Design of Mode Division Multiplexing for High Data Rate Passive Optical Networks Using Radio Over Fiber Technology

Tolossa Assefa Seyoume

A Thesis Submitted to Department of Electronics and Communication Engineering,

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Communication Engineering

Office of Graduate Studies

Adama Science and Technology University

June 2023

Adama, Ethiopia

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APPROVAL PAGE OF M.SC. THESIS

We, the advisors of the thesis entitled "**Design of Mode Division Multiplexing for High Data Rate Passive Optical Networks Using Radio Over Fiber Technology** "developed by **Tolossa Assefa Seyoume**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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I hereby declare that this Master Thesis entitled "**Design of Mode Division Multiplexing for High Data Rate Passive Optical Networks Using Radio Over Fiber Technology**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

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We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "**Design of Mode Division Multiplexing for High Data Rate Passive Optical Networks Using Radio Over Fiber Technology**" prepared under our guidance by **Tolossa Assefa Seyoume** submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electronics and Communication Engineering. Therefore, we recommend the submission of a revised version of the thesis to the department following the applicable procedures.

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LIST OF ABBREVIATIONS

AON	Active Optical Network
ATM	Asynchronous Transfer Mode
BON	Broad band passive optical network
BW	Bandwidth
BER	Bit error ratio
CO	Central Office
CPE	Customer Premises Equipment
CSRZ	Compressed Spectrum Return to Zero
DC	Direct Current
DPSK	Differential phase shift keying
DR	Dynamic Range
DSL	Digital subscriber line
HDTV	High-Definition Television
EDFA	Erbium-Doped Fiber Amplifiers
EPON	Ethernet Passive Optical Network
FiOS	FiOSFiber Optic Services
HFR	Hybrid Fiber Radio
FTTH	Fiber to the Home
Gbps	Gigabit per second
GPON	Gigabit Passive Optical Network
GSM	Global System for Mobile Gateway Router
GWR	Gateway Router
Hz	Hertz (Cycle per second)
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISDN	Integrated Service Digital Network
ISI	Inter-Symbol-Interference
ISP	Internet Service Provider
I	In phase

ITU-T	International Telecommunication Union
LG	Laguerre Gaussian
LR	Long Reach
NF	Noise Figure
nm	nanometers
MAC	Media Access Control
Mbps	Megabit per second
MDM	Mode Division Multiplexing
MMF	Multi-mode fiber
NF	Noise Figure
NRZ	Non-Return-to-Zero
MU	Mobile Unit
NG-PON	Next-Generation Passive Optical Network
ODN	Optical Distribution Network
OLT	Optical Line Terminal
ONU	Optical Network Unit
OFDM	Orthogonal Frequency Division Multiplexing
OOK	on-off Keying
PDM	polarization Division Multiplexing
PMP	point to multi-point
PON	Passive Optical Network
P2P	point to point
P2MP	Point-To-Multi-Point
PRBS	pseudo-random bit sequence
Q	Quadrature
QAM	Quadrature Amplitude Modulation
QOS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RN	Remote Nodes
RoF	Radio Over Fiber
SDH	Synchronous Digital Hierarchy

SONET	Synchronous Optical Network
SNR	Signal-to-Noise Ratio
SMF	Single-mode fiber
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TDM-PON	Time Division Multiplexing PON
UL	Uplink
VCSEL	Vertical Cavity Surface Emitting Laser
VGW	Voice gateway
WDM	Wavelength Division Multiplexing
WDM-PON	Wavelength Division Multiplexing
WIMAX	Worldwide Interoperability for Microwave Access

ABSTRACT

Passive Optical Networks (PON) are a recent technological development that has emerged in recent years. Nowadays, there is a growing and increasing need for high-speed data rates in wired and wireless networks. A cost-effective and efficient approach for deploying large bandwidth systems that can support high-speed connectivity is the implementation of the Radio-over-Fiber (RoF) system, which serves as a credible architecture for both wired and wireless access. The bandwidth limitation of access networks, coupled with the growing demand for high-spectrum bandwidth and restriction access technologies, has led to the implementation of fiber to the home (FTTH) as a means of providing high-speed services. MDM is investigated during transmitting of high data rates for increasing capacity in transmission systems and optical access networks. The aim of the thesis is to overcome the limits of traditional PONs by using MDM-based PONs with RoF technology to obtain a high capacity data rate for comparing RF and electrical constellation of 8-DPSK and 16-QAM. In this work, performance analyses were performed by Optisystem software by considering different parameters like eye diagrams, Q-factor, BER and the efficiency of the noise removal. From the analysis result good maximum Q-factor is 30.182 at 2.5 Gbps and 5km, which shows that the system performance is high, and the Good BER value2.03832e-200, at 5km, 2.5 Gbps and the choice between 8-DPSK and 16-QAM depends on the specific requirements of the communication system.16-QAM is preferred due to it has high spectral efficiency. The performance analysis of Mode division multiplexing during the Bessel filter and without the Bessel filter is understood. At a data rate of 2.5 Gbps and 20 km, the Q factor for MDM with a Bessel filter is 13.3265, and without a Bessel filter is 5.718. This indicates that using a Bessel filter can improve signal quality and result in a higher Q factor.

