term, SDSL may become obsolete in favor of HDSL [11].

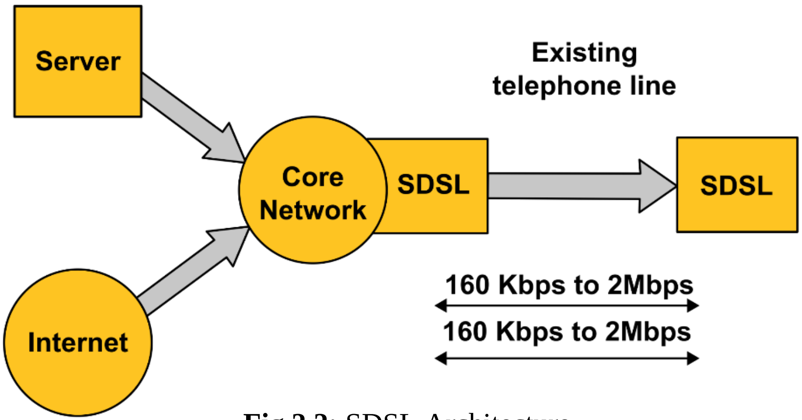


Fig 2.2: SDSL Architecture.

2.3.3. ADSL (Asymmetric DSL)

ADSL (Asymmetric Digital Subscriber Line) is the most common type of XDSL technology that is intended to complete the connection with the customer's premise. It transmits two separate data streams with much more bandwidth devoted to the downstream leg to the customer than returning. It is effective because symmetric signals in many pairs within a cable (as occurs in cables coming out of the central office) significantly limit the data rate and possible line length.

ADSL's success stems from its ability to leverage the fact that its target applications, including video-on-demand, home shopping, internet access, remote LAN access, multimedia, and PC services, can function well with a relatively low upstream data rate. For instance, MPEG movies require 1.5 or 3.0 Mbps downstream, but their upstream requirements range from 16 kbps to 640 kbps. Similarly, protocols governing internet or LAN access generally demand higher upstream rates, but they can typically operate with a 10 to 1 ratio of downstream to upstream bandwidth.

Applications that prioritize higher downstream data rates over upstream can benefit from ADSL technology. The asymmetric data stream reduces signal coupling and allows for higher data rates and longer distances to be achieved [13].

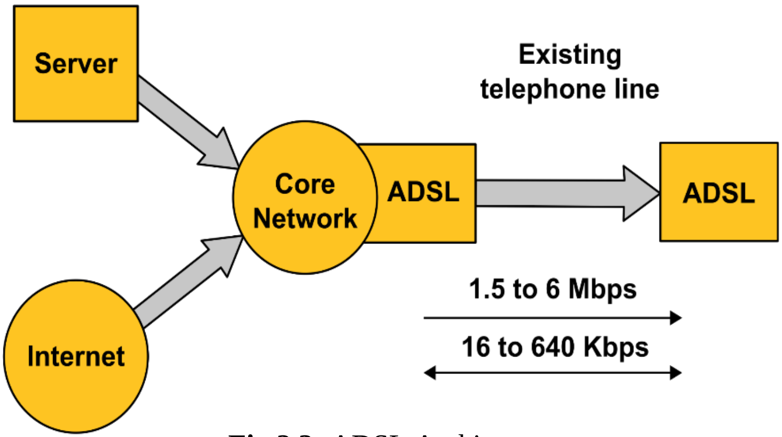


Fig 2.3: ADSL Architecture

2.3.4. RADSL (Rate Adaptive DSL)

Rate Adaptive DSL is a variant of ADSL, that also uses a single twisted pair [12]. Which is based on ADSL.

During the communication, the transmission rate is dynamically managed to provide the optimal speed on the connection line. RADSL has the potential to offer downstream speeds of 600 kbps to 7 Mbps and upstream speeds of 128 kbps to 1 Mbps for a maximum final segment of 5.4 km [11].

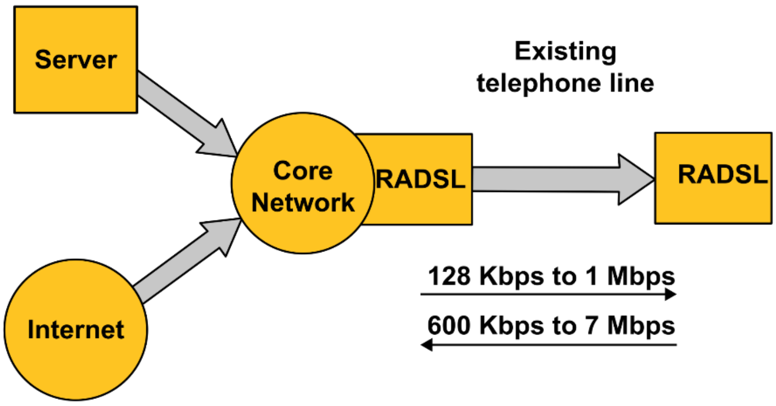


Fig 2.4: RADSL Architecture.

2.3.5. VDSL (Very high bit-rate DSL)

This "hybrid" technology can be used in both symmetrical and asymmetrical modes and may require the use of optical fibers for data transport. Originally intended for the transport of Asynchronous Transfer Mode (ATM), this technology is the most powerful since it can support upstream speeds of up to over 55 Mbps for a final section of 1 km [11].

VDSL is capable of providing both high-speed internet access and high-definition television (HDTV) over the same line, making it a popular choice for bundled services offered by telecommunications companies.

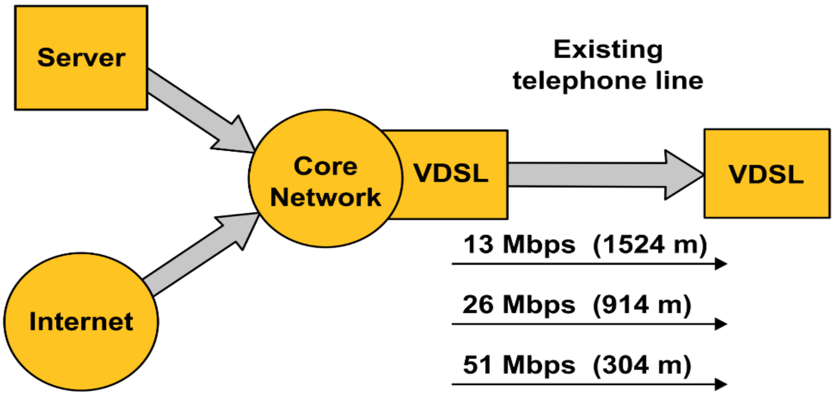


Fig 2.5: VDSL Architecture.

2.4. Optical fiber networks FTTx

The advancements in fiber optic networks have had a significant impact on a wide range of applications due to their high bandwidth and speed capabilities. This evolution has a profound impact on content providers and network operators as copper access networks around the world are largely replaced by fiber access networks.

This transition is driven by the increasing demand for bandwidth and immediacy of use, which the copper access network can no longer accommodate. The optical fiber's capacity to provide higher bandwidth over longer distances makes it a viable solution. To meet the demand for high-speed fiber connections, telecommunication companies have been deploying Fiber-To-The-x (FTTx) network technologies worldwide which provide fast fiber connections close to the end user's premises. The acronym FTTx was coined to encompass various configurations that have been implemented, with the letter 'x' representing the proximity of the fiber endpoint to the end user. These configurations include FTTN (fiber to the node), FTTC (fiber to the curb), FTTB (fiber to the building), and FTTH (fiber to the home), which are considered the most significant among them.

2.4.1. Fiber to the node (FTTN)

Fiber-to-the-neighborhood or node (FTTN) is a PON architecture that involves extending optical fiber cables to a distance of approximately 1 km from the homes and businesses served by the network. This setup enables the provision of broadband services, including high-speed Internet connectivity. To establish communication between the cabinet and the clients, high-speed protocols like broadband cable access or different forms of digital subscriber lines (DSL) are utilized. With FTTN, customers can experience speeds of around 20 to 25 Mbps, allowing them to access multiple services simultaneously, such as streaming four TV programs, watching an HDTV channel, and connecting to the Internet [14].

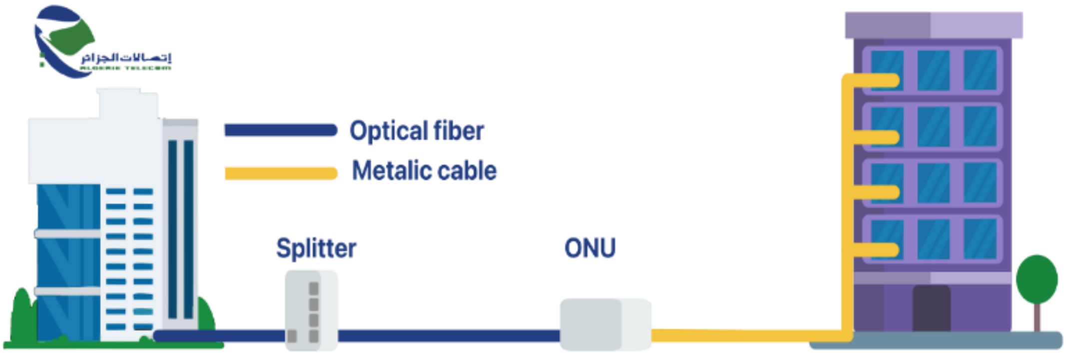


Fig 2.6: Fiber to the node.

2.4.2. Fiber to the curb (FTTC)

FTTc is a technology that involves the deployment of fiber optic cables from a central office to a communication switch that is located within a distance of approximately 300 meters from homes or businesses. The equipment near the curb or sidewalk uses various transmission media, such as coaxial cable, twisted-pair copper wires, or optical fiber lines, to connect to customers' premises.

FTTc broadband offers two variations, which deliver a downstream speed of either 80 Mbps or 40 Mbps. However, the actual speed of the service may be slightly lower than these figures, at around 78/39 Mbps. FTTc replaces traditional telephone services and eliminates the need for phone lines in neighborhoods [14].

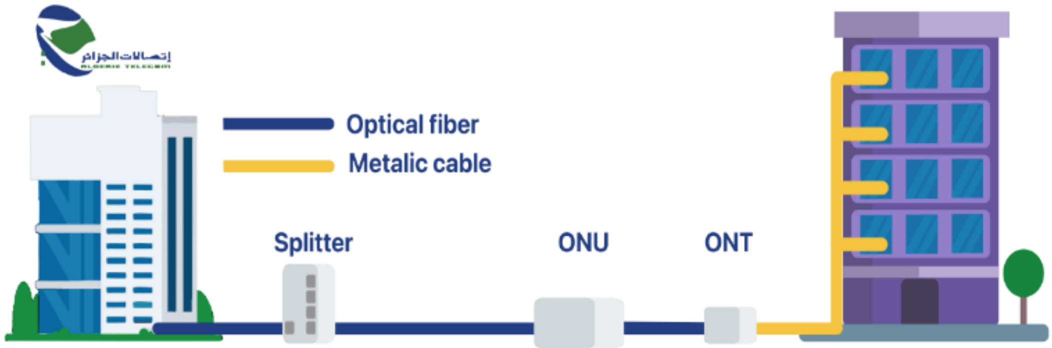


Fig 2.7: Fiber to the curb.

2.4.3. Fiber-to-the-building (FTTB)

Fiber-to-the-building (FTTB) technology is used primarily in densely populated areas that have multiple dwelling units (MDUs) such as apartment buildings, hotels, and condominiums. The fiber is brought into the building and is connected to the subscribers' premises using either VDSL2 technology over copper or gigabit ethernet over twisted pair CAT5 cables. This approach allows the installation of fiber to be done gradually, saving both time and money by making use of existing subscriber infrastructure [14].

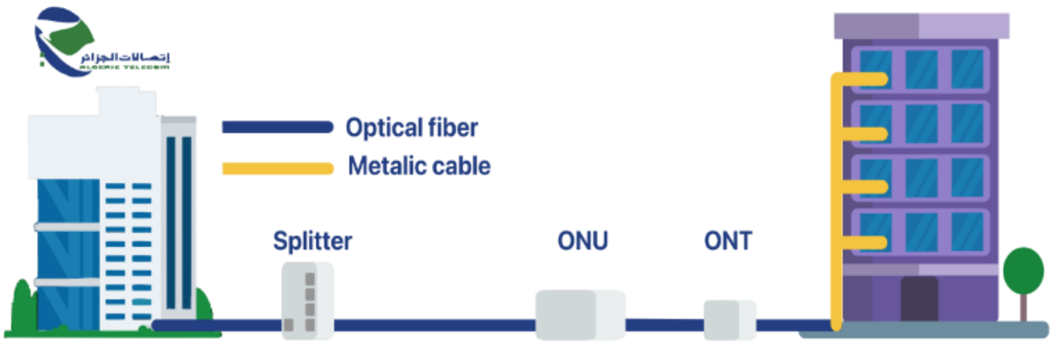


Fig 2.8: Fiber to the building.

2.4.4. Fiber to the Home (FTTH)

FTTh is based on the use of optical fiber cables and optical distribution systems adapted to this technology to distribute advanced services, such as triple play, telephony, broadband internet, and television, to households and business subscribers. The FTTh technology proposes the use of optical fiber in the user's home.

The difference between FTTB and FTTH is that typically businesses demand larger bandwidths over a greater part of the day than do home users.

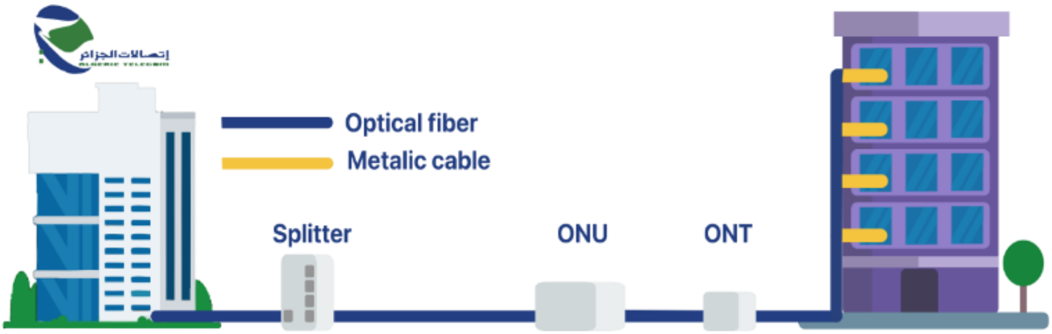


Fig 2.9: Fiber to the home.

The FTTH industry currently adopts two prominent architectures, namely the point-to-point (P2P) architecture and the point-to-multipoint (P2MP) architecture, further classified as active optical network (AON) and passive optical network (PON) [15].

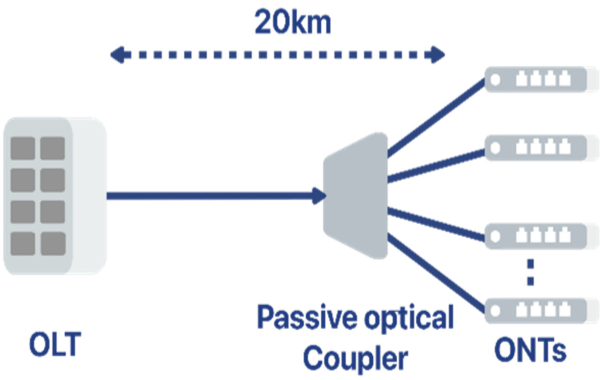


Fig 2.10: Passive optical network.

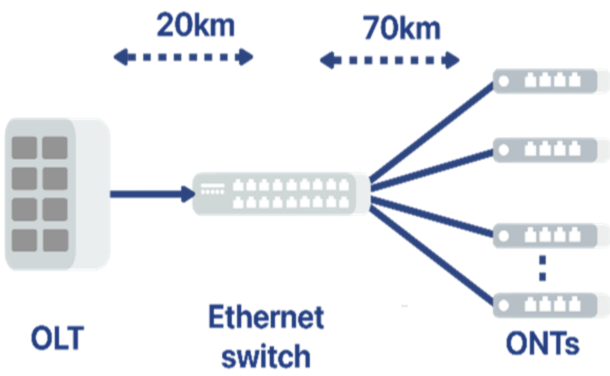


Fig 2.11: Active optical network.

The decision to adopt either a Point-to-Point (P2P) or Point-to-Multipoint (P2M) architecture for deployment depends on various factors such as the specific services to be provided, infrastructure costs, existing infrastructure, and plans for technology migration. While an Active Optical Network (AON) utilizes active devices and network elements to connect operators with end-users, a passive optical network operates differently, leveraging the inherent capabilities of optical fiber access to deliver a wide range of broadband services. In a PON, active components are eliminated between the server and the client, and replaced by optical passive components that facilitate traffic flow throughout the network. The core component of a PON is the optical splitter. The adoption of a passive architecture in FTTH networks can lead to cost reduction, but it should be noted that bandwidth is not dedicated but rather multiplexed in a single fiber at network access points. In essence, this configuration represents a point-to-multipoint network setup [16].

A comprehensive explanation of PONs, including their operational principles, network architecture, and deployment scenarios, will be discussed below, as PONs are critical to the success of an FTTH network.

2.5. Passive optical network (PON)

The International Telecommunications Union (ITU) and the Institute of Electrical and Electronic Engineers (IEEE) have played a significant role in the development of various PON architectures over the last 20 years [17].

A conventional PON architecture is presented in Figure 2.12

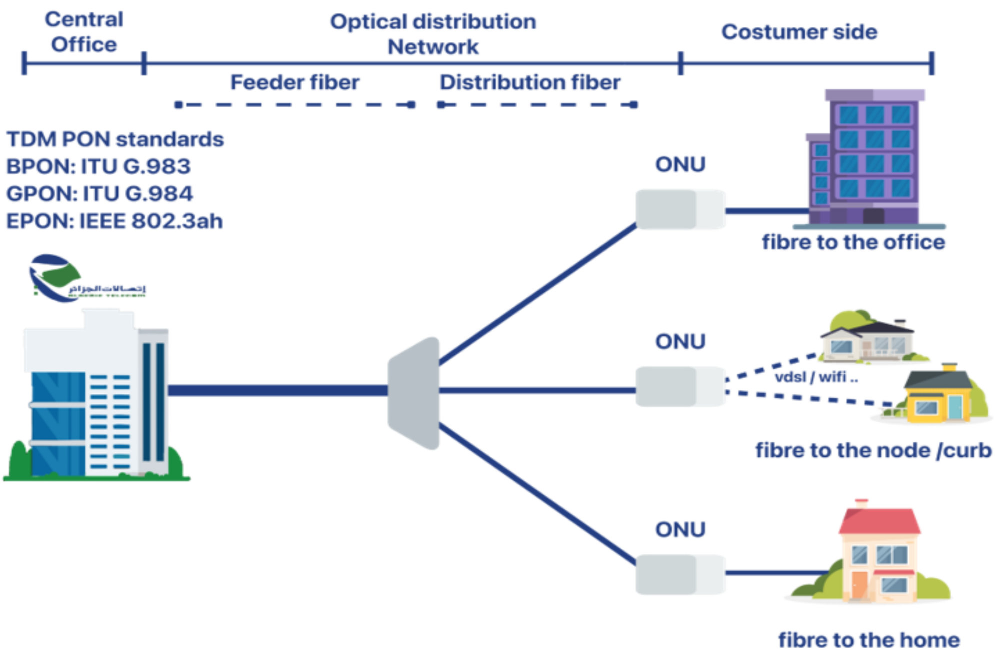


Fig 2.12: Passive optical network

PON architecture consists of three main units and the optical splitters that are connected to customer premises make PON a point-to-multi-point architecture (P2MP) [17]

An Optical Line Terminal (OLT) is located at the operator's central office and serves as the host for the active equipment, including laser TRx banks specific to the deployed standard.

A set of Optical Network Units (ONUs) that communicate with the OLT either directly with a separate wavelength or over a passive splitter. The number of ONUs deployed determines the splitting ratio and thus the power budget of the system [18]. The ONU could be located in a home, office, curbside cabinet, or elsewhere. Thus, comes the so-called fiber to the home/office/business/neighborhood/curb/user/premises/node. All of which are commonly referred to as fiber to the x [19].

A passive feeder network, also called Optical Distribution Network (ODN) is utilized to interconnect the OLT and ONUs. The ODN uses simple optical fiber and a power splitter and typically is in the form of a tree network architecture [18].

The topological structure of PON depends on the structure of ODN, which can be mainly divided into 4 topological structures [20]:

- **Star Topology:** which connects each ONU to the OLT via one or a pair of optical fibers, forming a passive network without splitters or active electronics. It has good confidentiality and simple maintenance but is expensive, requires many optical cables, and cannot share fibers or light sources.