Keywords*: BER, eye diagram, FTTH, Q-factor, MDM -PON, 8-DPSK, 16-QAM, RoF, RF.*

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

In recent times, the capacity of optical communication systems has seen exponential growth in response to the increasing demand for large bandwidth to handle data traffic. (Abdellaoui et al., 2021). The intensive use of internet services has caused a significant surge in internet traffic due to the intense use of internet services including Triple Play Services, video calls, online gaming, the Internet of things, cloud services, and high-definition television (HDTV). Due to technological improvements, delivering value-added services to subscribers has created several new economic options for telecom operators.

Many technologies have been implemented to address the need for high bandwidth, they are often overlooked in favor of longer-term growth in access networks. The demand for bandwidth on access networks has been increasing at an exponential rate over the past several years. (Almalaq & Matin, 2014). The high demand for bandwidth has led to the development of a broadband access network based on fiber-to-the-home (FTTH) technology. Among the various FTTH implementations, a passive optical network (PON) is considered the most suitable option. (Lee, 2005). A PON is a type of optical fiber connection that utilizes passive optical components to direct traffic signals within a range of wavelengths to the user premises and back to the central office, without requiring any active components or power supply. The passive optical network has several advantages over other access technologies, such as the ability to provide high bandwidth and large coverage area, as well as low maintenance costs due to the use of passive components in the network. Additionally, PONs can deliver significantly more bandwidth compared to coaxial cables(Almalaq & Matin, 2014). A PON consists of several components, including the Optical Line Terminal (OLT) located in the central office, Remote Nodes (RNs) equipped with couplers or splitters to multiplex and de-multiplex the downstream and upstream traffic, and multiple Optical Network Units (ONUs) that receive the downstream traffic from the RN and transmit upstream traffic back to the RN (Almalaq & Matin, 2014).

In the future of telecommunications networks, users will require high-speed data rates, mobility, and large capacity. In the past, radio signals were primarily used for voice and low-rate data communication, while optical signals were utilized for high-bandwidth wired communication systems. However, with the growing demand for internet-based services such as video on demand, video conferencing, gaming, and IPTV, new access methods are being developed to meet the bandwidth requirements of these applications.

Copper-based access networks have a limitation on both distance and bandwidth and are expected to run out of capacity shortly. But optical networking is well-established in long-haul and backbone networks is rapidly becoming the preferred technology for metropolitan and local area networks and may even be used in homes and offices. The Passive Optical Network (PON) is an access network that uses optical fiber to provide virtually unlimited bandwidth to subscribers. In a PON, a single shared optical fiber is divided towards individual subscribers using passive optical splitters, which means that there are no active elements within the access network other than at the central office.

A passive optical network with optical fiber is a promising candidate for providing substantially more bandwidth for triple play offering voice, video, and Data, extending the transmission distance, and ensuring the reliability of services. A passive optical network (PON) based on optical fiber is a highly promising solution for delivering significantly more bandwidth and extending transmission distance, a choice for triple-play services that require voice, video, and data transmission. Governments and private organizations across the globe have recognized the benefits of Fiber-to-the-Home (FTTH) technology, resulting in millions of homes and businesses being connected to optical fiber networks annually(Forzati et al., 2011).

Passive Optical Networks (PONs) are increasingly being used in the deployment of Fiber-to-the-Home (FTTH) infrastructure, driven by the need for high-speed transmission and the development of competitive signal processing platforms and switching devices. However, meeting the growing demand for broadband and mobile communications is a significant challenge for all network technologies. As a cost-effective solution to address this challenge, Wireless networks based on Radio-over-Fiber (RoF) technologies have been proposed to meet the ever-increasing bandwidth and wireless demands of users.

Radio-over-Fiber (RoF) technology is used to transmit high-frequency RF signals over an optical fiber by modulating a light carrier signal. RoF has several advantages, including low propagation loss that is independent of the RF signal, a large bandwidth, immunity to RF-induced interference, low complexity, and low power consumption. RoF is well-suited for applications such as base-station to base-station, base-station to mobile switching centers, central hubs to homes/offices for high-quality video distribution, and mobile broadband services. This technology enables the transmission of wireless signals over low-loss optical fibers, which is not possible through direct transmission of radio signals. The integration of wireless and wireline solutions using RoF has opened up promising opportunities for broadband networks, providing network and service providers with the ability to offer mobility, bandwidth, and multiple modes of connectivity to their customers (Almalaq & Matin, 2014).

To enable baseband and RF technologies to coexist in the same access network, broadband modulation techniques are being implemented. These techniques take advantage of the high bandwidth capabilities of optical fiber, allowing for the integration of a mix of services and technologies such as Passive Optical Networks (PONs), cellular mobile, and fixed wireless base stations on a single fiber infrastructure. The integration of these technologies over the same optical infrastructure is evaluated based on existing standards of fiber access and radio network. PONs is a popular type of fiber-optic network that is widely used to deliver broadband services to end-users.

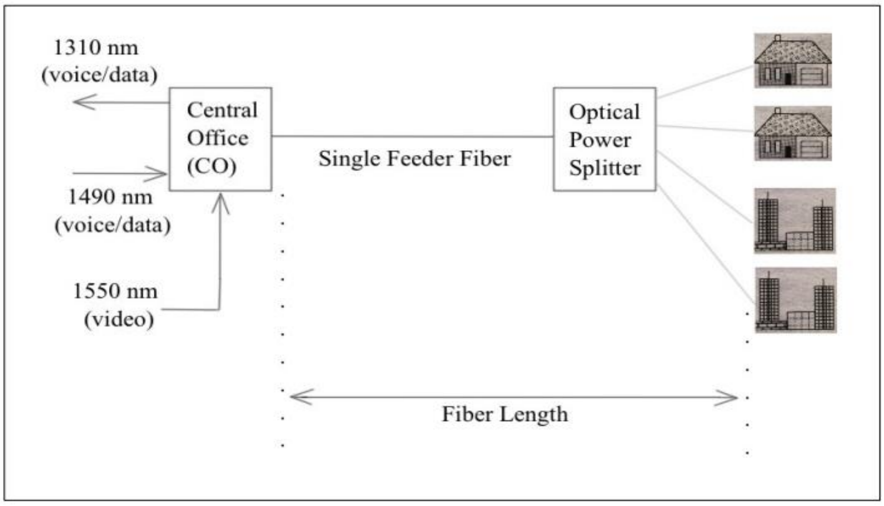

Figure 1. 1 PON architecture (Almalaq & Matin, 2014)

A PON system usually consists of an Optical Line Terminal (OLT) located in the central office and an Optical Network Unit (ONU) located at the end-user. In PON systems, the need for high-capacity data rates is driven by the increasing demand for bandwidth-intensive applications. One of the main advantages of PON technology is its ability to provide high-speed broadband services using a shared optical fiber infrastructure.

The total available bandwidth in a PON network is divided among multiple users using time-division multiplexing (TDM) or wavelength-division multiplexing (WDM) techniques. All users connected to the OLT thereby share the PON network's whole capacity. To meet the increasing demand for high-capacity data rate in PON systems, network providers have implemented different technologies such as wavelength division multiplexing (WDM-PON) which allows multiple wavelengths to be used to transmit data over the same fiber and symmetrical 10-Gigabit-capable passive optical networks. In addition to WDM-PON, Mode division multiplexing technologies are used for higher data rates and improved network performance to meet the changing demands of end-users for high-speed data services.

Mode Division Multiplexing (MDM) is an advanced technique used in Passive Optical Networks (PONs) to increase the capacity and data rates of systems. PONs use fiber optic cables to transmit data over long distances, and MDM allows multiple data signals to be transmitted on different modes of the same fiber. Radio over Fiber (RoF) technology is a technique used to transmit radio signals over optical fibers. RoF is useful in PONs because it allows the transmission of high-speed data over long distances, which is important for applications such as broadband internet and video streaming. MDM-based PONs and RoF technology work together to provide high-capacity data rates. MDM technology divides the available bandwidth on the fiber optic cable into separate modes, each capable of carrying data independently. This allows for multiple data streams to be transmitted simultaneously over the same fiber.