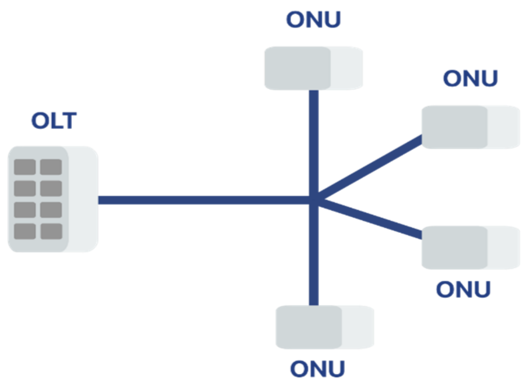


Fig 2.13: Star topology

- **Bus Topology:** that uses non-uniform light-splitting OBD arranged along a line, which separates OLT's signal and inserts signals from each ONU into the bus. It introduces small loss and is suitable for linear user environments, but requires
  a higher dynamic range of the ONU's optical receiver due to different signal strengths along the line.

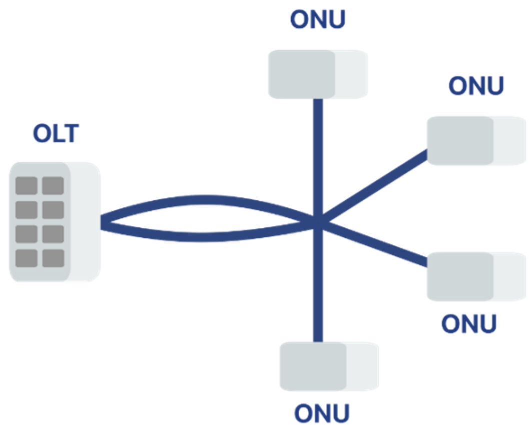


Fig 2.14: Bus topology

- **Ring Topology:** this is a closed-loop bus structure with a reliable self-healing ring network. It allows each OBD to pass signals to the OLT from two directions, improving reliability compared to the bus structure.

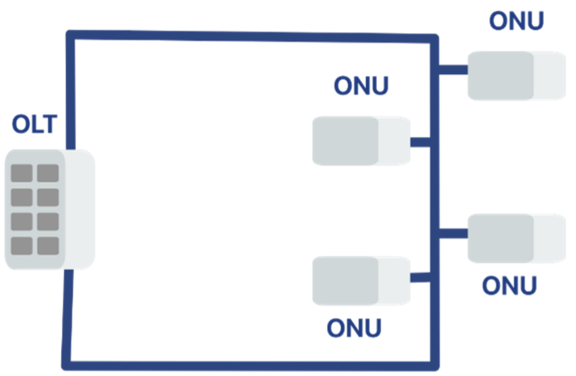


Fig 2.15: Ring topology

- **Tree Topology:** also called (multi-star topology) uses OBDs to divide light into n channels, expanding the PON's application range with high reliability and easy maintenance. However, the limited optical power from the OLT to all ONUs limits the number of connected ONUs and transmission distance. Two types of series OBDs are used: uniform and non-uniform optical splitting. Users can share some optical facilities.

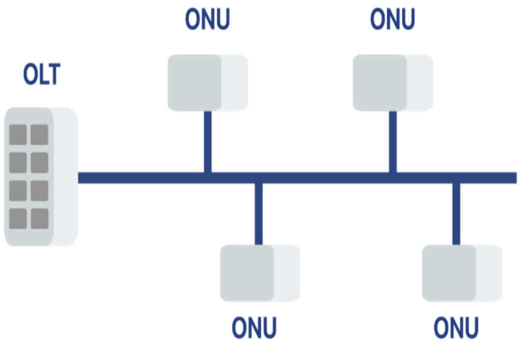


Fig 2.16: Tree topology

The choice of PON topology depends on factors such as user distribution topology, the distance between OLT and ONU, available technologies, optical power budget, upgrade requirements, reliability, and cable capacity [20].

PON technology has progressed through three generations: the initial generation (deployed PON), followed by next-generation stage 1 (NG-PON1), and next-generation stage 2 (NGPON2). The evolution of the PON architectures and their corresponding capacity features are discussed in the following pages [17].

2.5.1. APON

The first standard for a passive optical network (PON) based on asynchronous transfer mode (ATM) technology was approved by ITU in 1998 (ITU Recommendation G.983.1). The PON technology gained popularity for FTTH access networks by integrating ATM and PONs. The first APON specification had a maximum hierarchy ratio of 32 and a maximum bit rate of approximately 4.8 Mb/s for a single user. It was a symmetric variant, with a maximum capacity of 155 Mb/s, however, this variant was unsuitable for triple-play services.

In the second generation of APON, an asymmetric variant was introduced, providing a downstream transfer rate of 622 Mb/s and an upstream rate of 155 Mb/s. The maximum splitting ratio remained at 32, and the maximum bit rate for a single user in the downstream direction was approximately 19.4 Mb/s. In the third generation of the APON standard, a symmetrical variant was introduced, offering a transfer rate of 622 Mb/s. The maximum split ratio remained consistent with the previous generations. Multiple end-users were connected to a single ONU for economic reasons, and the typical reach of the APON system was about 10 km [17].

To limit power costs, the number of ONUs connected to the optical tree topology in APON was limited to 64. Static bandwidth allocation provided each of the 32 end-users with a transmission rate of 19.4 Mb/s in both directions. Dynamic bandwidth allocation (DBA) was introduced to allocate bandwidth based on actual needs, with three strategies specified in ITU Recommendation G.983.4 [17] : Report without status: traffic through the OLT unit is being monitored. When there is an increase in the occupancy of the associated queues, it is interpreted as a signal to expand the allocated bandwidth in response to the growing demand. The status report itself: the ONU reports its state to the OLT. If the ONU requires a higher bandwidth, it sends the request to the OLT. Hybrid report: involves a combination of the two previous types.

2.5.2. BPON

The Broadband PON (BPON) standard, defined in ITU Recommendation G.983.3, is the second standard for Passive Optical Networks (PONs). It introduced wavelength division multiplexing (WDM) technology in 2001, allowing multiple optical transmission paths to be used. BPON is backward compatible with the previous APON standard and offers the same transfer rates.

BPON brought several improvements, including expanded traffic classes with voice services and a division of downstream wavelengths into two bands. The first band is used for existing BPON protocols, while the second band is reserved for video service transmission. The ITU allocated a wavelength band of 1500-1550 nm for WDM, with 1550 nm specifically used for video signals. For wavelength multiplexing, 1310 nm is used for downstream transmission and 1490 nm for upstream transmission.

ITU-T G.983 also specifies the DBA, management interfaces, and network protection. BPON has been widely deployed for fiber-to-the-premises applications, but its maximum speed of 622 Mb/s is insufficient for high-definition digital signal transmission when divided among 32 end-users [17].

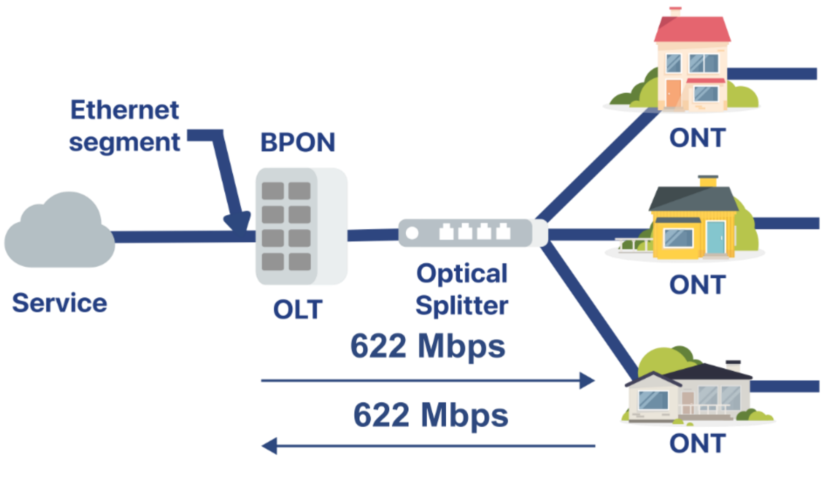


Fig 2.17: BPON architecture

2.5.3. EPON

ITU-T introduced BPON and GPON standards, but in parallel, the IEEE developed EPON as a PON standard based on Ethernet technology. EPON offered strong competition due to its lower acquisition costs compared to ATM switches and network components. The EPON physical media-dependent layer supports a maximum of 1.25 Gb/s downstream/upstream traffic. EPON encapsulates user data in Ethernet frames, making it a natural extension of local area networks and connecting them to Ethernet-based MAN/WAN infrastructure.

EPON equipment is less expensive than GPON, and its relaxed requirements on the physical media-dependent layer contribute to cost savings. EPON has gained widespread deployment, particularly in Asia (China, Korea, and Japan), where it has become the dominant PON technology, serving millions of users since 2005 [19].

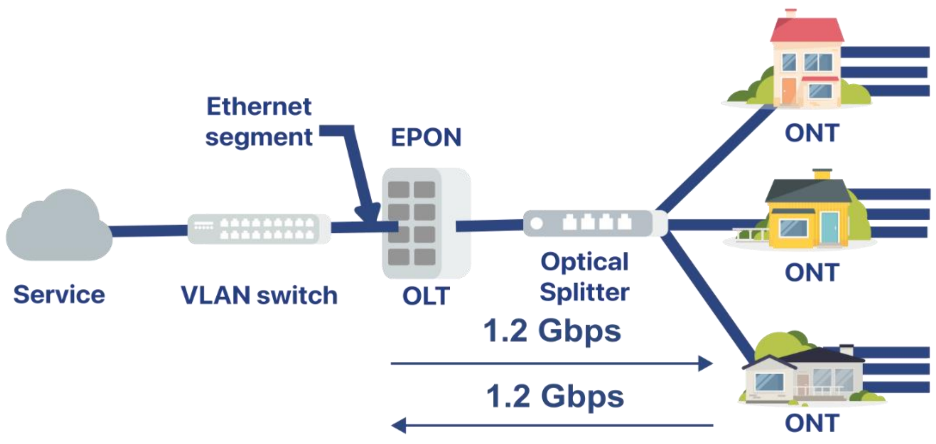


Fig 2.18: EPON architecture.

2.5.4 GPON

The demand for higher bandwidth in access networks led to the development of GPON, a high-capacity PON standard beyond APON and BPON. Defined in ITU Recommendation G.984 and approved in 2003, GPON uses GEM (a GPON encapsulation method) [19], through which it is possible to encapsulate frameworks of various transmission technologies (most often Ethernet frames), the frames are broadcast in the upstream direction and travel to all end units [17].

The TDM handles downstream communication, with each end unit exclusively receiving frames intended for it via unique identifiers within the frame. Consequently, only the designated unit processes the data. Downstream frames consist of a physical control block downstream (PCBd), which includes reserved sections for both ATM cell tracking and GEM If no data are requested for sending, the frames are forwarded in the downstream direction, In the upstream direction, TDMA techniques are used, with the OLT allocating varying time slots to ONUs. These slots synchronize the clustering of data transmitted in the upstream direction to the ONUs. GPON standard offers various transmission speed options, allowing for flexibility in both directions. In the downstream direction, speeds of 1244 or 2488 Mb/s can be used, while in the upstream direction, speeds of 155, 622, 1244, and 2488 Mb/s are supported. These speeds can be combined as needed. Among the available choices, the asymmetric variant with a downstream rate of 2488 Mb/s and an upstream rate of 1244 Mb/s is commonly used. With previous standards, speeds of 155 and 622 Mb/s are supported; thus, backward compatibility is maintained [17].

The wavelength ranges for GPON transmission are 1480-1500 nm for downstream and 1260-1360 nm upstream. An additional range of 1550-1560 nm is available for video signals. GPON networks have a splitting ratio of 1:64, with a planned ratio of 1:128 in the future. The logical reach is 60 km, while the physical reach is 10 or 20 km. GPON has gained significant deployment in North America, replacing older BPONs, and supports all telecommunication services [17].

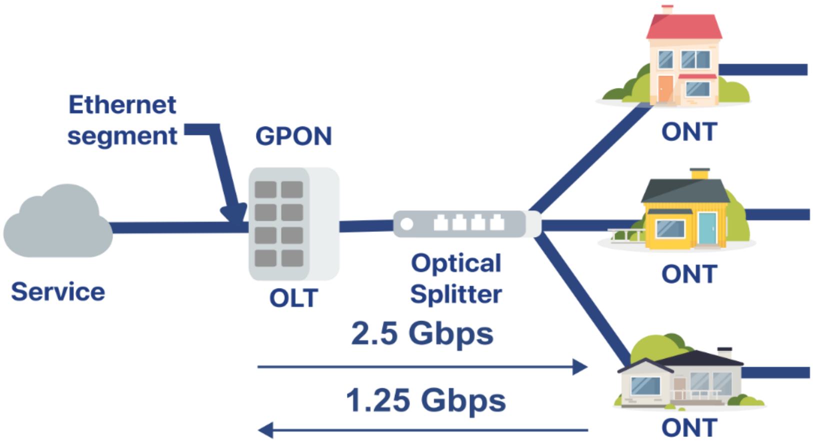


Fig 2.19: GPON architecture.

2.5.5. NGPON (Next-Generation PON)

During the development of the new generation of passive optical networks, which are known as the next-generation PON (NG-PON), this development was divided into two sub generations NG-PON1 and NG-PON2 depending on the possibility of joint operation with older PON standards on a common network infrastructure. The NG-PON study considered the development and deployment of a new standard from 2012 to 2015 (NG-PON1). Technologies that were not suitable for implementation during this period were included in the NG-PON2 study [17].

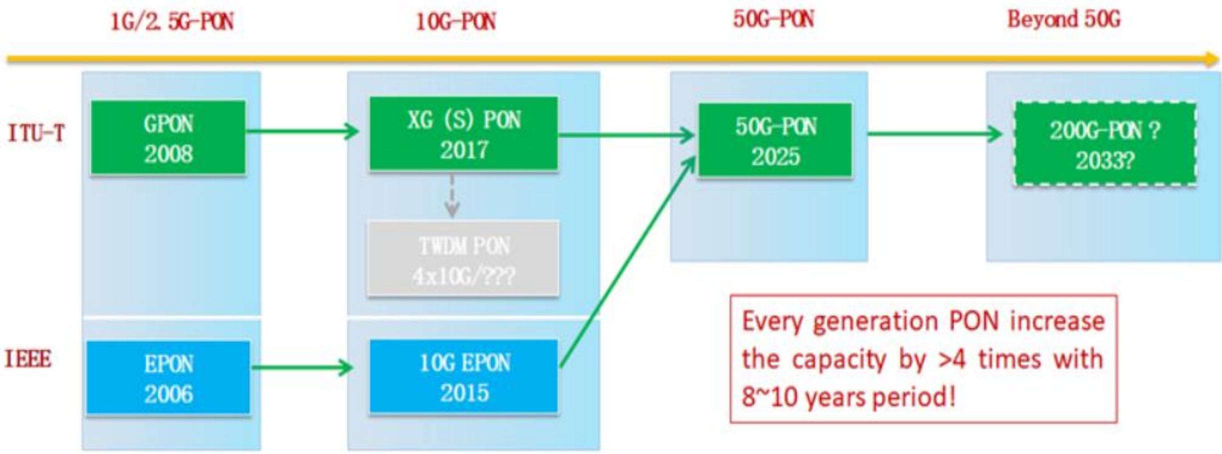


Fig 2.20: The evolution of PON technology [21].

Following the completion of the 10G PON standards, the International Telecommunication Union (ITU-T) initiated a study on PON technology surpassing 10Gb/s in 2016. After a comprehensive two-year feasibility study, an agreement was reached in 2018 to commence an ITU recommendation for a Higher Speed PON capable of operating at a 50Gb/s line rate. In September 2021, the ITU-T officially published the initial version of the 50G-PON standard, encompassing technical specifications that facilitate asymmetric rates (50G/12.5G, 50G/25G) and the coexistence of two PON generations (50G with 10G PON or GPON). Subsequently, in September 2022, the ITU-T approved the first amendment to the 50G-PON standard, incorporating technical specifications for symmetric 50G-PON (50Gb/s in both downstream and upstream) and supporting the coexistence of three PON generations (50G-PON, 10G-PON, and GPON on the same fiber network).

These two novel features unlock new service opportunities for operators and enhance the flexibility of their PON network upgrades [21].

2.5.5.1. XG-PON

The XG-PON standard (where X is a Roman numeral that indicates a transmission rate of 10 Gb/s) was defined in ITU- G.987 recommendations, this standard supports a downlink transfer rate of 10 Gbps and 2.5 Gbps in the upstream direction [17].

Two scenarios have been proposed to enable migration from GPON to XG-PON [22].

Green-field migration: involves the complete replacement of the existing copper connection with an optical connection to the premises. This means that the entire network infrastructure is built from scratch using optical technology.

Brown-field migration: is an upgrade of the existing GPON system. It involves replacing or upgrading specific network components, such as ONU units or OLT modules, as necessary. When considering an upgrade, it is important to take into account the coexistence of XG-PON1 with the already deployed GPON. Even though this approach decreases the overall cost, there is an additional cost associated with wavelength filtering that is required at the ONUs [22]. Figure 2.21 shows the coexistence scenario, where the CO consists of two OLTs, one to carry the GPON connection and the other to carry the XG-PON1 connection.

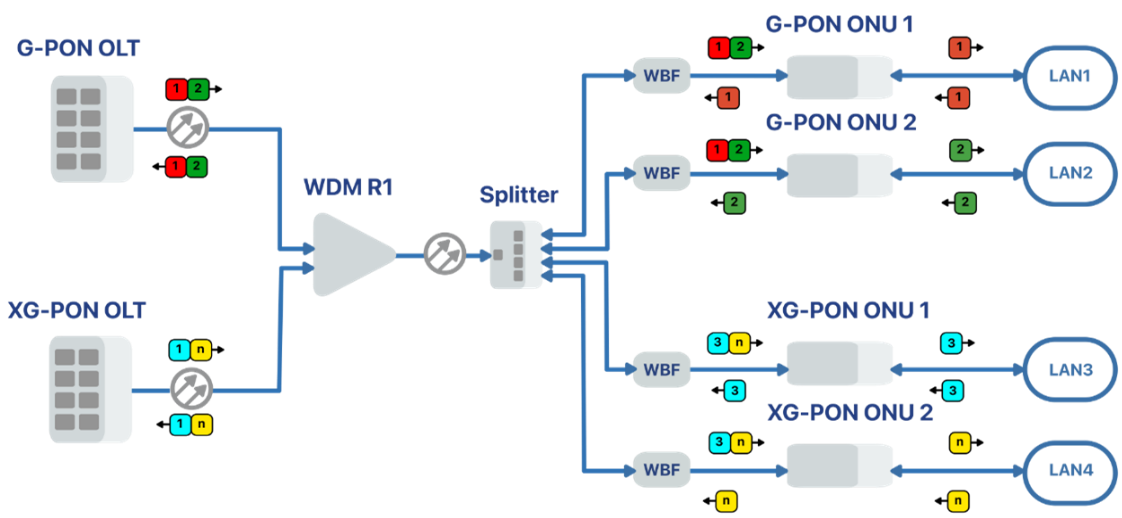


Fig 2.21: Coexistence of GPON and XG-PON1 [17] .

Existing GPON ONT units were equipped with wavelength-blocking filters utilized by XG-PON technology; specifically, the band range of 1575 to 1625 nm was reserved for the downstream direction. For the upstream direction of the XG-PON technology, a wavelength range of 1260 to 1280 nm was used. For this reason, the original range of the GPON for the upstream direction was limited to 1290 to 1330 nm [17].

New equipment named WDMr1 is installed at the CO. This WDM filter is used in Multiplexing/Demultiplexing split wavelengths of individual signals and connects the OLT units of both standards with the ODN [22]. On the user’s side, a Wavelength Blocking Filter (WBF) is required to block certain wavelengths and prevent undesirable interactions in the common functioning of two generational different standards [17].

The ratio of 1:64 is the minimum splitting ratio to ensure the coexistence of the GPON and XG-PON standards. The system supports a splitting ratio of 1:256 (with the extension planned) and has to support transmission in a distance range of 20 km up to 60 km [17].

2.5.5.2. XGS-PON

Based on the supported transfer rates another variant of XG-PON called XGS PON or XG-PON2 is defined as a 10 Gigabit Capable Symmetric Passive Optical Network. The design of XGS-PON takes into account the key requirements of NG-PON1, allowing it to coexist with the currently deployed G-PON system and use its Optical Distribution Network (ODN) that constitutes a significant portion (70%) of the overall investment in PON deployment, this approach maximizes the utilization of existing infrastructure.