RoF technology then converts the data into a radio frequency signal that is transmitted over the fiber, increasing the range over which the data can be transmitted. The combination of MDM and RoF provides a high-bandwidth, low-latency communication system, making it well-suited for applications such as video streaming, cloud computing, and virtual reality. MDM-PONs can be used to meet the demands of modern communication networks that require high-speed data transmission. By using MDM-PONs with RoF technology, users can benefit from high-speed internet and other digital services, such as video conferencing, online gaming, and cloud-based storage. Therefore, the Mode division multiplexing-based passive optical network with RoF technology provides a high-capacity and high-speed data transmission solution that is suitable for future communication networks.

1.2 Statement of Problem

The rapidly growing demand for data capacity and transmission bandwidth worldwide has made optical fiber a preferred transmission medium for access networks.

To enhance transmission capacity and bandwidth, various multiplexing technologies such as wavelength division multiplexing (WDM), time division multiplexing (TDM), and polarization division multiplexing (PDM) are being explored. However, the capacity of standard single-mode optical fibers is currently facing a crisis. Mode division multiplexing (MDM) technology is being explored as an effective solution for the capacity crisis, as it can keep bandwidth for a single transceiver significantly higher by increasing the total transmission capacity. Therefore, considering the MDM technique based on passive optical and Radio over fiber will be reduced the problem of capacity and bandwidth efficiency of the optical access network of fiber to the home with a High data rate. The purpose of this thesis is to overcome the capacity limitation in single mode by using MDM-based PONs with RoF technology to obtain a high capacity data rate.

1.3 Objective of the study

1.3.1 General Objective

The main objective of this thesis is to investigate mode division multiplexing-based passive optical networks for high-capacity data rates via radio over fiber technology.

1.3.2 Specific Objectives

The specific objectives of this work are;

- To design Mode Division Multiplexing Passive optical network for high data rates by using 8-DPSK and 16-QAM digital modulation.
- To measure the performance and efficiency of the noise removal systems by using a Bessel filter at various optical transmission lengths.
- To compare the performance, like BER, eye diagram, and Q-factor of the system at various optical transmission lengths with Digital modulation of 8-DPSK and 16-QAM.

1.4 Scope of the Study

This thesis focuses on improving the capacity of Passive Optical Networks (PON) for high data rates over a single fiber. Radio over fiber and mode division multiplexing are selected for delivering high data rates. Digital modulation of 8-DPSK and 16-QAM are applied to increase the data transfer for high data rates. The performance systems are compared by using a Bessel filter and without Bessel at various optical transmission lengths. Finally, the comparison of the Q-factor, BER and Eye diagram at the various transmission are considered to e3get good performance of the system. All simulations of the proposed are done using by Optisystem 20 software communication tools.

1.5 Significance of the Study

The deployment of Passive Optical Network (PON) technology is primarily aimed at residential markets, where it enables the provision of triple-play services, including voice, data, and video simultaneously. Thus, the significance of this thesis is that it provides a new approach to increasing the data rate and capacity of optical networks. The radio over fiber technology enables the implementation of advanced modulation schemes, providing high bandwidth and reduced latency, and the MDM-PON technology increases the capacity of the optical fiber network by using the light's spatial modes. Therefore, the significance of this study lies in its potential to improve optical network performance and provide a solution to meet the increasing demand for high-speed data transmission services.

1.6 Thesis Contribution

This thesis identifies the potential of MDM-based PONs to support high-capacity data rate transmission. It investigates the use of different MDM techniques such as spatial mode multiplexing, mode selector, and multimode generator. Capacity crisis in single fiber reduced by using Radio over fiber technology and MDM which supports the transmission of high-capacity data from the central office to the optical unit terminal of the end user. The thesis evaluates the transmission quality of the system using different performances such as bit error rate, Quality factor, and eye diagram analysis. The thesis demonstrates the performance of MDM-based PON over conventional PON in terms of transmission rate and distance. Therefore, the main contribution of this thesis is to overcome capacity crisis over single fiber by using mode division multiplexing by using radio over fiber technology.

1.7 Limitations of the Study

This thesis is limited only to simulation-based results by using optisystem software and the performance of all passive optical networks for high capacity data rate are evaluated based on simulation results only.

1.8 Organization of the Thesis

The thesis is organized into five chapters, with the first chapter providing an introduction, including a statement of the problem, research objectives, scope, significance, and primary contribution of the thesis.

Chapter 1 (**Introduction):** chapter provides the background of the study, an introduction to the research topic, research objectives, a statement of the problem, the scope of the study, and an explanation of the significance of the thesis.

Chapter 2 (Literature Review): This chapter provides a Review of different literature on radio over fiber, Mode division multiplexing, and passive optical networks.

Chapter 3 (Methodology): This chapter mainly focuses on the system model, materials, and methods used to accomplish the research work, modulation technique, and simulation parameters by using Optisystem 20 software.

Chapter 4 (Results and Discussion): This chapter is dedicated to the presentation and analysis of simulation results obtained with OptiSystem software, with a particular focus on the results related to bit error rate (BER) and Q-factor.

Chapter 5 (Conclusion and Future Work): The final chapter of the thesis presents a comprehensive summary of the research findings, a conclusion based on the results, and recommendations for the future.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction.

Optical fiber-based access networks have the potential to meet the growing demand for connections with fast data transfer rates, and one of the emerging technologies that can support this demand is Passive Optical Networks (PONs). Existing fiber-to-the-home access networks need to be upgraded to meet future bandwidth demands. To increase network throughput, it is not recommended to replace the existing Passive Optical Network (PON) infrastructure, as these networks are expected to have a lifespan of over 25 years (Chauhan, 2019). Implementing fiber-based access systems may necessitate support for high-speed networks. Passive Optical Networks are one of the recent technological advancements. To provide clients with large bandwidths, fiber-to-the-house (FTTX) has long been envisioned as an appealing future access option. The implementation of fiber-based access systems has faced obstacles due to the prevalence and advancement of copper-based broadband technologies such as cable modems and digital subscriber lines. Currently, the global development of fiber access networks is being driven by the increasing demand for high-bandwidth services, such as IP television and video on demand, as well as changing competitive and regulatory factors. (Forge & Vu, 2020)**.**

The increased usage of P2P, HDTV, 3DTV, and Cloud Computing has led to a rise in bandwidth requirements, which creates new challenges for bandwidth deployment and operation. Passive Optical Networks (PONs) are a cost-effective optical access network architecture that is increasingly popular as they are shared among multiple customers and do not involve any active components, such as electronic switches or routers, between the central office or local exchange and the customer. An optical network that connects a central office optical line terminal to multiple remote optical network units using one or more optical splitters is called a point-to-multipoint (PON) optical network. There is passive networking between the ONU and OLT. The evolution of PON is a serious problem for the telecom sector. As the demand for bandwidth continues to rise, the need for next-generation passive optical networks is becoming increasingly important, with standardization efforts underway by ITU-T and IEEE. The future access network will also need higher bit rates of up to 10 GB/s to meet the growing traffic demands. The FSAN group has proposed two stages of NG evolution, NG-PON1, and NG-PON2. The current optical 2 distribution network (ODN) is compatible with NG-PON1 and an extension of the existing G-PON standards.

The long-term remedy is NG-PON2, which uses a brand-new kind of optical network. On the other hand, NG-PON1 is a short-term improvement over the G-PON system that is backward compatible with the currently deployed fiber networks. Additionally, known as XG-PON1, NG-PON1 is a proton. XG-PON1 offers an asymmetrical transmission speed of 10 Gbps downstream and 2.5 Gbps upstream(N. Sharma & Gupta, 2016). To transmit large amounts of data cost-effectively, a downstream transmission speed of 10 Gbps is preferred. However, the 10 Gbps burst mode time division multiple access presents a challenge due to its high data rate in the upstream direction. Designing and manufacturing components that can handle 10 Gbps upstream transmission is complex and expensive, making it an unrealistic option. Therefore, an affordable and practical alternative is to upgrade to a 2.5 Gbps upstream transmission speed(Xu et al., 2007).

The first PON generations are currently standardized and available. LR-PONs represent a significant development in the progress of access-metro optical networks. These networks are characterized by a larger number of optical network units and a greater distance between the optical line terminal and the ONUs. Additionally, they use a single upstream and downstream channel(Davey et al., 2006). Standard PONs usually have a maximum reach of 20km, but LR-PONs are designed to cover much longer distances of up to 100km. Advanced optical communication technologies, such as optical amplification, can be used to extend transmission distances even further, allowing for the integration of multiple optical communication systems into a single Long-Reach/Amplifier PON (Mondal, 2016).

2.2 PON Access Technology Evolution

Optical networks use optical fiber access technology to provide a range of broadband services to users. PON is a telecommunications network that utilizes fiber-optic lines for data transmission and does not require active components between the central office and the customer. Instead, passive optical components manage traffic, with the splitter being a critical component that enables a single fiber-optic line to serve multiple users. PON's cost-effectiveness makes it an attractive option for end-user networks, and it is a P2MP system that offers a more efficient data transmission method than point-to-point networks such as SDH/SONET(Novak et al., 2016). The point-to-multipoint (P2MP) architecture has emerged as a popular solution for deploying Fiber to the X (FTTx) networks among telecommunications operators. In this architecture, the Optical Line Terminal is the central location, and the individual destinations are Optical Network Units. The network between the OLT and the ONUs is passive, which means it does not need a power supply(Gaur et al., 2014).