The minimum specifications for XGS-PON include supporting a fiber distance of at least 20 km and a splitting ratio of 64. To achieve longer reach, higher capacity, larger bandwidth, and accommodate more users, the ITU-T has proposed the use of higher power transceivers and Reach Extenders (RE). Previous research has suggested the use of inline optical reach extenders that can operate within a hybrid PON system, offering a maximum distance of 30 km and a link loss budget of 31 dB. Another option explored is the deployment of an underground optical amplifier-based GPON reach extender, which demonstrated error-free operation over 28 dB of distribution loss. An alternative approach involves the usage of an Optical-Electrical-Optical (O-E-O) device as an inline RE, located 80 km from the Optical Line Terminal (OLT), supporting a 128-splitting ratio with a 59 dB link loss budget [23].

However, challenges arise due to the lack of electrical power sources in the current ODN, and the implementation of inline RE introduces complexity and cost. Distributed Raman amplification has been proposed as a solution to overcome these challenges [19]. However, it is not optimal for 1270 nm transmission, and its wide amplification spectrum may interfere with other PON systems, making coexistence impractical [23].

Considering these requirements and limitations, the symmetrical variant of XGS-PON becomes more expensive, and market demand for this solution has not shown significant traction. As a result, the development of the symmetrical variant has been temporarily suspended. Nonetheless, XGS-PON continues to serve other network service needs.

2.5.5.3. WDM-PON

Another PON variant is the Wavelength Division Multiplexing PON or WDM-PON. In this architecture, ONUs do not share wavelength capacity but each

ONU possesses its wavelength, directly routing its traffic to the OLT (as Figure 2.22 illustrates) [18] .

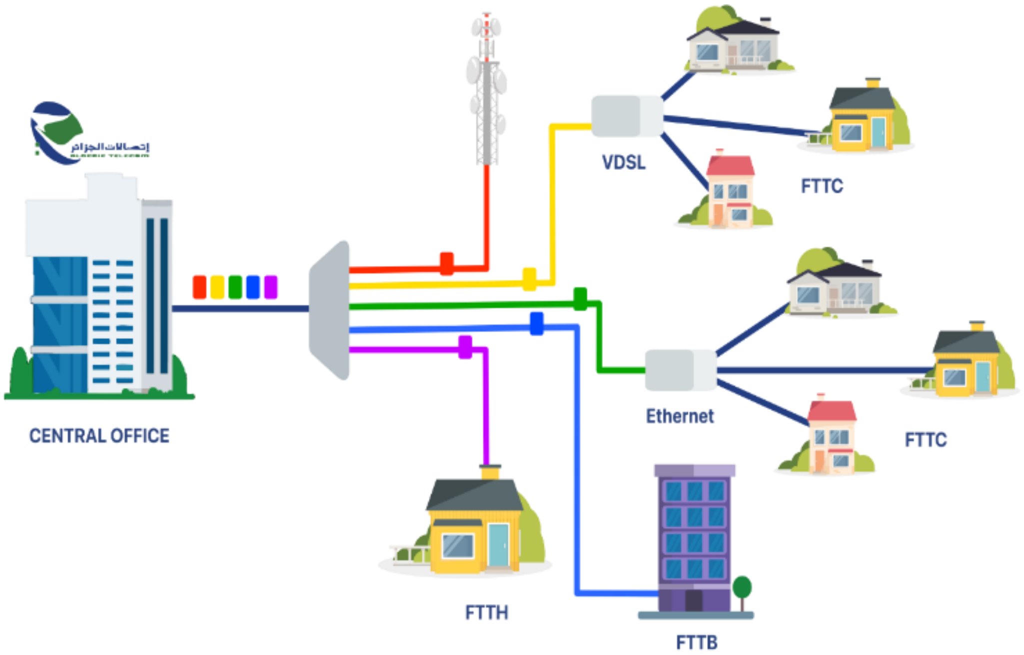


Fig 2.22: Wavelength-Division-Multiplexed Passive

The different wavelengths may coexist on the same fiber or maybe router over different ones. WDM-PONs offer higher-speed, scalability, and the ability to support a large number of ONUs by utilizing wavelength division multiplexing (WDM) technology. WDM-PONs can be implemented as wavelength-routed or wavelength-switched architectures.

In wavelength-routed WDM-PONs, an Array Wavelength Gratings (AWG) device is used in the optical distribution network (ODN), allowing each ONU to transmit on a specific wavelength assigned by the AWG port. This architecture reduces power loss, offers lower insertion loss, and supports higher data rates. However, the OLT requires a standard receiver and wavelength de-multiplexing device [22].

In wavelength-switched WDM-PONs, a power splitter is used to distribute signals equally to all ONUs. Each ONU is equipped with a wavelength filter to select a specific wavelength. While this architecture has a simpler structure, it incurs higher signal loss compared to wavelength-routed PONs. WDM-PONs are classified based on the number of supported wavelengths and the spacing between individual wavelengths transmitted over a single fiber.

DWDM and CWDM are two classes of WDM-PON with defined wavelength plans (ITU-T G.694.1 and G.694.2). DWDM aims to increase network capacity by minimizing wavelength spacing, while CWDM focuses on cost reduction with wider spacing for precise transmitter control. The proposed approaches for WDM-PON implementation include:

- Externally seeded WDM-PON: Spectrally splitting light source to reflective ONUs.
- Wavelength reuse WDM-PON: Assigning specific wavelengths to each user for downstream and upstream transmission.
- Tunable WDM-PON: Using low-cost tunable transmitter modules and tunable receivers.
- Ultra-dense Coherent WDM-PON: Utilizing coherent detection with tightly spaced channels and expensive systems.
- Self-seeded WDM-PON: Generating seed light at the common port of the wavelength splitter.

WDM-PON offers benefits such as capacity upgrades, improved security, and individual user upgrades without impacting others. However, limitations and high implementation costs make it unsuitable for NG-PON2, including restricted wavelengths and inefficient bandwidth utilization. NG-PON2 requires more cost-effective solutions without the need for additional equipment like colored ONUs and transceivers for each wavelength at the OLT [24].

NG-PON was designed to provide high transmission capacity for various services, including mobile networks. P2P WDM allocated specific wavelength bands for mobile networks, while TWDM designated wavelength ranges for other network services [22].

The next figure illustrates an example of the network infrastructure:

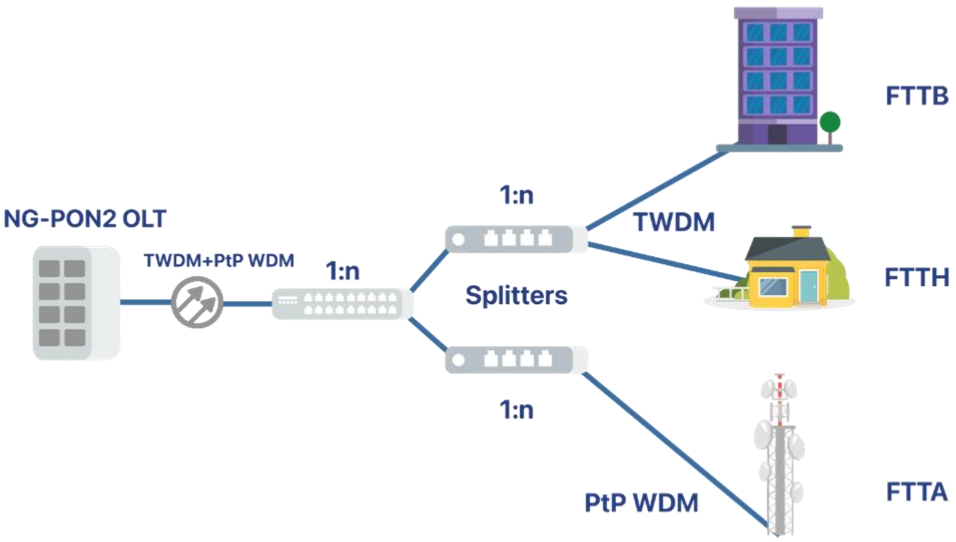


Fig 2.23: TWDM and point to point wavelength division multiplex (P2P WDM) usage.

2.6. Components of FTTH access network

2.6.1. Optical Line Terminal (OLT)

The OLT, located at a central office, controls bidirectional information flow across the ODN. It supports up to 20 km transmission distances (extendable with EDFA). In the downstream direction, the OLT broadcasts voice, data, and video traffic from the long-haul network to all ONT modules on the ODN. In the upstream direction, it accepts and distributes traffic from network users. Different wavelengths are used for each direction, enabling simultaneous transmission of various service types on the same fiber. Downstream uses 1490 nm for voice and data, and 1550 nm for video. Upstream employs 1310 nm for voice and data using TDM, WDM, or both [7].

Fig 2.24: Optical Line Terminal (OLT) [7].

2.6.2. Optical splitters

The optical splitter, also referred to as a beam splitter, plays a crucial role in passive optical networks (PONs) by evenly dividing the fiber optic light into multiple parts at a specific ratio. There are two primary categories of optical splitters available, namely Fused Biconical Taper (FBT) splitters and Planar Lightwave Circuit (PLC) splitters. Each of these options presents unique benefits and advantages [25].

- PLC splitters use the newer Planar Lightwave Circuit technology and provide a superior solution for applications that require larger split configurations. They support a wide range of wavelengths (1260 to 1650 nm), making them suitable for various wavelength adjudication needs. However, their production process involves more complex semiconductor technology, making PLC splitters relatively more difficult and costly to manufacture.

- FBT splitters are based on traditional technology that involves closely welding two or more fibers together using heat. These splitters are cost-effective and compatible with both single-mode and multi-mode fibers, making them widely used in passive networks, particularly for smaller split configurations (e.g., 1×2, 1×4, 2×2). FBT splitters are available in various materials, such as steel, fiber, and hot dorm. They offer a lower price point, which contributes to their cost-effectiveness. However, achieving precise signal evenness in FBT splitters is challenging due to a lack of signal management capabilities.

Fig 2.25: PLC Splitters.

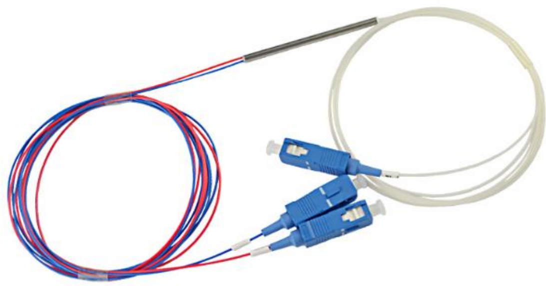


Fig 2.26: FBT Splitters.

2.6.3. Optical distribution network (ODN)

The Optical Distribution Network is an integral part of the PON system, providing the optical transmission medium that connects OLT and ONUs. It reaches 20 km or farther.

The optical distribution network (ODN) is composed of five key segments: feeder fiber, optical distribution point, distribution fiber, optical access point, and drop fiber. The feeder fiber originates from the optical distribution frame (ODF) located in the central office (CO) telecommunications room and stretches to the optical distribution point, covering extensive distances. On the other hand, the distribution fiber extends from the optical distribution point to the optical access point, enabling the distribution of optical fibers to nearby areas. The drop fiber connects the optical access point to the terminals (ONTs). It is important to note that the quality of the ODN directly impacts the performance, reliability, and scalability of the PON system [7].

2.6.4. Optical network terminal (ONT)

At a customer's premises, Optical Network Terminals (ONTs) are installed, which are connected to the central office OLT through an optical fiber link without any active elements. In GPON, the physical link between the customer premises and the central office Optical Line Terminal (OLT) is established through the transceiver in the ONT. The WDM triplexer module is responsible for separating the three wavelengths, namely 1310nm, 1490nm, and 1550nm, with the ONT receiving data at 1490nm, transmitting burst traffic at 1310nm, and receiving analog video at 1550nm. To avoid collisions during upstream data transmission from different homes, the Media Access Controller (MAC) manages the upstream burst mode traffic in a regulated manner [7].

Fig 2.27: Optical Network Terminal (ONT).

When considering the network architecture, design, construction, maintenance, and operation of the optical access network, telecommunication companies should primarily focus on the following factors to determine the appropriate approach and select optical components for FTTH:

- Scalability
- Survivability
- Functionality
- Construction and maintenance costs
- Network upgradeability
- Operability and suitability over designed network lifetime.

2.7. Conclusion

Optical networks have experienced a rapid expansion in recent years, driven by the increasing demand for high-speed downloads such as videos, images, and video conferencing. To satisfy this demand, broadband-based FTTH networks have been established, with Passive Optical Networks (PON) being a popular implementation due to their ability to offer customers high data rates, extended coverage, reduced fiber deployment, and cost-effective maintenance through passive components.

In this chapter, PON and FTTH networks were the main focus as they are of great importance in the evolution of access networks.

Chapter 3

Simulation tests and results

3.1. Introduction

In this chapter, OptiSystem software is being used for the design and simulation of different PON architectures for the FTTH network, it starts with the software presentation and then covers the simulation methodology, including the setup of the simulation environment and the performance metrics used to evaluate the quality of service in each of the five different architectures BPON, GPON, XG-PON, XGS-PON, and next-generation WDM-PON.

The simulation results primarily focus on analyzing PON performance by evaluating the key quality of service parameters in response to variations in fiber length, bitrate, and attenuation. Additionally, different scenarios are considered, including the presence or absence of amplifiers and the use of different fiber types, to gain valuable insights into the performance characteristics and evolution of various architectures employed in FTTH networks.

3.2. Description of the OptiSystem software

The OptiSystem software is an advanced optical communication system simulation tool developed by the company "Optiwave." It was created to fulfill the needs of system designers, optical communications engineers, and researchers in academia. This software encompasses the design, testing, and optimization of various functions within broadband optical networks, including virtual optical connections. Its application ranges from long-distance communication systems to local area networks (LANs) and metropolitan area networks (MANs). OptiSystem boasts an extensive database of active and passive components, offering a wide array of parameters such as power, wavelength, loss, and other relevant properties. These parameters enable users to analyze and optimize device-specific technical aspects affecting system performance. The software provides a robust simulation environment along with accurate component and system classification definitions. It operates at the system level, realistically modeling fiber optic communication systems. Furthermore, OptiSystem supports easy expansion through user-defined components and seamless integration with various tools. The software's comprehensive graphical user interface (GUI) facilitates control over optical component layout, component models, and presentation graphics.

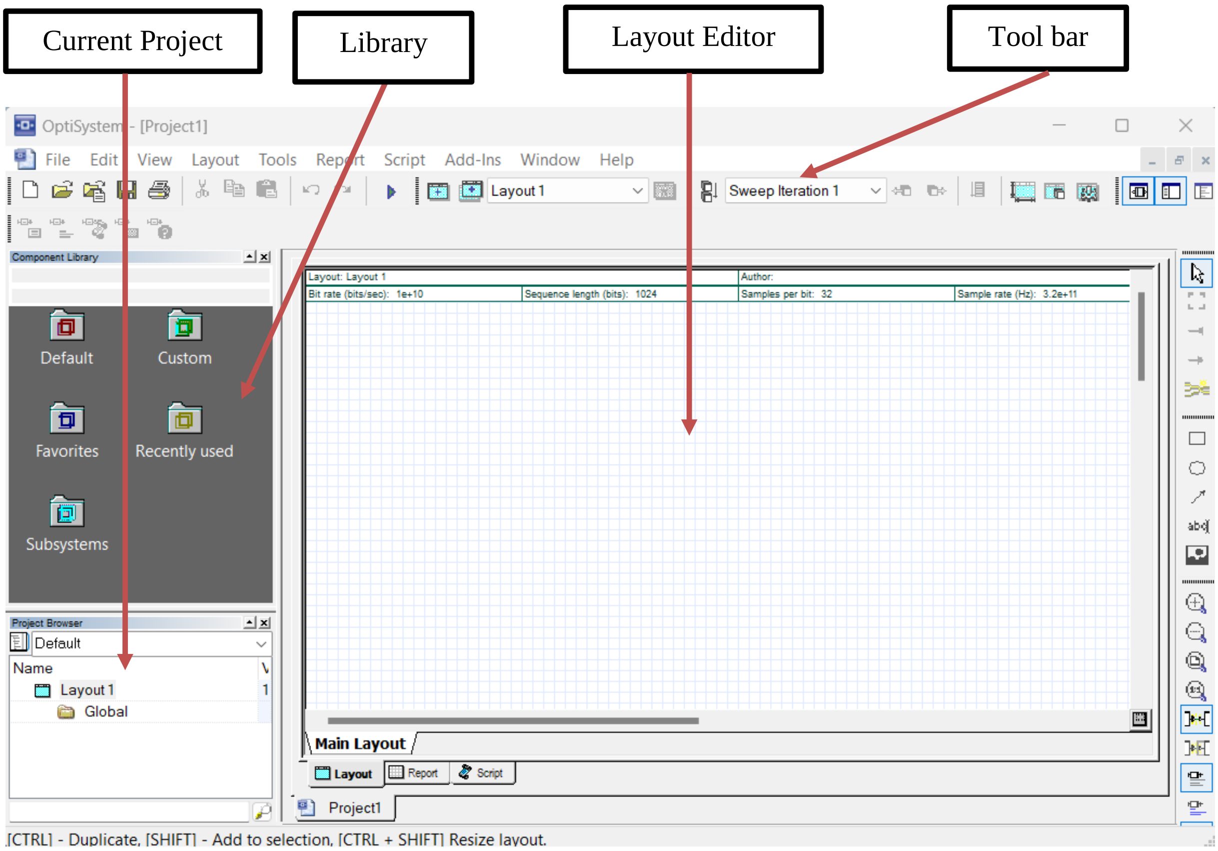


Fig 3.1: Graphical user interface (GUI) of OptiSystem

OptiSystem essentially consists of a main window that is divided into several parts:

- Layout Editor: allows for the editing and configuration of the current design schema.
- Current Project: displays the various files and components corresponding to the current project.
- Project Overview: provides a miniature view of the layout currently being edited.
- Library: a database of various existing components, containing all types of models that allow for the realization of different design schemas.

Among its various applications, these are the most used:

- Optical communication system design from component to system level at the physical layer
- CATV or TDM/WDM network design
- Passive optical networks (PON)
- Free space optic (FSO) systems
- Radio over fiber (ROF) systems
- SONET/SDH ring design
- Transmitter, channel, amplifier, and receiver design

- Dispersion map design
- Estimation of BER and system penalties with different receiver models and link budget calculations.

3.3. Overview of Quality of Service (QoS)

3.3.1. Definition

In the context of optical networks, Quality of Service (QoS) pertains to the ability to ensure efficient transmission of specific types of traffic, encompassing factors such as availability, transmission speed, accuracy, jitter, and packet loss rate. As a crucial concept in network resource management within the field of optical communication, QoS aims to optimize resources to guarantee optimal performance for critical applications. By implementing appropriate protocols at the network level, QoS enables the delivery of faster speeds and response times tailored to different applications and activities. Moreover, it facilitates service providers in efficiently allocating their infrastructure resources based on the transfer characteristics of application data within client divisions.

3.3.2. Quality parameters of an optical link

To evaluate the proper functioning of a system and measure the quality of optical transmission, three main criteria are essential: the quality factor, the bit error rate, and the eye diagram.

A. The quality factor

The quality factor, also known as the Q-factor, is a parameter characterizing the quality of a signal during transmission, given by the following relation:

$$Q = \frac{I_1 - I_0}{\delta_1 - \delta_0} \qquad \textbf{(Eq 3.1)}$$

Here, I_1 and I_0 are the average photo-current values of symbols 1 and 0, δ_1 and δ_2 are the square roots of the variances of the probability densities of symbols 1 and 0.

Experimental measurement of the Q-factor of a signal is difficult, meaning that I_1, I_0, δ_1, and δ_2 are often not directly measurable. To solve this problem, we can use the relation of the optimal BER (Bit Error Rate) as a function of the Q-factor, assuming Gaussian probability distributions of signal levels:

$$BER = \tfrac{1}{2}[\mathrm{erfc}\,(Q/\sqrt{2})] \qquad \textbf{(Eq 3.2)}$$

Where erfc is the error function.