2.3 Types of Passive Optical Networks

Access technologies have employed different PON systems over time, including APON, BPON, EPON, GPON, 10G EPON, and Next-Generation PON1 (NG-PON1).

2.3.1 Asynchronous PON (APON)

The ITU-T FSAN group standardized the first generation of the PON series in the mid-1990s, which aimed to establish end-to-end ATM connections via a point-to-multipoint tree configuration. This was because ATM was the primary protocol for telephone networks and data transfer at that time. APON networks could serve up to 32 subscribers and offer an upstream data rate of 155 Mbps and a downstream data rate of 622 or 155 Mbps (asymmetric). The IEEE 802.3 family specified the maximum data rate for APON to be between 622 Mbps and 1.244 Gbps(Chang, 2008).

2.3.2 Broadband PON (BPON)

ITU-T G.983 series defined Broadband PON (BPON) as an improvement over APON, with the goal of cost-effective deployment of broadband optical access systems. BPON offers various broadband services, including ATM, Ethernet access, and video distribution. Like APON, BPON uses ATM as the signaling and transport protocol but provides enhanced security. The main difference between BPON and APON is that BPON allows for video distribution, while APON did not prioritize video. BPON also utilizes Wavelength Division Multiplexing more effectively by adding extra wavelengths for video distribution. The digital signals in BPON operate at ATM rates of 155, 622, and 1244 Mbps(Lam, 2007).

2.3.3 Ethernet PON (EPON)

EPON, an IEEE standard (IEEE 802.3. ah), utilizes Ethernet frames for data transmission and offers seamless integration with IP and Ethernet technologies. EPON is widely adopted due to its scalability, simplicity, and capability to provide full-service access. Furthermore, EPON safeguards the Ethernet framing format, enabling it to carry variable-length packets without damage. EPON operates symmetrically at a data rate of 1.25Gbps in both the upstream and downstream directions, with a maximum distance of 20 km and 32 splits(Lamb, 2009).

2.3.4 10G-EPON

The 10G-EPON, also known as the IEEE 802.3av standard, was introduced in 2009 to increase the data rate of the EPON system from 1Gbps to 10Gbps. 10G-EPON uses the MPCP protocol of EPON and focuses on the physical layer. The IEEE 802.3av standard aimed to increase data rates to 10 Gbps while ensuring coexistence with the previous EPON version (802.3. ah) on the same Optical Distribution Network (ODN) network, allowing for simpler upgrades. 10G-EPON offers symmetric performance, with both upstream and downstream speeds at 10 Gbps. It also has an asymmetric structure with upstream speeds at 1 Gbps on the same 1310 nm wavelength and downstream speeds at 10 Gbps on the 1270 nm wavelength(Lin & Huang, 2011).

2.3.5 Gigabit PON (GPON)

GPON, or Gigabit PON, provides symmetrical data rates of 2.488 Gbps in both the downstream and upstream directions and supports the transport of Ethernet, ATM, and TDM. It also features robust Operation Administration, Maintenance, and Provisioning capabilities that offer end-to-end service management. GPON uses GEM Encapsulation to provide greater bandwidth and range than APON, BPON, and EPON. There is close competition between GPON and EPON, with some countries preferring FTTx deployments in the EPON architecture while others favor GPON. GPON uses a 1490 nm wavelength laser for downstream data transmission and a 1310 nm wavelength laser for upstream data transmission(Alobaidan, 2017).

2.3.6 Next Generation-PON

The ITU established the Next-Generation Passive Optical Network (NG-PON2) in 2015 as a telecommunications network standard for a passive optical network (PON). The standard defines an architecture that can provide symmetric upstream and downstream speeds of up to 10 Gbps to each subscriber, with a total network capacity of 40 Gbps. The NG-PONs consist of two stages: NG-PON1 and NG-PON2. NG-PON2 is a long-term solution that is independent of existing technologies, while NG-PON1 is a mid-term solution designed to be compatible with current technologies. NG-PON1 specifies both symmetric and asymmetric 10Gbps data rates, with 10G-EPON being an example of NG-PON1 technology. ITU-T G.987, also known as XG-PON, is another standard that demonstrates NG-PON1 technology(Veen et al., 2011). 10G-PON is a networking protocol that provides shared internet access rates of up to 10 Gbps downstream and 2.5 Gbps upstream. XG-PON is ITU-T's latest standard that improves upon G-PON and offers additional enhancements. XG-

PON2 is a further improvement over GPON, offering a symmetrical data rate of 10 Gbps(Kani et al., 2009).