B. The bit error rate

A transmission of digital data in a communication system is a sequence of 0s and 1s. To evaluate the performance of the system, it is necessary to compare the transmitted bits with the received bits, in other words, the bit error rate (BER), which is the ratio of the number of received bits to the number of erroneous bits. The "1" is sometimes detected in place of a "0" due to signal distortion caused by noise and propagation. The probability of an erroneous decision on a binary element is defined by BER, as follows:

$$\text{BER} = \frac{Number\ of\ erroneous\ bits}{Number\ of\ transmitted\ bits} \qquad \textbf{(Eq 3.3)}$$

A system is next considered to be of good quality in optical transmission if this BER is less than a value of 10^{-9}, 10^{-12} or 10^{-15}.

C. The eye diagram

The eye diagram represents the synchronous superposition of all the binary symbols of the transmitted sequence to estimate the quality of a signal in a visual way (see Figure 3.2).

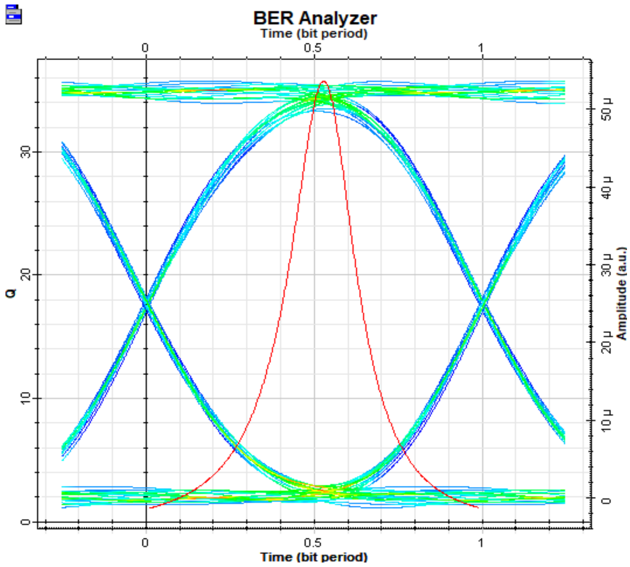


Fig 3.2: Example of the eye diagram.

This diagram is characterized by:

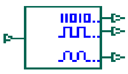
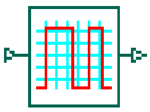
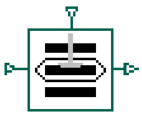
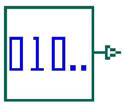
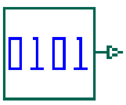
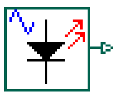
- Temporal broadening (Temporal widening) of signal pulses due to chromatic dispersion caused by interference between symbols,
- Of signal pulses due to chromatic dispersion caused by interference between symbols,
- Temporal jitter arises due to the effects of dispersion and coupling between pulses, as well as the presence of amplified emission noise.

- In the link, the amplitude noise results from the accumulation of amplified transmission noise on the signal throughout its path.

3.4. FTTH network simulation and results

A PON architecture has been divided into three main categories. Firstly, Optical Line Terminal (OLT), secondly Optical Distribution Network (ODN) and thirdly Optical Network Terminal/Unit (ONT/ONU). OLT is part of the Central office (CO). ODN includes the portion in between OLT and ONT. In ODN, optical splitters and arrayed wave-guides grating (AWG) can be employed. ONT is the part that connects the end user to the passive optical network. The number of end users depends on the splitting ratio of the optical splitter or AWG.

The table below identifies the components used in the design and simulation. The different blocs' designs are shown in figures 3.3, 3.4, and 3.5

Element name	Block in OptiSystem	Description
3R Regenerator		It's a type 3R repeater. Its role is to resynchronize the optical signal.
NRZ Pulse Generator		The modulation used in this link is NRZ (Non-return to zero), Binary data "1" is associated with an optical pulse of duration equal to the symbol time (inverse of the bit rate), data "0" corresponds in the absence of the signal. It is simple to implement.
Mach-Zehnder Modulator		This is the most used type of external modulator because of its low cost, allows it to gain in distance, and allows it to have a great flow.
Pseudo-Random Binary Sequence (PRBS)		is used to generate a random binary sequence.
user-defined binary sequence generator		Same concept as the PRBS but it generates a user-defined bit sequence binary sequence.
CW Laser		Laser to generate a continuous wave optical signal.

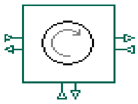
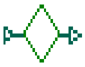
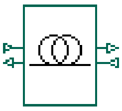
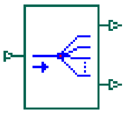
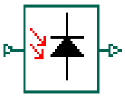
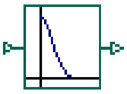
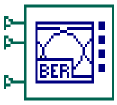
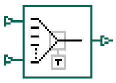
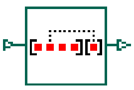
Circulator Bidirectional		A component with three ports its role is to route the incoming signals to the various outputs, Separating upstream and downstream signals.
Optical Delay		Generates delays of an optical signal and adds delay to make the bidirectional signals pass at the same time.
Optical Null		Its role is to generate an optical signal with “zero value”.
Bidirectional Optical Fiber		Allows optical signals to travel in both directions at the same time.
1xN Bidirectional Splitter		Splits the signal into the required number of signal streams to transmit it to ONUs.
Photodetector PIN		It is a Photodetector. Convert an optical signal to an electrical signal It was chosen because of its low cost.
Low pass Bessel Filter		It allows the user to select the frequencies below its cutoff frequency. Fc = 0.75 * bit rate (hz)
BER Analyzer		It is the method used to evaluate the performance of a system and compare the bits sent with the bits received, thanks to this tool, we visualize the eye diagram, (measures the performance of the system based on the signal before and after propagation).
Dynamic Y select		It is used to control the various attenuation values and the phase values
Buffer selector		is Used to selecting signal data associated with a specified iteration from a series of iterations.

Table 3.1: the components used in the design and simulation.

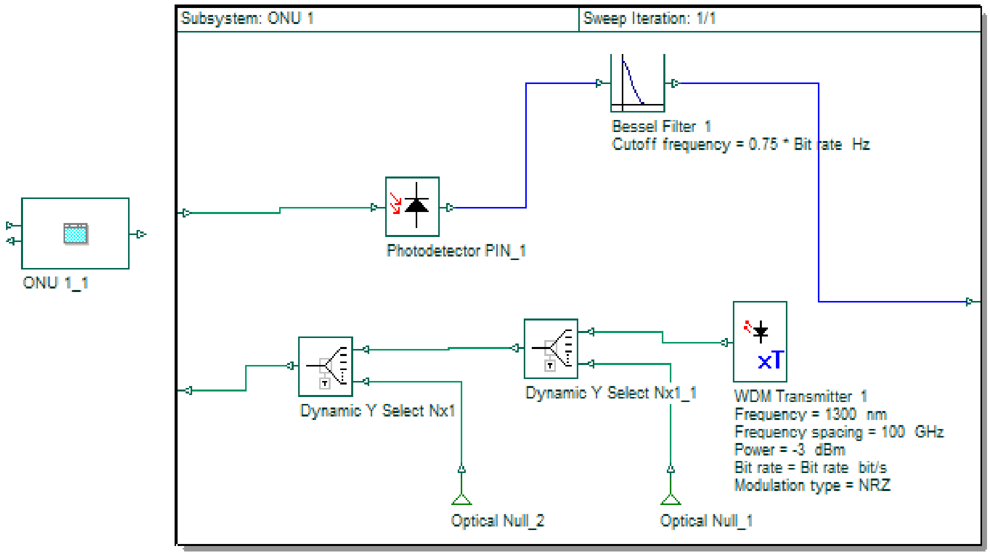


Fig 3.3: The components of ONU block of BPON/GPON.

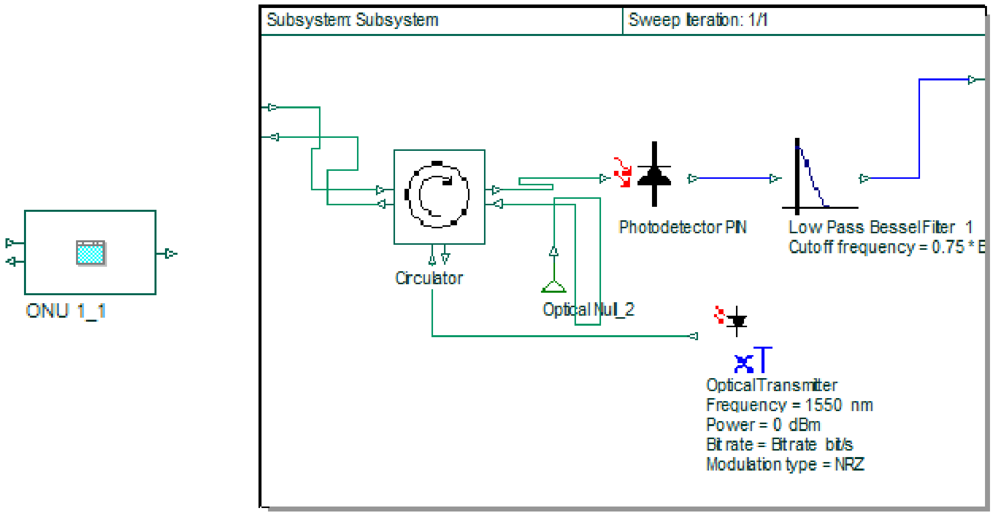


Fig 3.4: The components of WDM ONU block

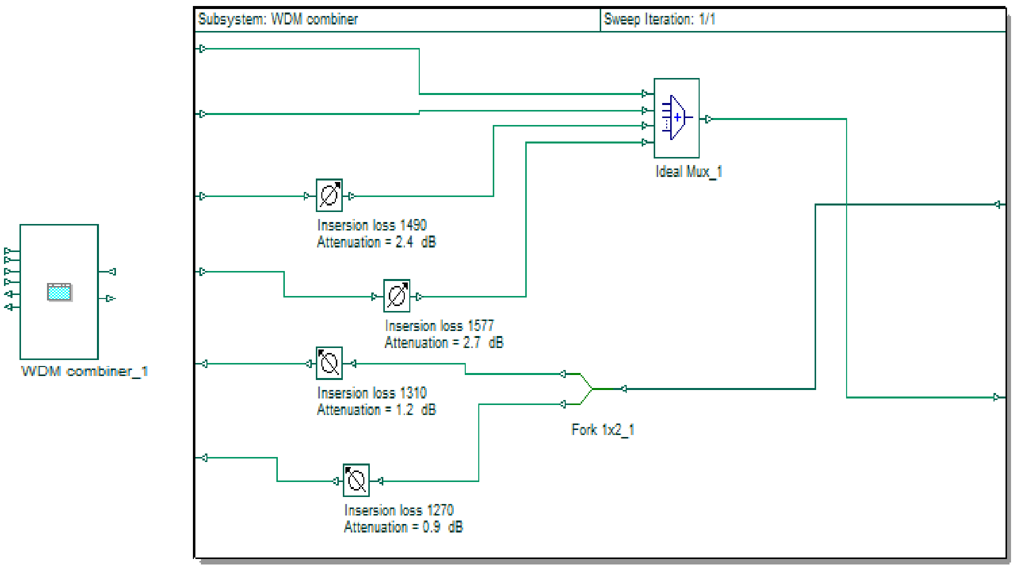


Fig 3.5: The components of the WDM combiner

3.4.1. FTTH network simulation for (B-PON) and (G-PON) architectures

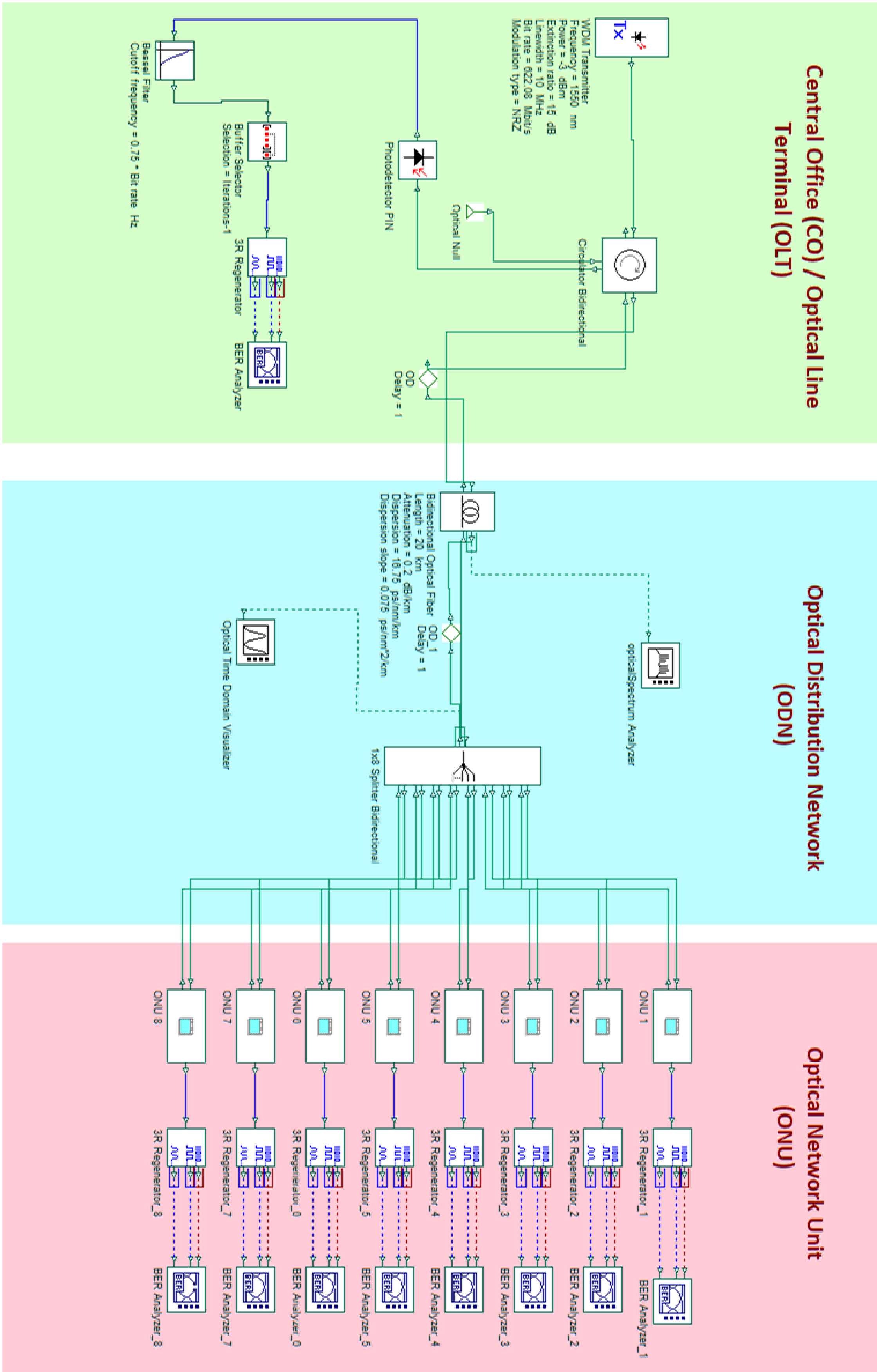


Fig 3.6: B-PON based FTTH network architecture Scheme.

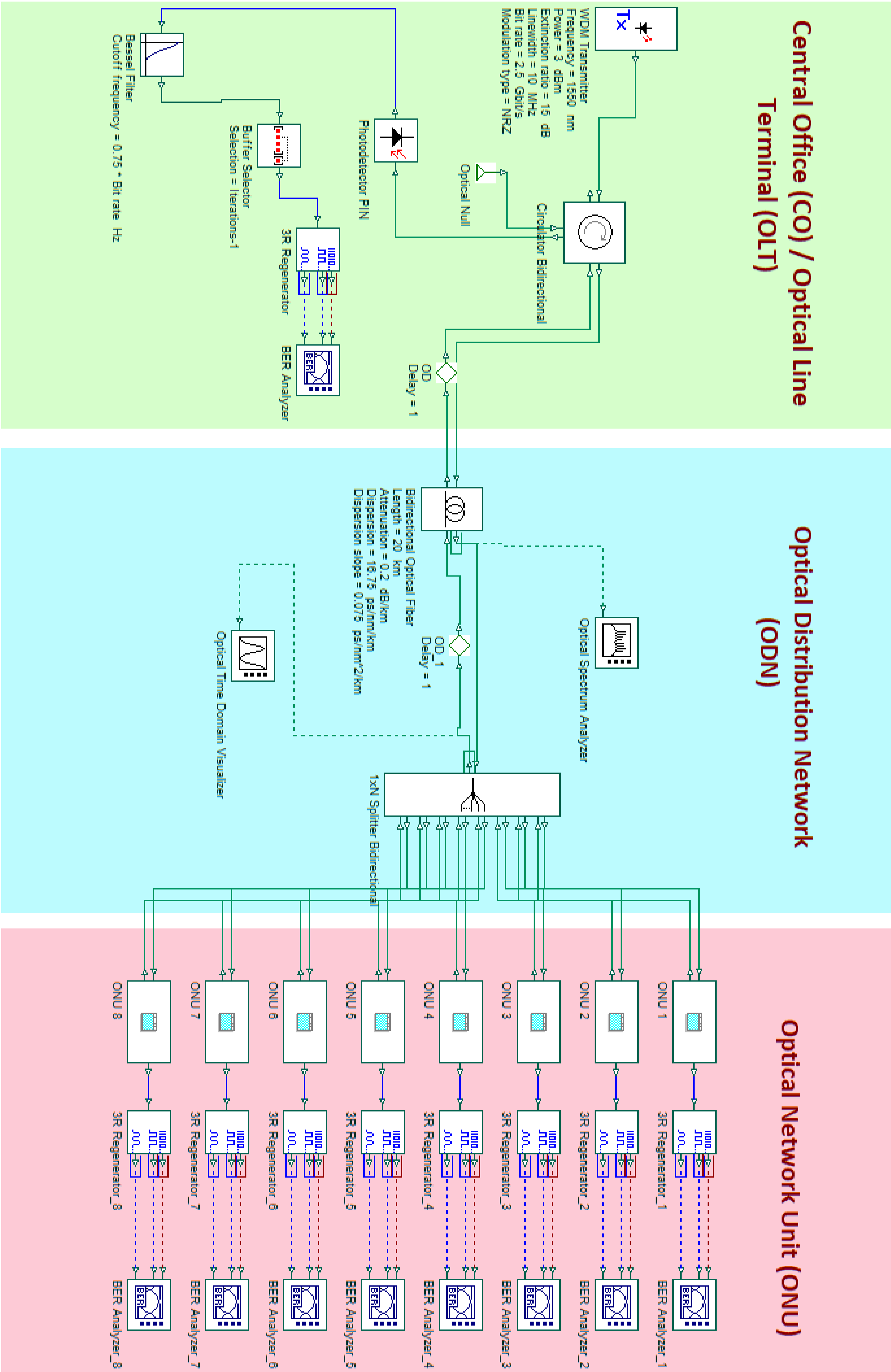


Figure 3.7: G-PON based FTTH network architecture Scheme.

The architecture illustrated in Figure 3.6 showcase a bidirectional Broadband Passive Optical Network (BPON) design that provides a symmetric bit rate of 622 Mbps for both downstream and upstream transmission. The downstream signal is transmitted at a wavelength of 1490 nm, while the upstream signal is transmitted at a wavelength of 1310 nm.

And the architecture illustrated in Figure 3.7 depicts a bidirectional Gigabit Passive Optical Network (GPON) scheme. The downstream direction offers a bit rate of 2.5 Gbps, while the upstream direction set to a bit rate of 1.25 Gbps. GPON downstream signals use a wavelength of 1490 nm, while the upstream signals use a wavelength of 1310 nm.

Both of These network configurations operate over a fiber length of 20 km, with an attenuation rate of 0.2 dB/km.

3.4.1.1. Influence of distance variation on the quality factor

Q-factor values in table 3.2 and figure 3.8 bellow are found to be influenced by the length of fiber, Q-factor decreases as the distance increases in both architectures due to signal losses. Notably, it is better at distances that are less than 20km.

	Distance (km)	**5**	**10**	**20**	**30**	**40**	**50**	**60**
Q-Factor	**B-PON**	14.43	11.73	7.19	4.59	2.99	0	0
	G-PON	30.81	23.85	15.12	9.52	5.92	3.64	2.44

Table 3.2: Effect of distance variation on Q factor (B-PON / G-PON)

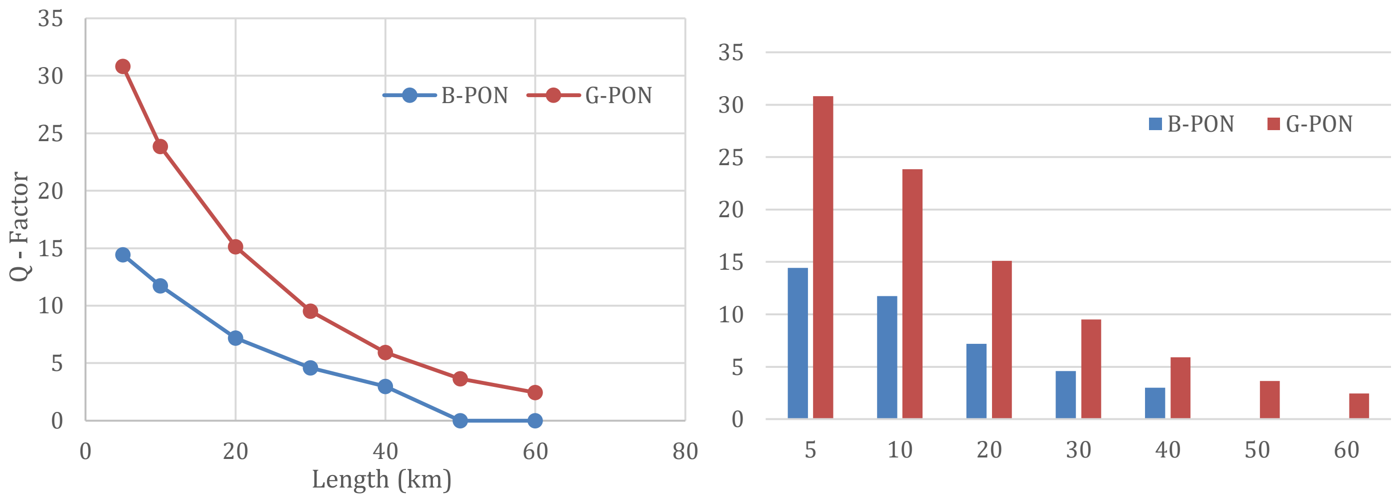


Fig 3.8: The influence of distance variation of the Q-factor (B-PON / G-PON)

The eye diagram in Figure 3.9 demonstrates a progressive degradation caused by the increase in distance. This degradation is evident through the opening of the eye at 5 km and the subsequent closure of the eye at 40 km for both architectures. Hence, the length of the fiber plays a critical role, and it is essential to keep it below 20 km for B-PON and 40 km for G-PON to ensure a high-quality transmission.

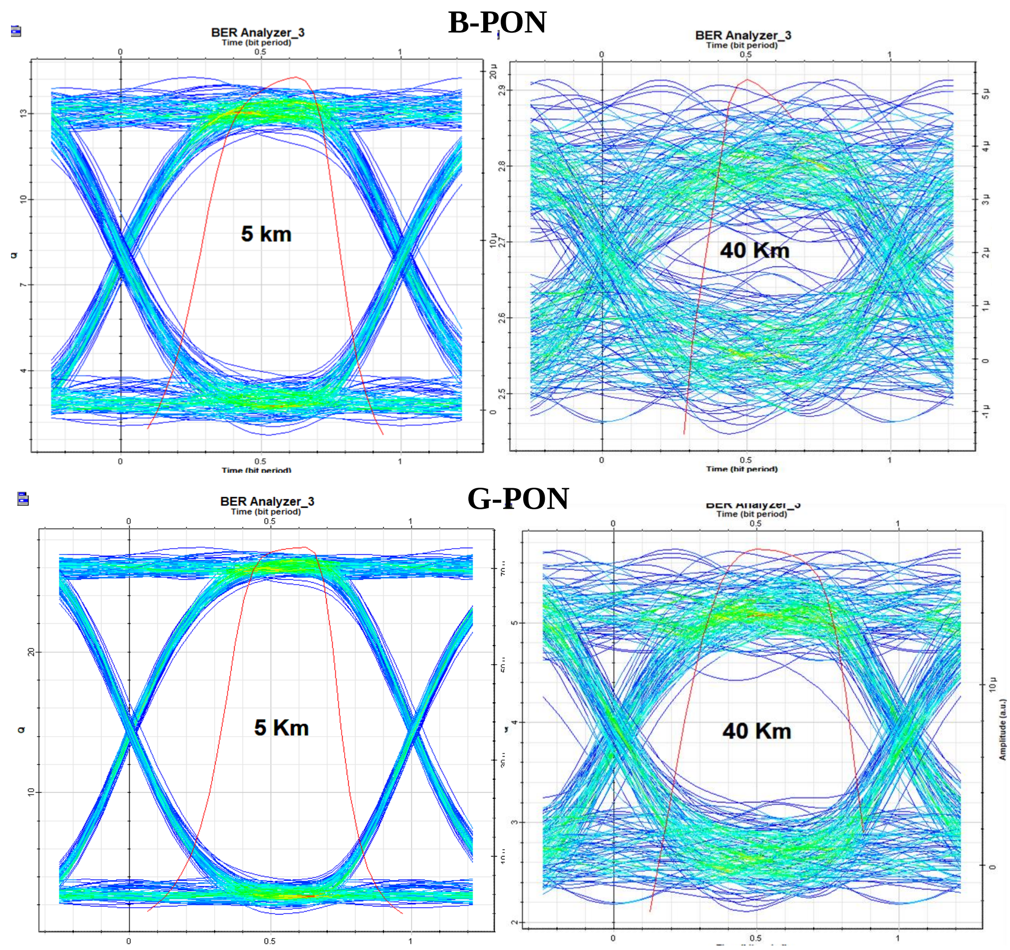


Fig 3.9: Eye diagram with variation of distance (B-PON / G-PON)

3.4.1.2. Influence of transmission rate on the quality factor

The performance analysis of B-PON and G-PON at different bit rates values is studied bellow

	Bit rate (Gb/s)	0.5	1	2	2.5	5	10
Q-Factor	B-PON	8.30	5.50	4.70	3.64	2.55	0
	G-PON	33.67	22.74	16.22	14.27	10.04	6.80

Table 3.3: Effect of bit rate variation on the Q factor (B-PON / G-PON)

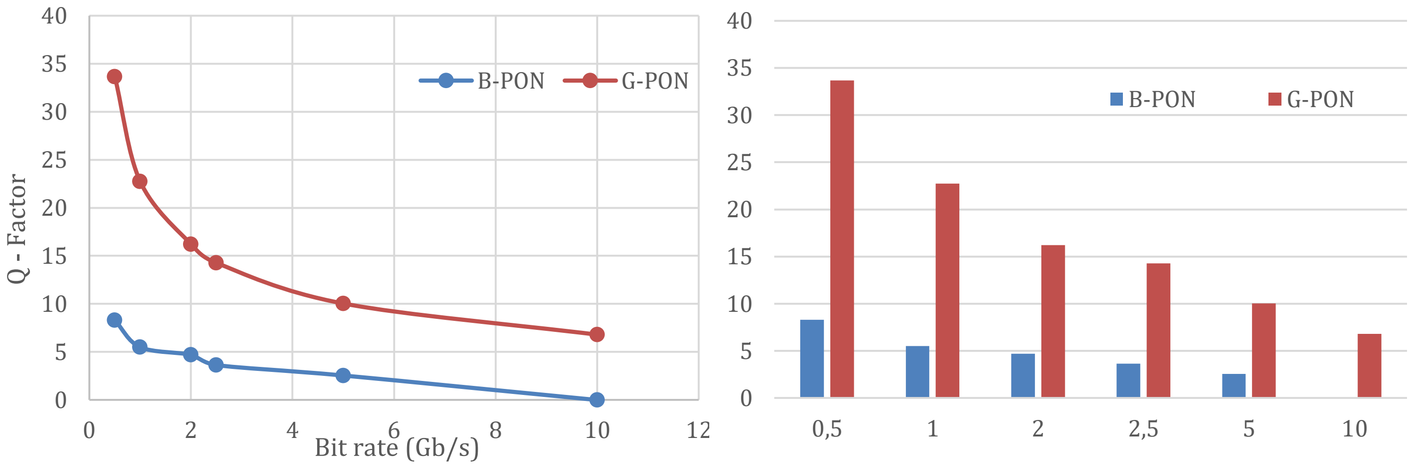


Fig 3.10: The influence of bit rate variation of the Q-factor (B-PON / G-PON)

As the bit rate increases, we observe a decreasing trend in the Q-Factor is observed in table 3.3 and fig 3.10 above. Indicating a significant degradation in signal quality with higher bitrates. The eye diagram in Fig 3.11 for the G-PON architecture, at 1 Gbps demonstrates a wider and well-defined eye-opening, reflecting excellent signal quality. The G-PON architecture is designed to support higher data rates, and thus it maintains good performance at this speed. Even at 5 Gbps, the eye diagram for G-PON remains relatively open, indicating better resilience to noise and inter-symbol interference compared to B-PON. This highlights the superior performance and suitability of G-PON.

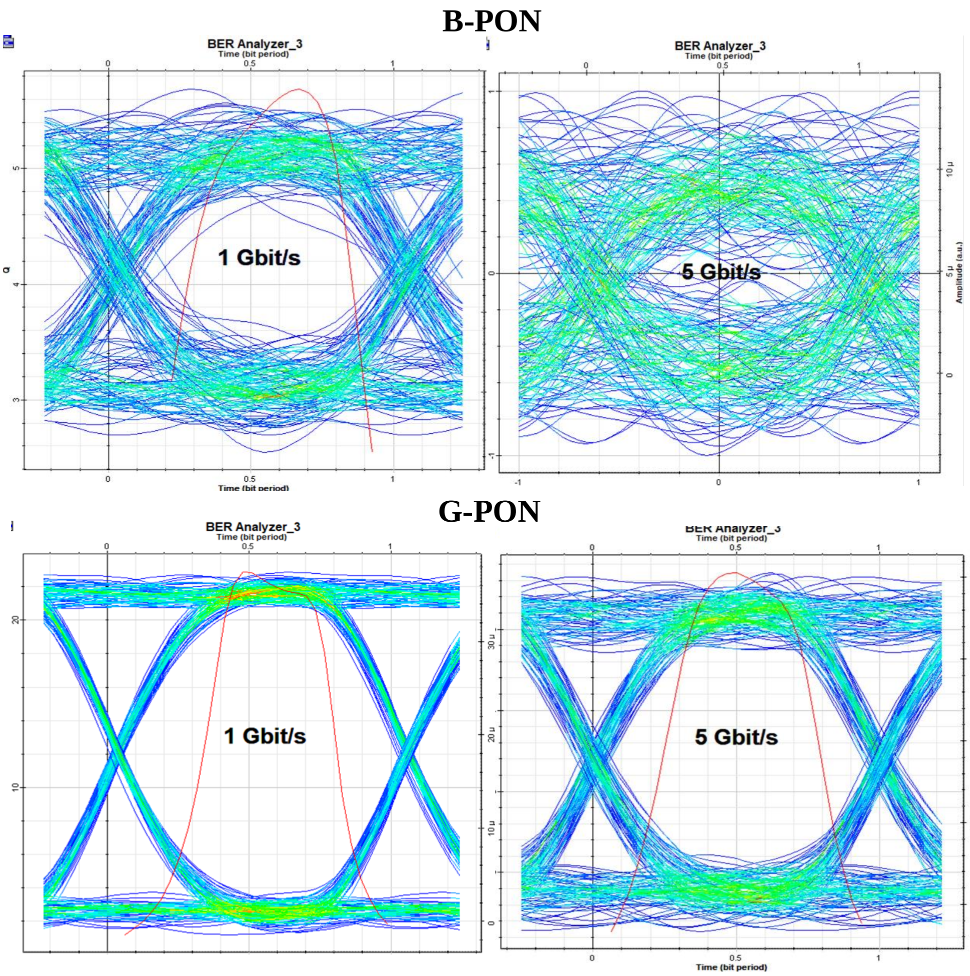


Fig 3.11: Eye diagram with variation of bit rate (B-PON / G-PON)

3.4.1.3 Effect of attenuation (loss) on optical transmission

Attenuation from 0.1 dB/km to 0.5 dB/km are varied for the same distance and bitrate and note the quality factor in transmission, the results are presented in the table below.

	Attenuation (dB/km)	0.1	0.2	0.3	0.4	0.5
Q-Factor	B-PON	11.24	7.17	4.77	2.71	0
	G-PON	22.31	14.08	9.06	5.50	4.20

Table 3.4: Effect of attenuation variation on the Q factor (B-PON / G-PON)

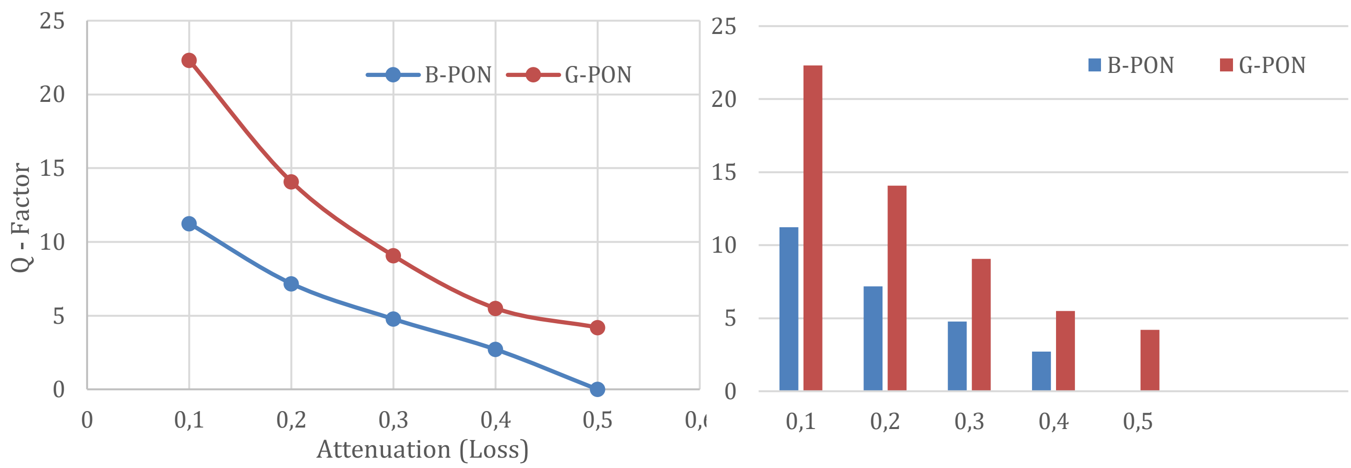


Fig 3.12: The influence of attenuation variation of the Q-factor (B-PON / G-PON)

For B-PON architecture, as the attenuation increases from 0.1 dB/km to 0.5 dB/km, the Q- Factor decreases from 11.24 to 0, and in G-PON architecture, a similar trend is observed. With increasing attenuation levels, the Q-Factor diminishes from 22.31 to 4.20, indicating a significant degradation in signal quality with higher attenuation levels.

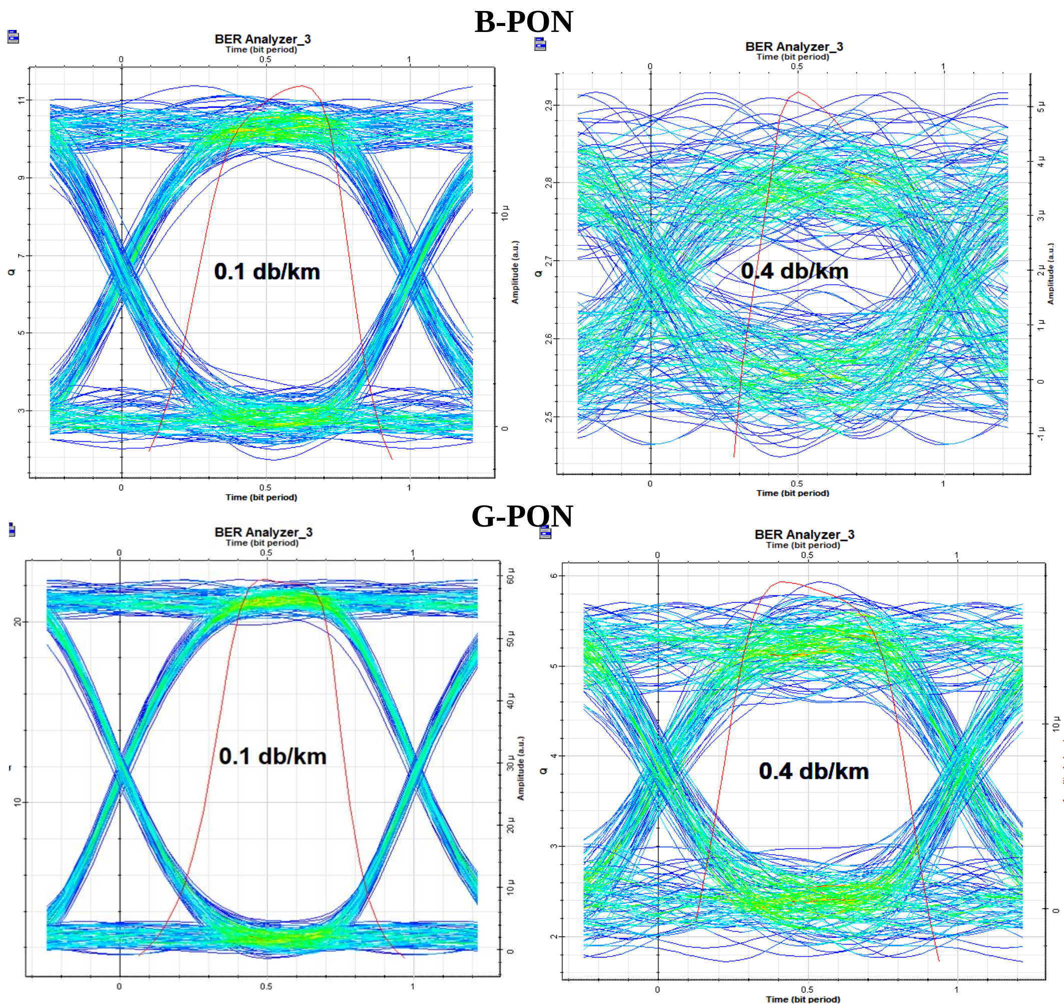


Fig 3.13: Eye diagram with variation of attenuation (B-PON / G-PON)

Figure 3.13 shows the eye diagram of the B-PON and G-PON networks for two values of attenuation (0.1 dB/km and 0.4 dB/km). It is observed that as the attenuation increases, the eye tends to close.

3.4.1.4 Effect of amplifiers (EDFA) on optical transmission

The quality of transmission is compared in the presence and absence of an EDFA amplifier (Gain=5dB) for a distance of 20km.results are showed in Fig 14 it is noted that by adding the amplifier the quality factor become significantly higher which can be inferred that amplifiers play a significant role in the transmission chain as they ensure the regeneration of the optical signal, particularly for long-distance transmissions.

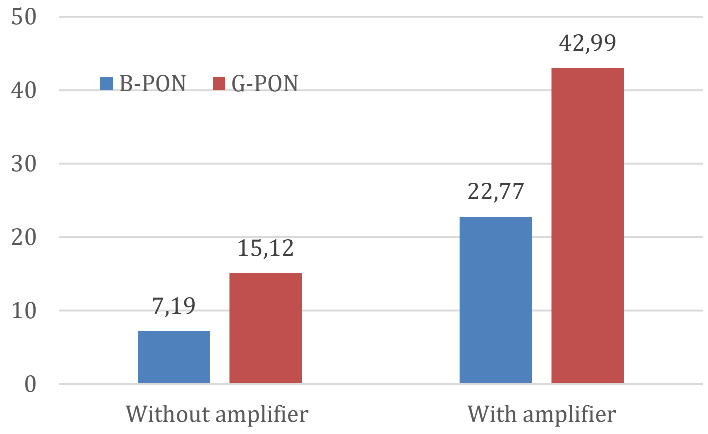


Fig 3.14: Quality factor in the presence and absence of EDFA

3.4.1.5 Effect of link type (bidirectional and unidirectional)

As seen in Fig 3.15 below, when the bidirectional fiber is changed to unidirectional fiber in order to observe the effect on the quality factor. It is noted that both architectures perform better when using unidirectional links.