Figure 2. 1 Passive Optical Network Generations(Steinke, 2020).

2.4 Active Optical Network

An Active Optical Network is a network design that utilizes a dedicated optical fiber feeder to transmit all traffic from the central office to a Remote Node located near the end user. AON is also known as the Active Ethernet Network since it uses a unified Ethernet standard to provide TV, telephone, and internet services to users. The active components of the network are located in the Remote Node (Kocher, 2012). In an Active Optical Network (AON), the active components are responsible for managing the data frames sent from the Optical Line Terminal at the CO to the Optical Network Unit at the Remote Node and distributing only the necessary frames to the ONUs of the end-users. Depending on the application, single optical fibers are routed from the RN to the ONUs and their destinations, such as cabinets/curbs, residences, or buildings, as shown in Figure 1.2.

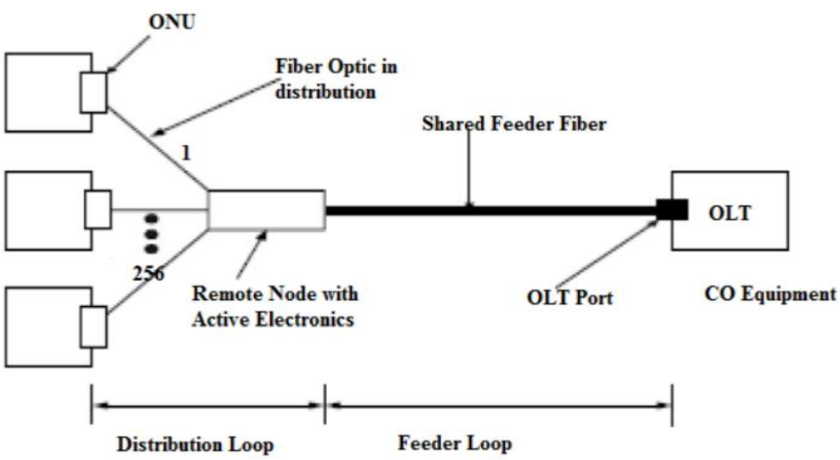

Figure 2. 2 Active Optical Network architecture (Kocher, 2012)

Active Optical Networks (AONs) use electrically driven switching equipment, such as routers, switch aggregators, repeaters, or shaping circuits, to manage signal distribution and direct it to the appropriate end-users. These switches operate by opening and closing to ensure that incoming and outgoing messages are traveling in the correct direction. Each subscriber in an AON has a fiber optic strand. While Passive Optical Networks (PONs) are typically limited to fiber cable runs of up to 20 km, Active Optical Networks can span a range of approximately 100 km. However, AONs have higher building costs compared to PONs due to their need for more fiber.

2.5 Passive Optical Network (PON)

Passive Optical Networks have been considered a promising access technology for more than 20 years, since the release of the initial ITU Recommendation G.983.1 in 1998(Horvath et al., 2020). A Passive Optical Network utilizes an optical splitter to transmit signals through a single optical cable to multiple end-users. The optical splitter divides the signal into multiple fibers, each directed towards an end-user. The "last mile" between an Internet Service Provider (ISP) and its customers is commonly referred to as the domain of Passive Optical Networks (PONs). While recent advancements in telecommunications have increased the capacity of backbone networks, there has been little development in the access network, resulting in a bottleneck between high-capacity local area networks and ISPs. To address this bottleneck, practical solutions include a Radio over Fiber infrastructure and an open fiber based PON that is accessible to all users, including businesses and homes.

A passive Optical Network is an optical access network that uses a point-to-multipoint architecture without any active components in the signal pathway from the source to the destination. In PON, an optical splitter/combiner is primarily utilized for all transmissions between the Optical Line Terminal and the Optical Network Units. The OLT connects the optical access network to the Wide Area Network or Metropolitan Area Network located at the Central Office. The ONUs, on the other hand, typically furnish users with broadband phone, data, and video services at Fiber-to-the-Curb, Fiber-to-the-Building, or Fiber-to-the-Home locations. PON reduces costs and optimizes the use of fiber optic infrastructure for power supply, equipment distribution, and equipment.