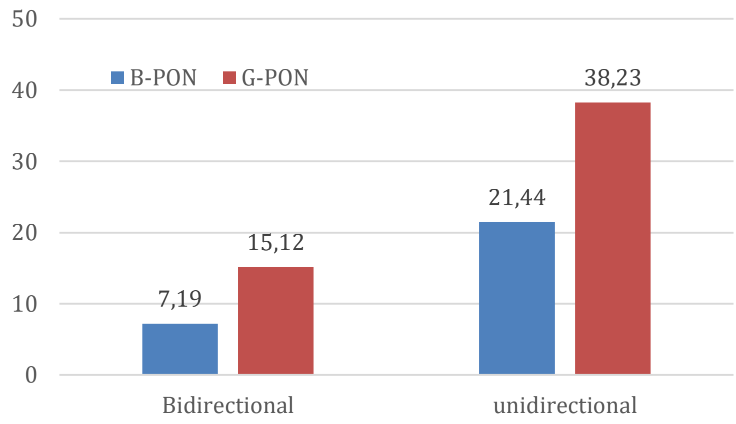


Fig 3.15: Quality factor in the bidirectional and unidirectional fiber

3.4.2 FTTH network simulation for (XG-PON) and (XGS-PON) architectures

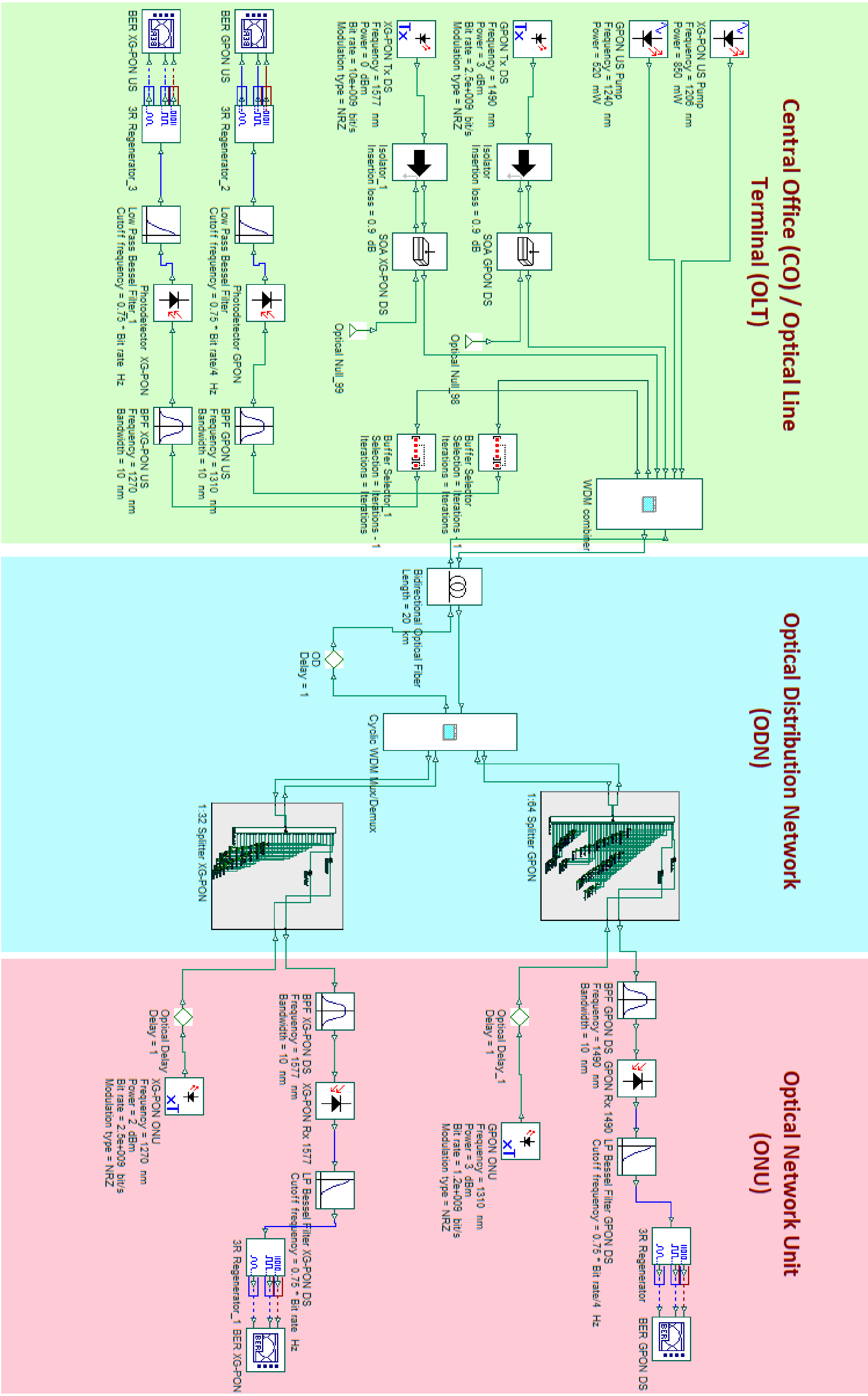


Figure 3.16: XG-PON based FTTH network architecture Scheme

The architecture illustrated in Figure 3.16 showcase a coexistence scenario of XG-PON (10 Gigabit Passive Optical Network) and GPON with split ratio 1:32 and of 1:64 respectively, The fiber link span a distance of 20 km, with an attenuation of 0.2 dB/km. the XG-PON system is configured with a downstream capacity of 10 Gbps and an upstream capacity of 2.5 Gbps. The signals are transmitted on different wavelengths. 1577 nm for the downstream,1270 nm for the upstream signals. XGS-PON is an upgraded version of XG-PON that provides symmetrical capacity for both transmissions, to simulate the architecture with XGS-PON the upstream data rate is increased to 10 Gbps.

3.4.2.1 Influence of distance variation on the quality factor

The table 3.5 shows the Q-Factor values for both XG-PON and XGS-PON architectures at different distances. The Q-Factor is a measure of the quality of an optical signal, with higher values indicating better signal quality.

	Distance (km)	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**80**
Q-Factor	**XG-PON**	33.12	32.07	30.27	27.31	22.99	15.72	12.65	5.68
	XGS-PON	37.97	32.70	32.11	28.85	24.53	17.28	13.55	5.86

Table 3.5: Effect of distance variation on the Q factor (XG-PON / XGS-PON)

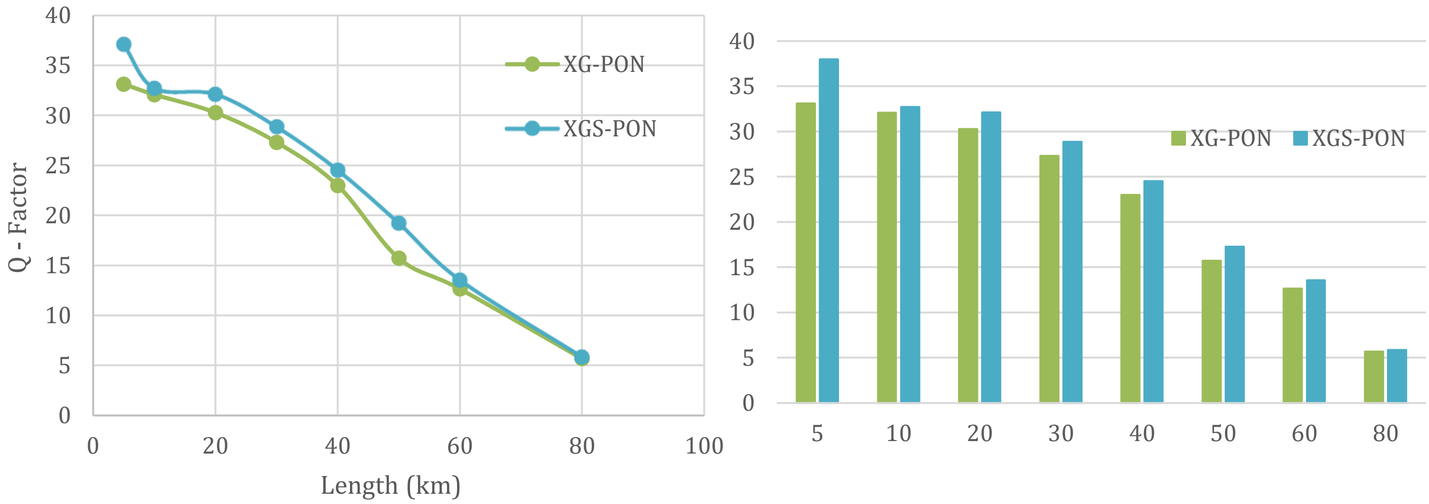


Fig 3.17: The influence of distance variation of the Q factor (XG-PON / XGS-PON)

It is observed that in XG-PON, at shorter distances (5 km and 10 km), the Q-Factor for XG-PON is relatively high, indicating good signal quality, as the distance increases, the Q-Factor decreases significantly, especially beyond 20 km. This suggests a decrease in signal quality.

Comparing XGS-PON with XG-PON, it shows slightly higher Q-Factor values at most distances. The improvement in the Q-Factor becomes more significant as the distance increases.

Beyond 20 km, XGS-PON maintains a higher Q-Factor compared to XG-PON, indicating better signal quality over longer distances.

(XG-PON / XGS-PON)

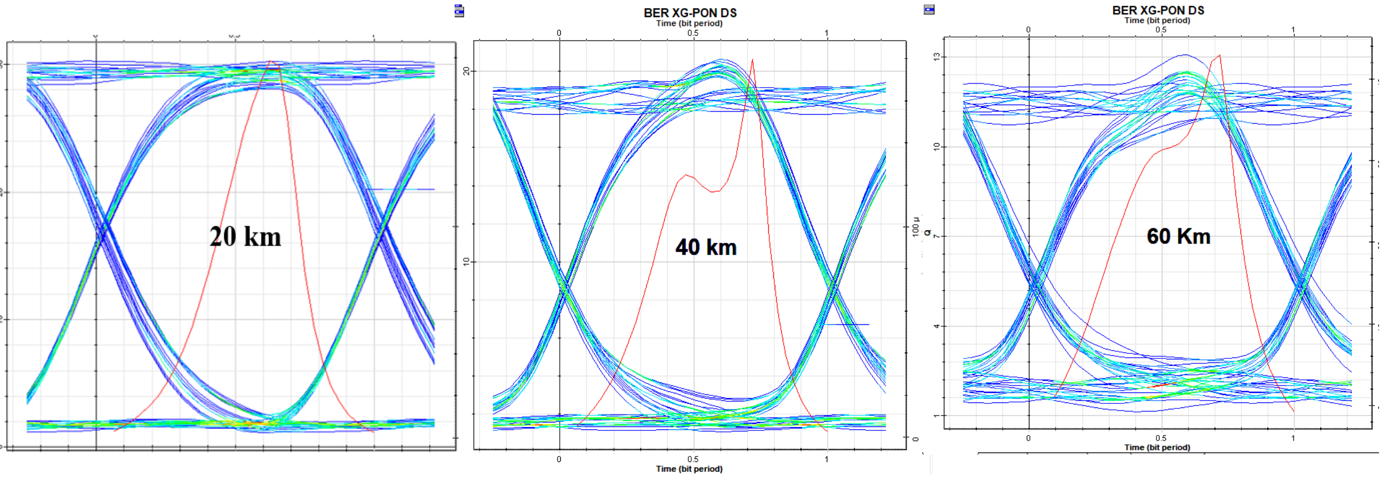


Fig 3.18: Eye diagram with variation of distance (XG-PON / XGS-PON)

The eye diagram in Figure 3.18 demonstrates a wide and clear opening of the eye suggesting excellent to good signal transmission at distance of 20km to 40 km respectively however a degradation of signal is noted with the subsequent closure of the eye at 60 km for both architectures.

3.4.2.2 Influence of transmission rate on the quality factor

Table 3.6 presents the Q-Factor values for both XG-PON and XGS-PON at different bit rates at 20km, Q-Factor values above 20 typically indicate good signal quality, ensuring reliable communication.

	Bit rate (Gb/s)	5	10	20	40	100
Q-Factor	XG-PON	25.64	20.41	14.53	6.16	1.26
	XGS-PON	25.90	20.95	14.81	6.34	1.37

Table 3.6: Effect of Bit rate variation on the Q factor (XG-PON / XGS-PON)

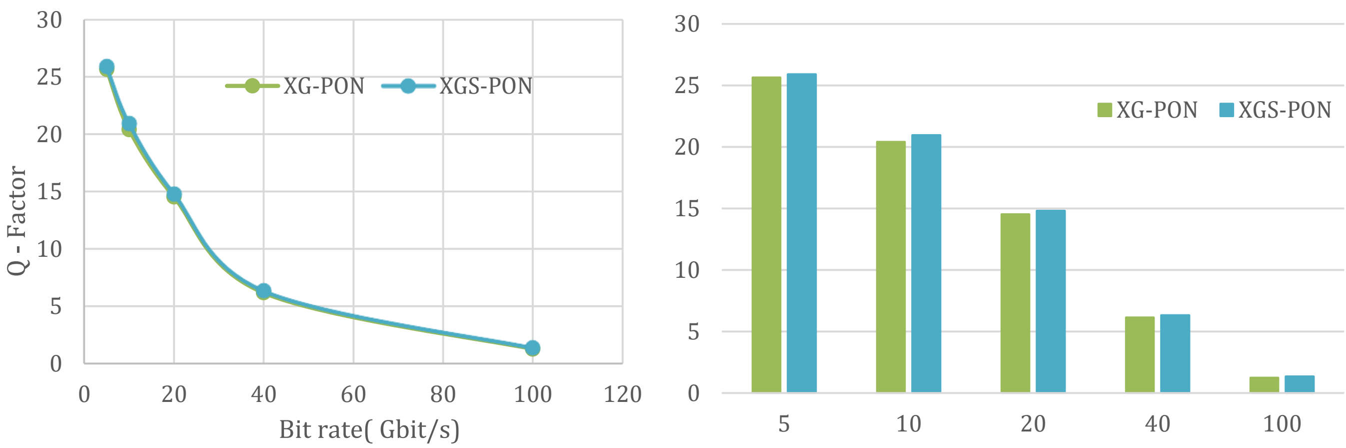
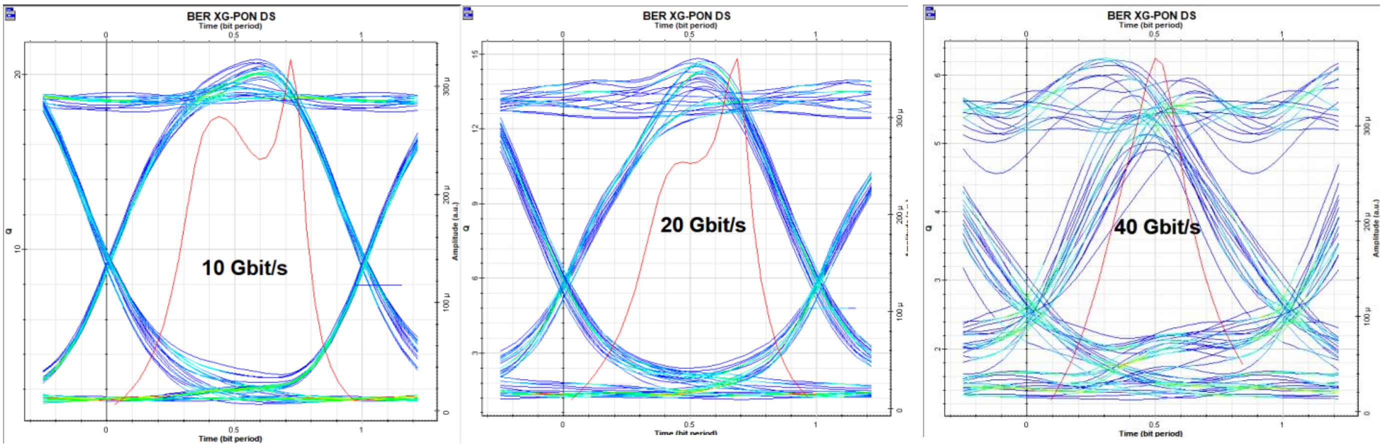


Fig 3.19: The influence of Bit rate variation of the Q factor (XG-PON / XGS-PON)

XG-PON and XGS-PON experience a decrease in signal quality, as indicated by the decreasing Q-Factor values. However, XGS-PON generally exhibits slightly better signal quality compared to XG-PON across different bit rates.

At a bit rate of 10 Gbps, XG-PON demonstrates a Q-Factor of 20.41 and XGS-PON demonstrates a Q-Factor of 20.95, indicating relatively good signal quality as shown in figure 3.19 however as the bit rate increases to 20 Gbps, and above, the Q-Factor decreases significantly indicating degraded signal quality.

XG-PON



XGS-PON

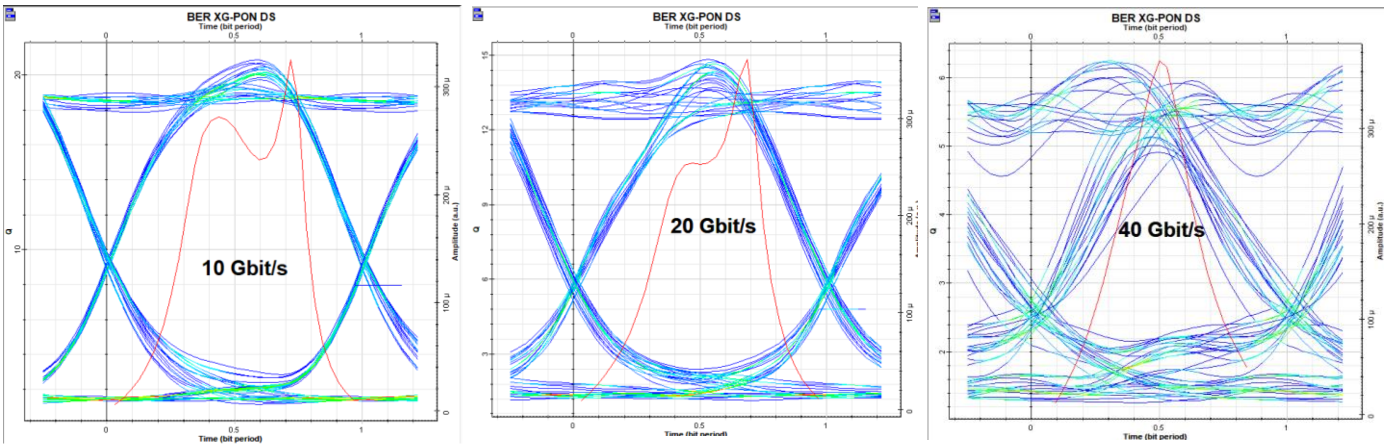


Fig 3.20: Eye diagram with variation of Bit rate (XG-PON / XGS-PON)

The eye-opening at 10 Gbps shown in eye diagram Figure 3.20 is relatively wide, indicating good signal quality and appears almost identical in both architectures, whilst at higher bitrates the eye tends to close.

3.4.2.3 Effect of attenuation (loss) on optical transmission

The table below shows the impact of increasing attenuation on signal quality for XG-PON and XGS-PON at 10 Gbps and 20 km. It indicates that higher attenuation levels result in reduced signal quality, as reflected by lower Q-Factor values illustrated in Figure 3.21. XGS-PON generally demonstrates better signal quality compared to XG-PON at various attenuation levels.

	Attenuation (dB/km)	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Q-Factor	**XG-PON**	35.11	30.27	29.56	25.14	17.49
	XGS-PON	35.20	32.11	30.57	29.73	19.49

Table 3.7: Effect of attenuation on the Q factor (XG-PON / XGS-PON)

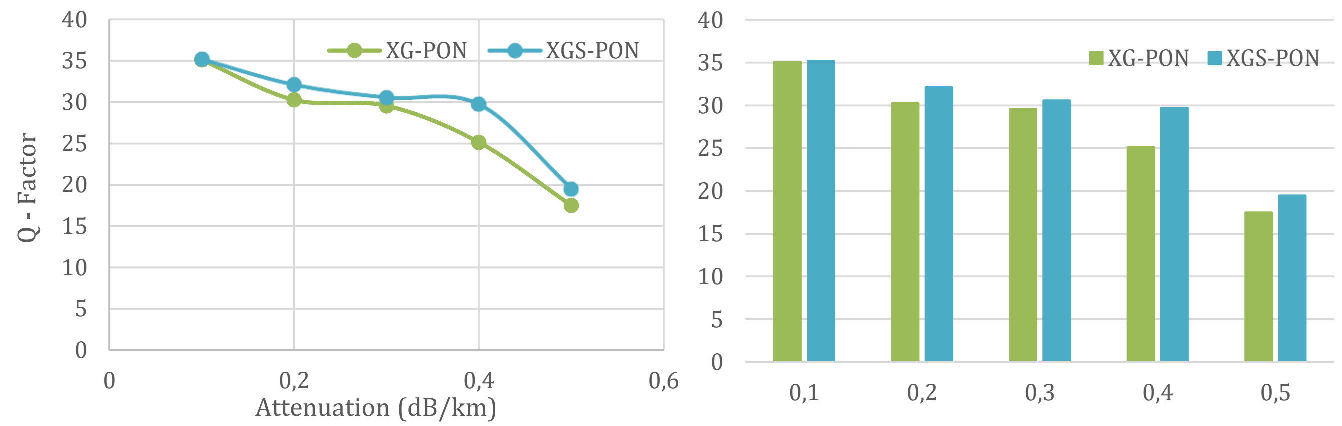


Fig 3.21: The influence of attenuation variation of the Q factor (XG-PON / XGS-PON)

XG-PON

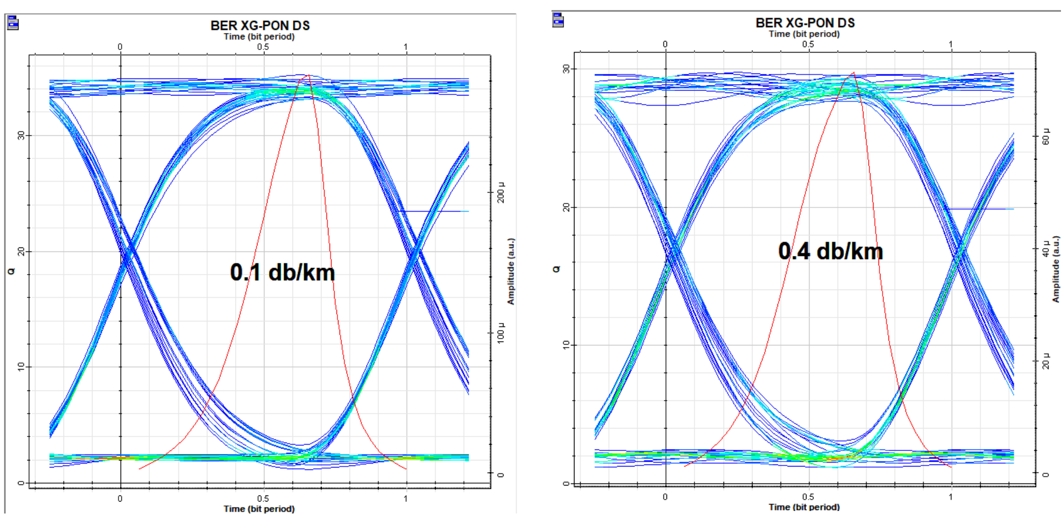


Fig 3.22: Eye diagram by variation of attenuation (XG-PON / XGS-PON)

A wider eye opening is noted in the eye diagram at attenuation value of 0.1 than of 0.4 dB/km as shown in figure 3.22.

3.4.3 FTTH network simulation for the next generation WDM-PON architecture

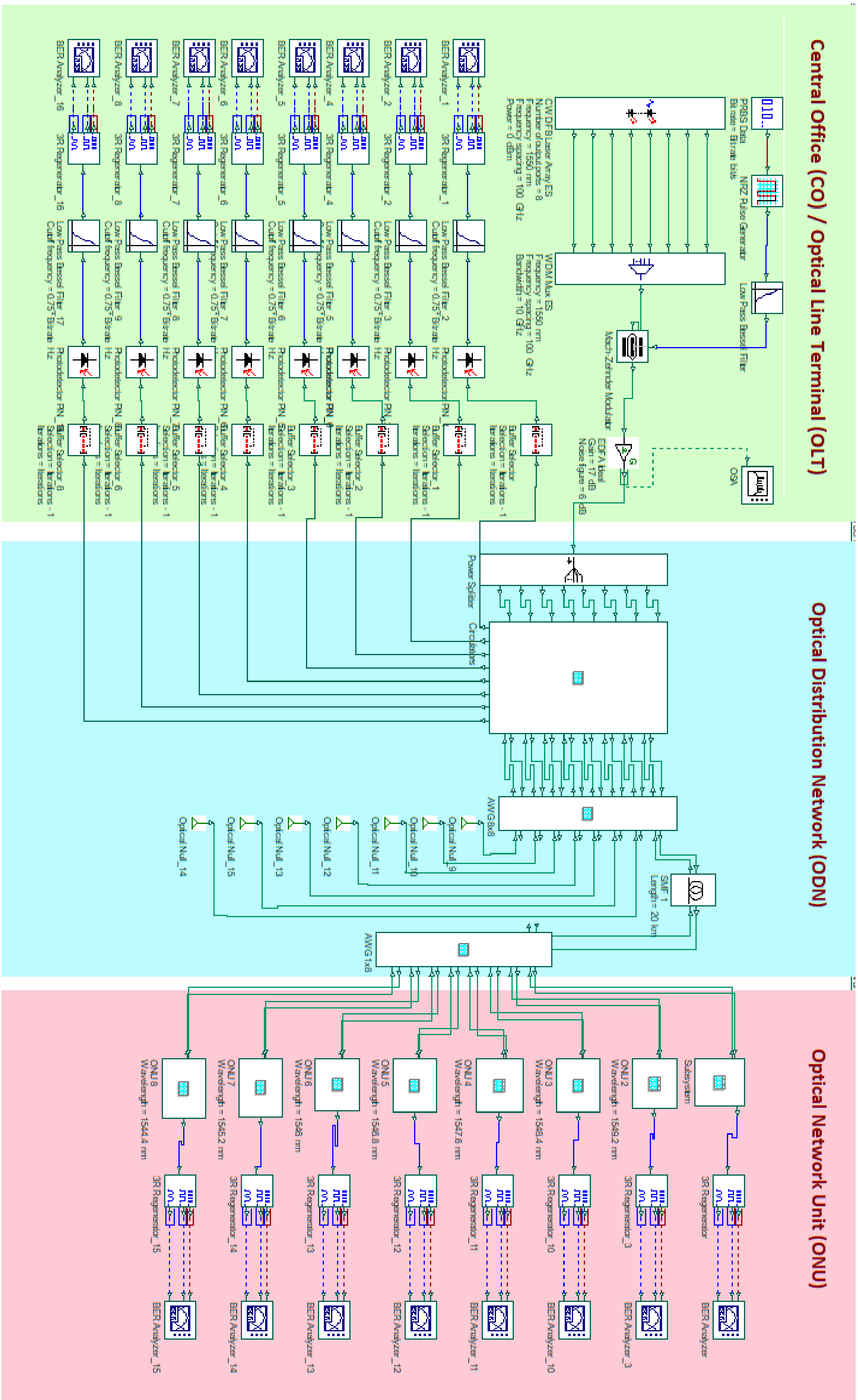


Figure 3.23: Next generation WDM-PON based FTTH network architecture Scheme

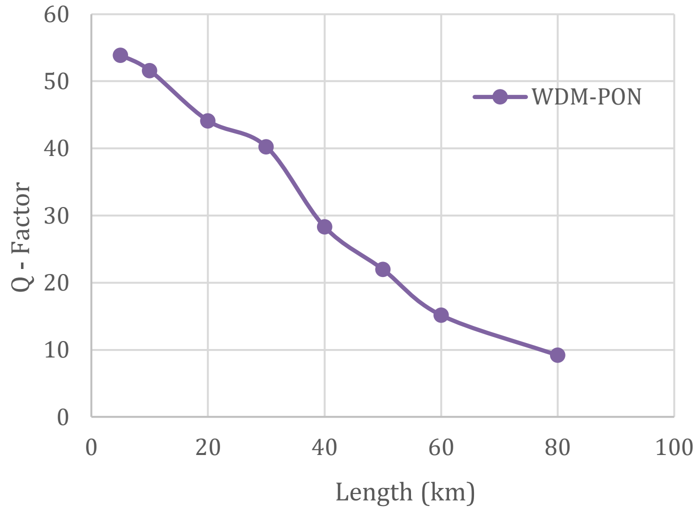
The design in Fig 3.23 presents the WDM-PON (Wavelength Division Multiplexing Passive Optical Network) system for NG-PON2 (Next Generation 2 of Passive Optical Network). This design aims to achieve high-speed data transmission over a realistic long-haul optical transmission distance. The fiber length is set to 20 km and attenuation to 0.2 dB/km. various components and techniques have been incorporated to ensure efficient signal transmission, including the use of EDFA (Erbium-Doped Fiber Amplifier) to compensate for the signal loss and maintain signal strength and multiple wavelengths for channel multiplexing. eight channels are used Each is assigned a specific wavelength and operates at a bitrate of 2.5 Gbps giving the architecture a total capacity of 20 Gbps (2.5 x 8) with a split ratio of 128 The primary analysis of the WDM-PON architecture was carried out based on the eye diagram and Q factor value.

3.4.3.1 Influence of distance variation on the quality factor

The following study demonstrates the influence of different lengths of fiber on Quality of Service (QoS) as represented by the Q-Factor. The values in the table represent the Q-Factor values for different distances ranging from 5 up to 80 km. for a bit rate of 20gbps (2.5 Gbps per channel ×8) and constant EDFA gain 17db and fiber attenuation of 0.2db/km

Distance (km)	**5**	**10**	**20**	**30**	**40**	**50**	**60**	**80**
Q-Factor	53.89	51.69	44.11	40.25	28.33	22.00	15.18	9.21

Table 3.8: Effect of distance variation on the Q factor (WDM-PON)



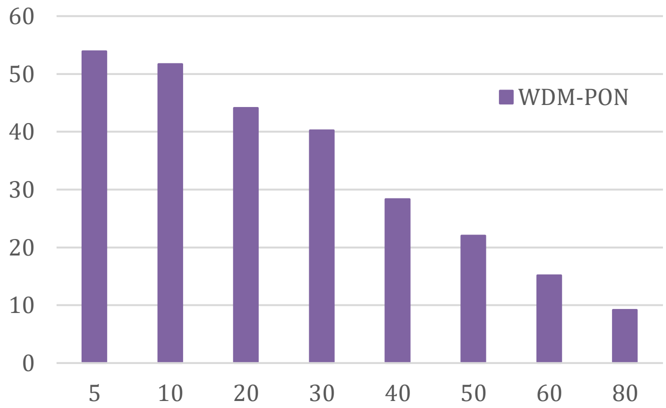


Fig 3.24: The influence of distance variation of the Q factor (WDM-PON)

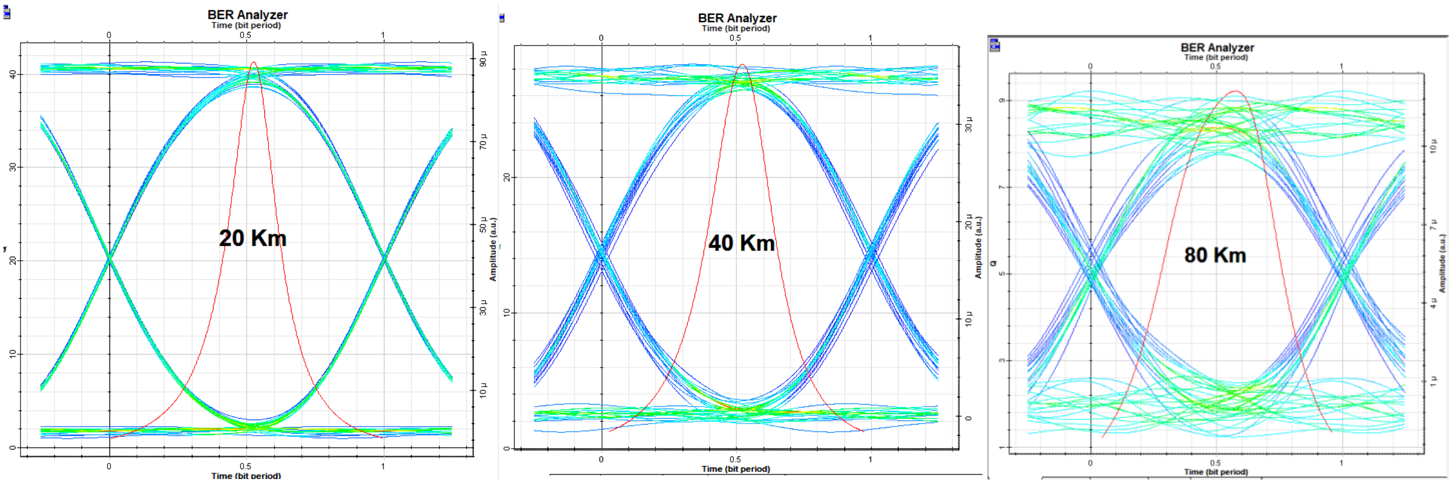


Fig 3.25: Eye diagram by variation of distance (WDM- PON)

It is noted that as the distance increases, the Q-Factor generally decreases, this reduction is not linear with distance. In Fig 3.24 due to the cumulative effect of signal degradation factors that become more pronounced over longer distances, however, the values of the Q-factor are considerably high in this NG-PON2 design compared to the previous architectures seen above in a distance of 20 km and it is relatively good to acceptable at higher lengths of fiber up to 80km as the eye-opening is shown to be very clear in the eye diagram with distances greater than 20km

3.4.3.2 Effect of the increase of EDFA's gain on the performance at longer distances

In order to analyze an optimized performance at longer coverage areas supported EDFA's gain is increased to 20db and to 30db along with the length of the fiber of 60 and 80 km, simulation results represented in Fig 3.26. It is noted that an increased gain of 30 dB permits the system to achieve superior performance at 80 km as the Q-factor value is up to 42.9 compared to 4.78 with 17db. This optimization is also presented as a clearer and wider eye diagram in Fig 3.28 thus it is important to set proper EDFA parameters as they affect very much the performance of the design.

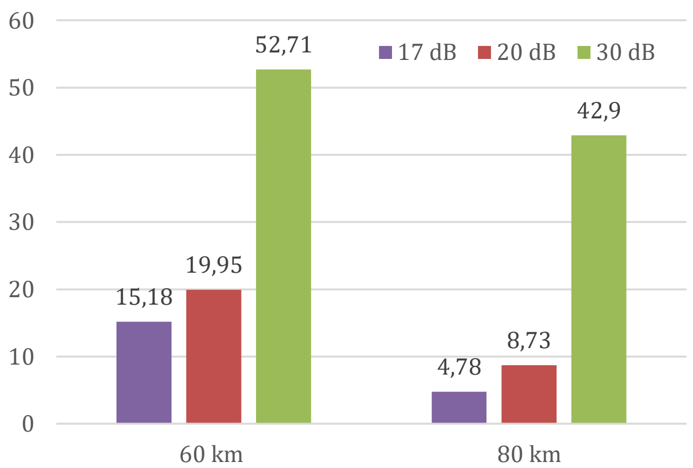


Fig 3.26 Performance analysis with an increase in the EDFA's gain

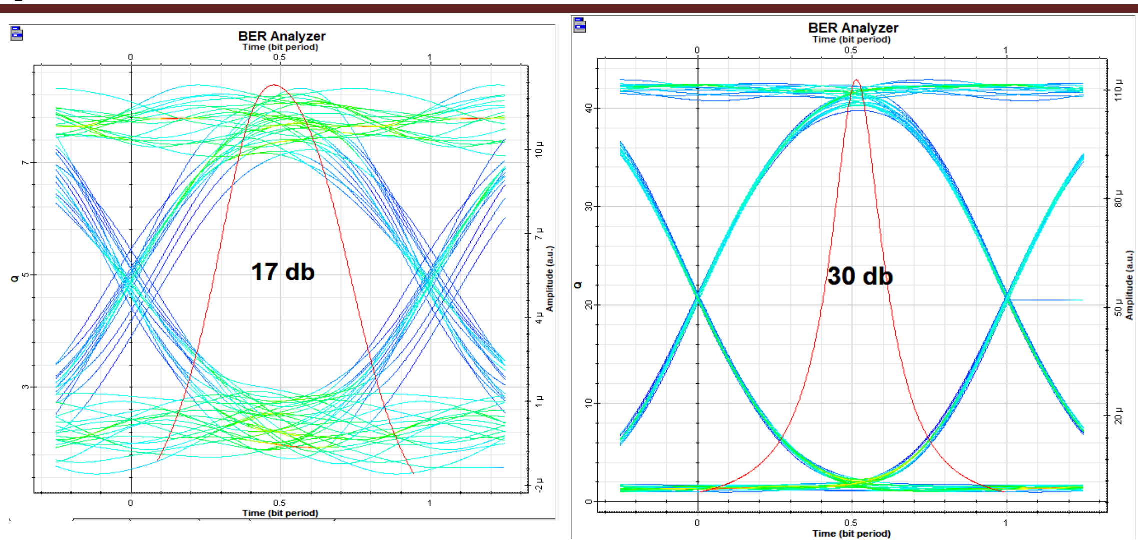


Fig 3.27: Eye diagram of WDM-PON with variation of EDFA's gain

3.4.3.3 Influence of transmission rate on the quality factor

To study the transmission rate capacity of this architecture, the data rate was increased from 1.5-2.5 to 5-10 Gbps and at last to 12.5 Gbps per channel (8 channels) respectively, with the same distance of 20 km, attenuation of 0.2db/km and EDFA gain of 17db. the Q factor values are presented in table 3.9 and Fig 3.28.

Bitrate (Gbps) x 8 channels	12.5	20	40	80	100
Bitrate (Gbps) per channel	1.5	2.5	5	10	12.5
Q-Factor	63.84	44.11	18.59	4.66	2.12

Table 3.9: Effect of Bit rate variation on the Q factor (WDM-PON)

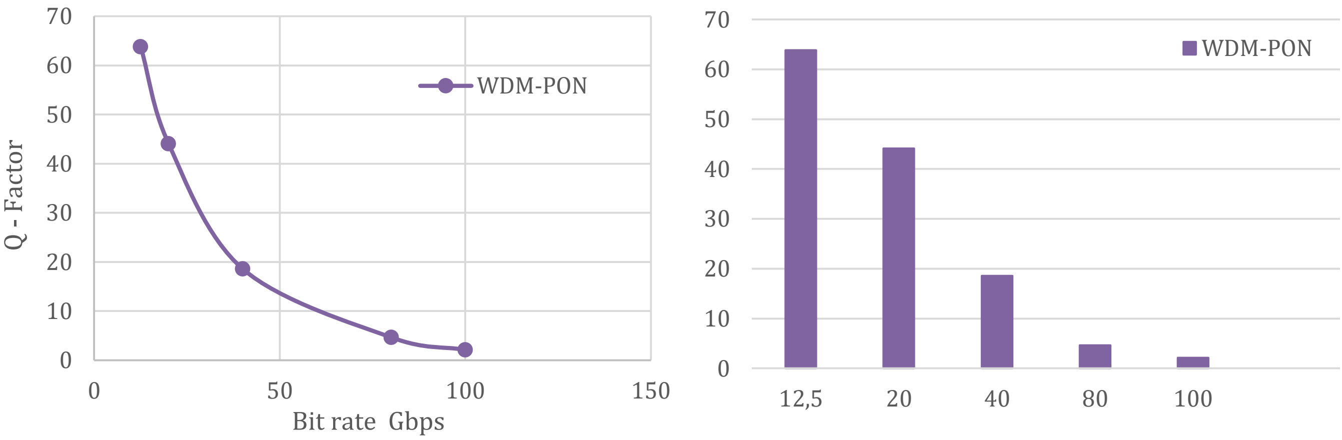


Fig 3.28: The influence of Bit rate variation of the Q factor (WDM-PON)

It is noted that a Q-Factor of 44.11 is obtained at a bit rate of 20 Gbps (2.5x8) indicating favorable signal quality in the considered WDM-PON system. It suggests that the system can support high-speed data transmission while maintaining a satisfactory level of signal integrity.

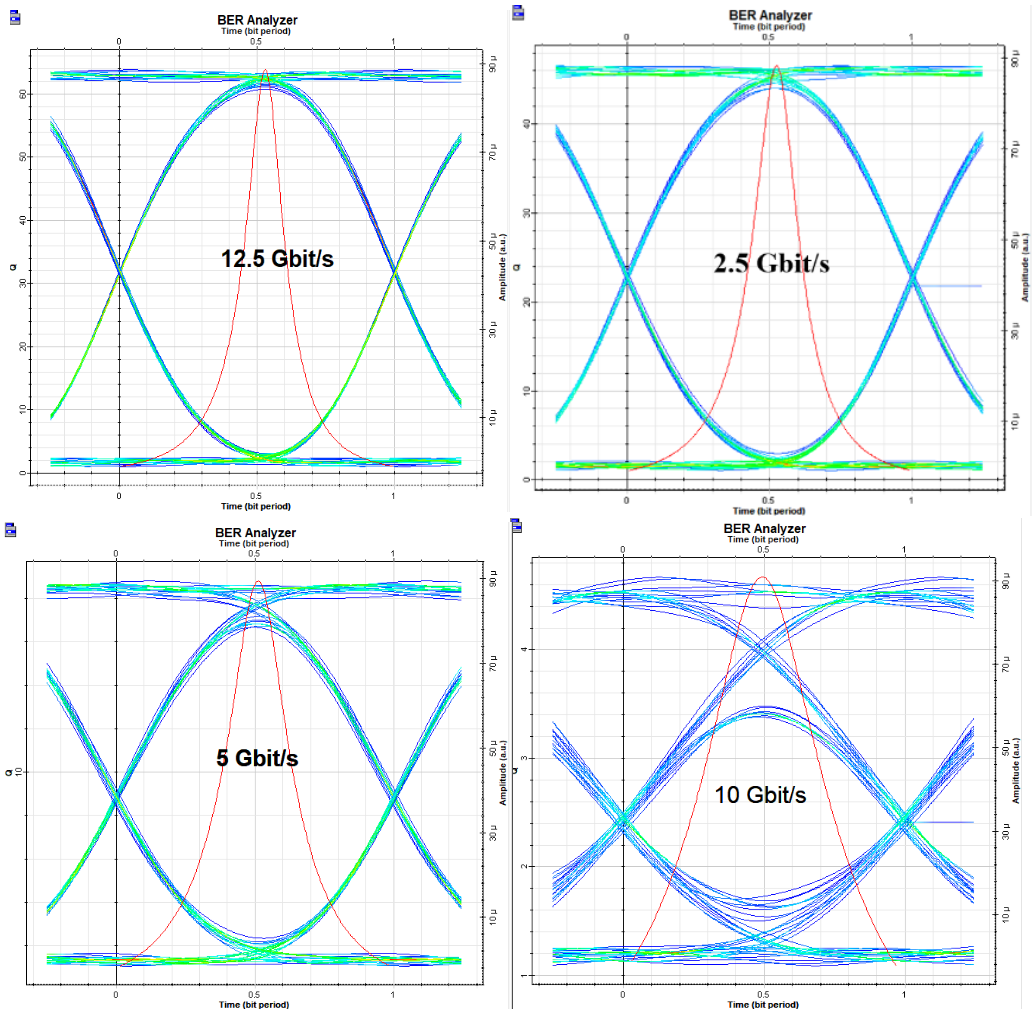


Fig 3.29: Eye diagram with variation of Bit rate (WDM- PON)

At 20 km, with data rates up to 5 Gbps, wide eye-opening was noted in eye diagrams in Fig 3.29. But with higher data rates the eye tends to close as shown for 10 Gbps, However, the significant reduction in the Q-Factor at higher bitrates highlights the challenges associated with transmitting data in NG-PON2 systems and the requirement to implement appropriate measures and techniques.

3.4.3.4 Effect of attenuation (loss) on optical transmission

The presented table shows the effect of attenuation on the optical transmission by evaluating the Q factor at different attenuation values at a distance of 20km

Attenuation (dB/km)	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**
Q-Factor	57.29	45.87	37.43	30.16	21.94

Table 3.10: Effect of attenuation variation on the Q factor (WDM-PON)

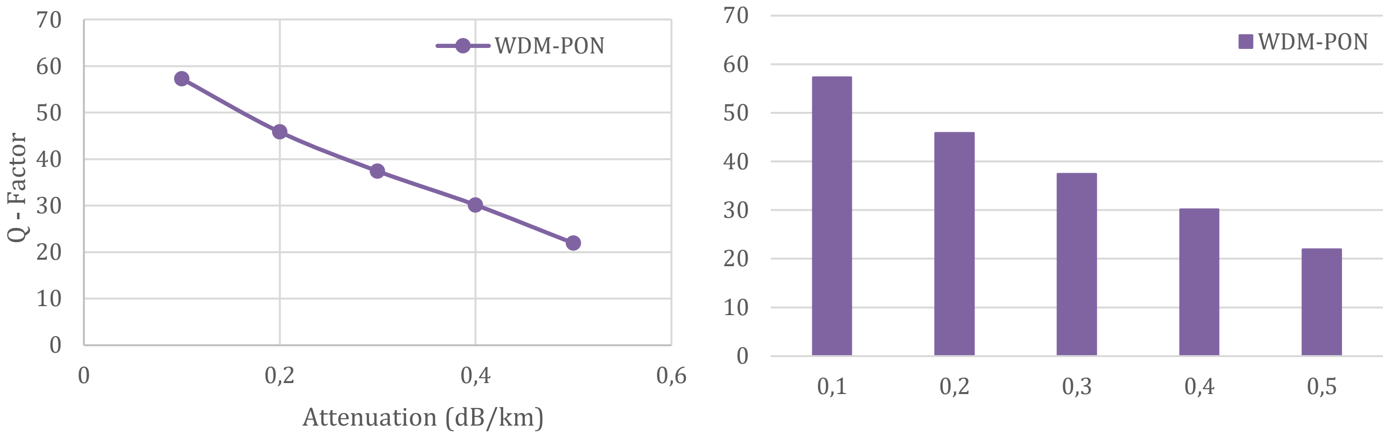


Fig 3.30: The influence of attenuation variation of the Q factor (WDM-PON)

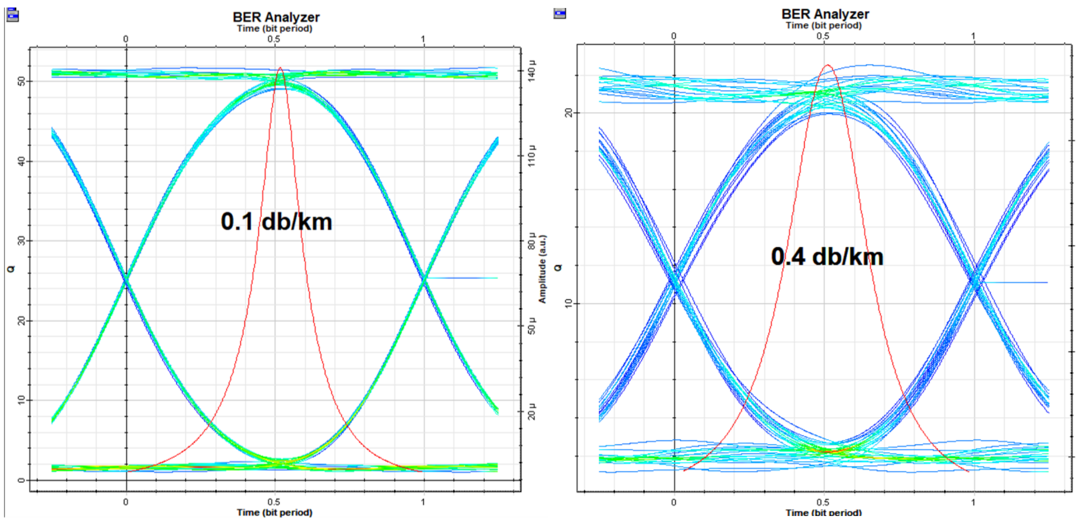


Fig 3.31: Eye diagram with variation of attenuation (WDM- PON)

As the attenuation increases, the Q-Factor decreases. This indicates that higher levels of signal attenuation result in a degradation of signal quality.

3.4.3.5 Effect of link type (bidirectional and unidirectional)

When the bidirectional fiber is changed to unidirectional fiber to observe the effect on the quality factor. It is noted that this last drop significantly from 47.97 to 12.99 with unidirectional fiber.

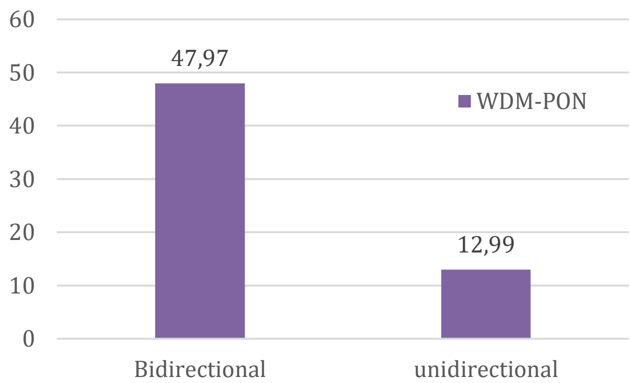


Fig 3.32: Quality factor in the bidirectional and unidirectional fiber

3.5. Performance parameters analysis

To compare the previous results, Figure 3.33 and 3.34 compare the PON performances at different distances and at different bitrates respectively, and Figure 3.35 displays the eye diagram and performance parameters of the PON architectures at 20 km.

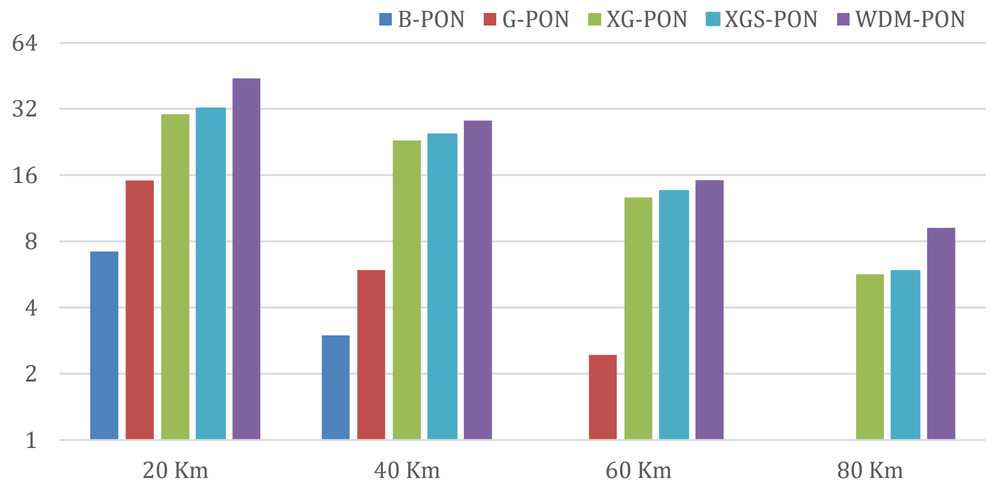


Fig 3.33: Q-factor of PON architectures at different distances

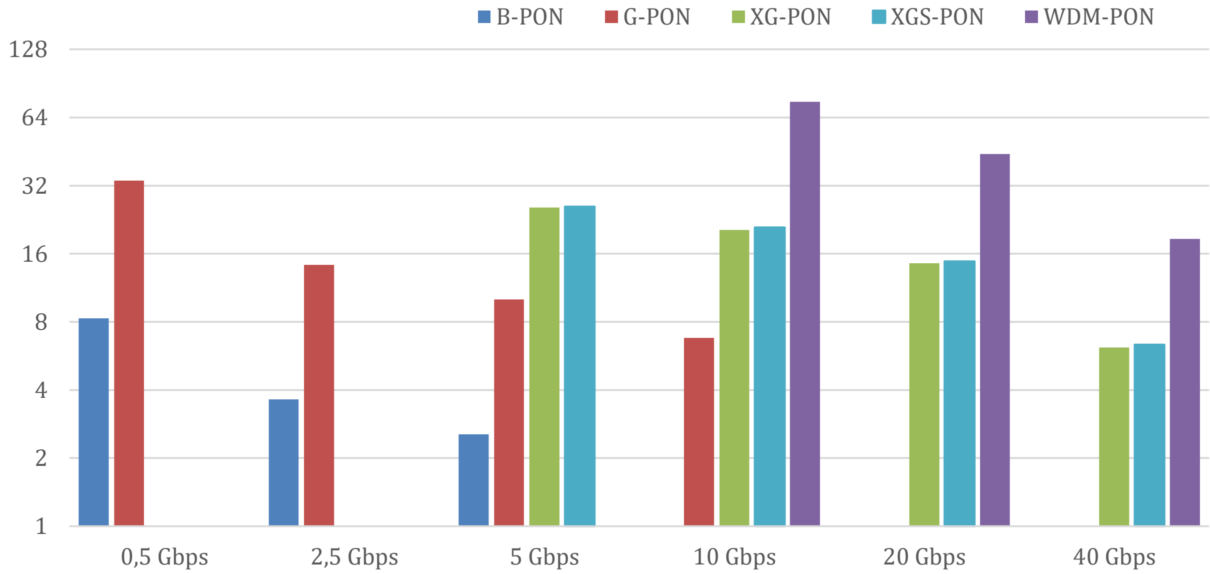
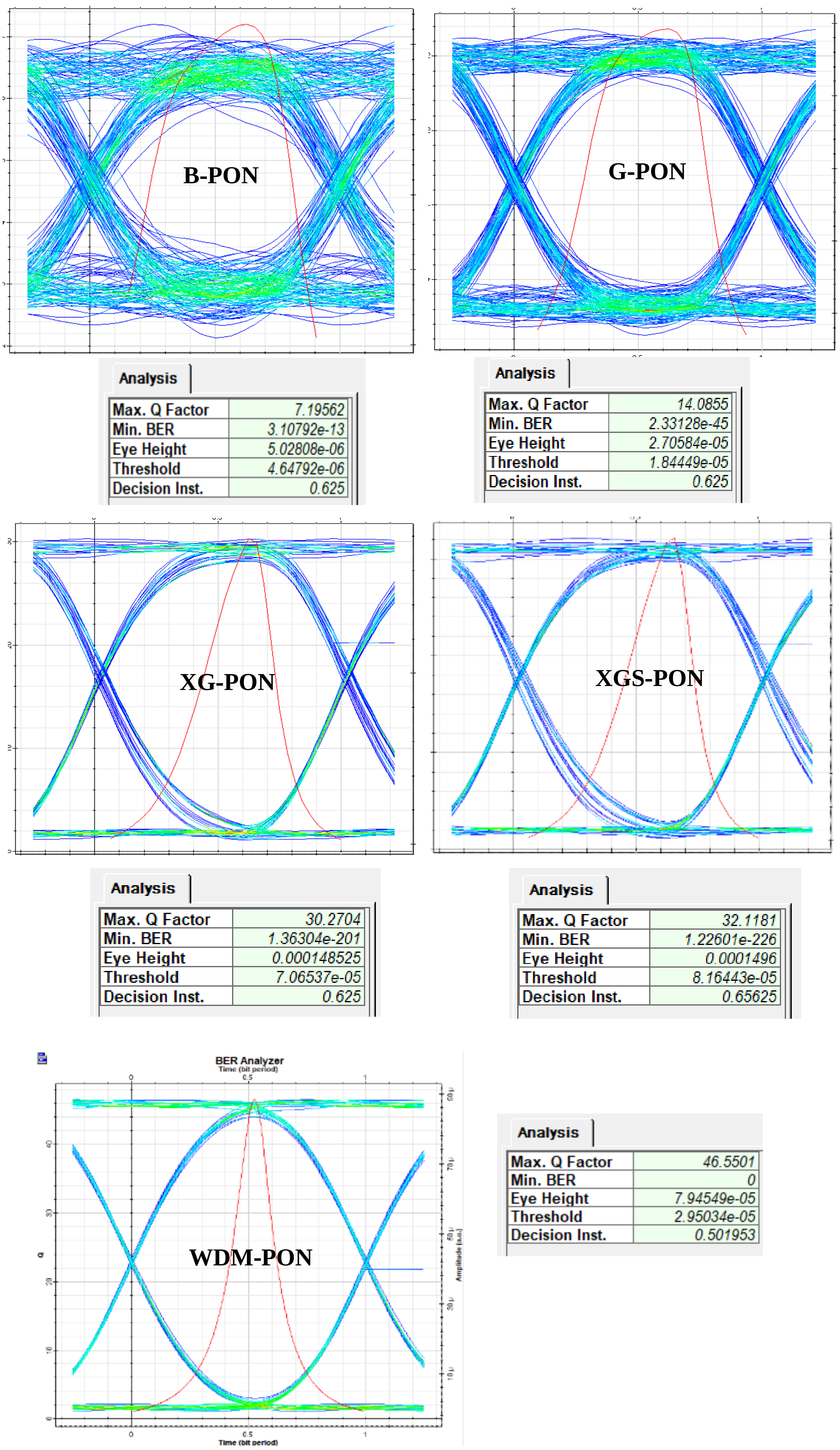


Fig 3.34: Q-factor of PON architectures at different bitrates



Analysis (B-PON)

Max. Q Factor	7.19562
Min. BER	3.10792e-13
Eye Height	5.02808e-06
Threshold	4.64792e-06
Decision Inst.	0.625

Analysis (G-PON)

Max. Q Factor	14.0855
Min. BER	2.33128e-45
Eye Height	2.70584e-05
Threshold	1.84449e-05
Decision Inst.	0.625

Analysis (XG-PON)

Max. Q Factor	30.2704
Min. BER	1.36304e-201
Eye Height	0.000148525
Threshold	7.06537e-05
Decision Inst.	0.625

Analysis (XGS-PON)

Max. Q Factor	32.1181
Min. BER	1.22601e-226
Eye Height	0.0001496
Threshold	8.16443e-05
Decision Inst.	0.65625

Analysis (WDM-PON)

Max. Q Factor	46.5501
Min. BER	0
Eye Height	7.94549e-05
Threshold	2.95034e-05
Decision Inst.	0.501953

Fig 3.35: Display of performance analysis of PON architectures

Regarding transmission distances, all PON architectures experience a decrease in Q-Factor values Figure 3.33 as the distance increases, However, XG-PON, XGS-PON, and WDM-PON exhibit better signal quality retention over longer distances compared to BPON and GPON. Also in terms of bit rates figure 3.34, XG-PON, XGS-PON, and WDM-PON consistently outperform BPON and GPON, offering higher Q-Factor values across a range of bit rates.

This was observed in Eye diagrams in Figure 3.35 as a larger eye-opening indicated superior signal quality and lower error rates, making them capable of supporting higher data rates and demanding applications. Notably, the next-generation WDM-PON shows the highest Q-Factor values, showcasing its potential for accommodating higher bit rates and providing excellent signal quality even at longer distances.

3.6. Conclusion

In this chapter, we conducted simulations to analyze the performance of various generations of PON systems considering variations in distances, transmission rates, and attenuation.
The Q-Factor and the size of the eye-opening were identified as critical parameters for assessing Quality of Service (QoS). It is concluded that good performance was achieved by XG(S)-PON and potentially even better performance is predicted with the next generation WDMPON. These architectures, have demonstrated remarkable progress in terms of signal quality compared to earlier PON technologies like BPON and GPON.

We believe that our work contributes to the advancement of optical communication systems for FTTH networks by giving a perspective for future developments in high-speed, long-distance data transmission.

General conclusion

The rapid growth and development of Fiber-to-the-Home (FTTH) networks have transformed the landscape of broadband access, providing high-speed and reliable connectivity to homes and businesses.

This research paper has delved initially into the fundamental concepts of optical transmission, laying the foundation for understanding the design and optimization of PON architectures and their evolution, and then provided an in-depth exploration of different FTTx types also discussed the evolutive standard architectures, technical specifications, and implementation requirements of PON-based FTTH networks.

The third chapter focused on the performance evaluation of various PON architectures using OptiSystem software as it outlined the simulation methodology, including the setup of the simulation environment and the performance metrics used to evaluate the five different architectures: BPON, GPON as the applied generation XG-PON, XGS-PON as next generation 1(NG-PON1), and Next-generation WDM-PON as the proposed technology for NG-PON2. The simulation results, considering parameters such as fiber length and bit rate, provided valuable insights into the network performance, assessed through metrics like Q-factor and eye diagram, which are essential for evaluating the quality of service (QoS)
Through this research, it has become evident that next-generation PON, such as XG-PON and NG-PON2 offer enhanced performance, flexibility, and support for future network upgrades. These architectures address the increasing bandwidth demands including higher speed and extended coverage driven by emerging technologies like 5G, IoT, and cloud computing. Standardization of higher data rates has become imperative to meet evolving needs, particularly with the surge in demand during the COVID-19 pandemic.

Looking ahead, the future of FTTH networks holds immense potential. As technologies continue to evolve, the integration of advanced PON architectures, along with emerging technologies like WDM-PONs and hybrid-PONs, will further expand the capabilities of FTTH networks. This will enable the seamless integration of smart homes, autonomous vehicles, remote healthcare, and immersive multimedia experiences. Furthermore, ongoing research and standardization efforts in next-generation PON technologies will drive continuous advancements in bandwidth capacity, coverage, and cost-effectiveness.

We conclude that the findings in this research contribute to the understanding of the advantages and performance characteristics of these architectures, laying the groundwork for the continued evolution of FTTH networks and offering a glimpse into the promising future of high-speed broadband connectivity for all.

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