2.6 Passive Optical Network Architecture

A Passive Optical Network is an optical fiber access network that includes an Optical Line Terminal located at the central office node, numerous user nodes known as Optical Network

Units or Optical Network Terminals, and an Optical Distribution Network consisting of fibers and splitters. The OLT serves as the connection between the PON and the service provider's core network, which typically utilizes Fast Ethernet, Gigabit Ethernet, or 10 Gigabit Ethernet standards for IP traffic. The ONU terminates the PON and provides a consolidated interface, such as DSL, coaxial cable, or multiservice Ethernet, to the user(Yuang et al., 2010). Copper-based access technologies such as Digital Subscriber Lines (DSL) use point-to-point networks, which eliminates bandwidth sharing. However, they are limited by noise and have lower bandwidth capacity. Wireless access systems, on the other hand, are cost-effective due to their lower installation costs but typically use point-to-multipoint architecture, which results in bandwidth sharing. These systems may not have sufficient bandwidth to support video applications and may be impractical for high-bandwidth applications(Zhu et al., 2012).

The primary advantage of a Passive Optical Network (PON) architecture is its cost-effectiveness, which makes it a popular choice for end-user networks. PON uses a point-to-multipoint (P2MP) configuration, which offers a more effective method of data transmission than point-to-point networks, such as SDH/SONET. P2MP architecture is the preferred solution for Fiber to the X (FTTx) deployment among operators. The Optical Line Terminal (OLT) is the central point of a PON, while the individual endpoints are known as Optical Network Units (ONUs). The network that connects the OLT to the ONUs is passive, meaning that it does not require any power source(Gaur et al., 2014)**.**

2.6.1 Optical Line Terminal (OLT)

The Optical Line Terminal (OLT) is situated in the central office and functions as the control point for two-way data transmission across the Optical Distribution Network (ODN). The maximum transmission distance of the OLT across the ODN is typically 20 km, but this can be increased using Erbium-doped fiber amplifiers (EDFAs). In the downstream direction, the OLT receives voice, data, and video traffic from the long-haul network and distributes it to all the Optical Network Terminal (ONT) modules on the ODN. In the upstream direction, the OLT accepts and distributes all traffic from network users(Keiser, 2013).

In a Passive Optical Network, different wavelengths are assigned for each direction in the Optical Distribution Network (ODN) to facilitate the simultaneous transmission of multiple types of services over the same fiber. The PON system uses a 1490 nm wavelength for combined phone and data traffic, a 1550 nm wavelength for downstream video distribution, and a 1310 nm wavelength for upstream voice and data traffic. Each Optical Line Terminal

(OLT) avoids interference between the downlink and uplink channels by using two different superimposed wavelengths. Measuring optical power at the OLT is necessary to ensure sufficient power delivery to the Optical Network Terminals (ONTs), and it should be done during the initial activation because it cannot be repeated without disrupting the entire network. The OLT converts the standard signals used by a Fiber Optic Services service provider to the frequency and framing used by the PON system and coordinates the multiplexing between the conversion devices on the ONTs located at the customers' premises. The OLT consists of a Voice Gateway (VGW) uplink card, a Gateway Router (GWR), Passive Optical Network cards, and a Central Processing Unit (CPU). By utilizing optical splitters, it can deliver data signals to users at 1490 nm and serve up to 128 ONTs at a range of up to 12.5 miles(Steinke, 2020).

2.6.2 Optical Distribution Network (ODN).

An Optical Distribution Network is a network infrastructure that enables the distribution of optical signals from a central office (CO) or headend to multiple locations. ODNs are widely used in fiber-optic communication systems, which use optical fibers to transmit information rapidly and efficiently over long distances and provide an optical transmission path connecting an Optical Line Terminal (OLT) and an Optical Network Unit. ODNs are designed to distribute optical signals using passive optical elements such as splitters, couplers, and connectors from a central location to multiple endpoints. These components do not require power or active electronics, making the ODN more reliable and easier to maintain than traditional copper-based networks.

2.6.3 Optical Network Unit (ONT)

An Optical Network Unit is a network device that is commonly used in Passive Optical Networks (PONs) to connect end-user devices to the core network. The ONU is located on the customer's premises and receives the optical signal from the PON network. The purpose of an Optical Network Terminal is to convert the optical signal into an electrical signal, which can be utilized by end-user devices such as computers, phones, and televisions. An ONT is a specialized form of Optical Network Unit that serves only one subscriber. When used together with an Optical Line Terminal, an ONU provides a data port, phone port, and 10/100M auto-negotiation, with a full bandwidth of up to 200Mbps in full duplex mode. This can support users with various broadband services, including Voice over Internet Protocol (VoIP), High Definition Television (HDTV), and video conferences (Steinke, 2020).

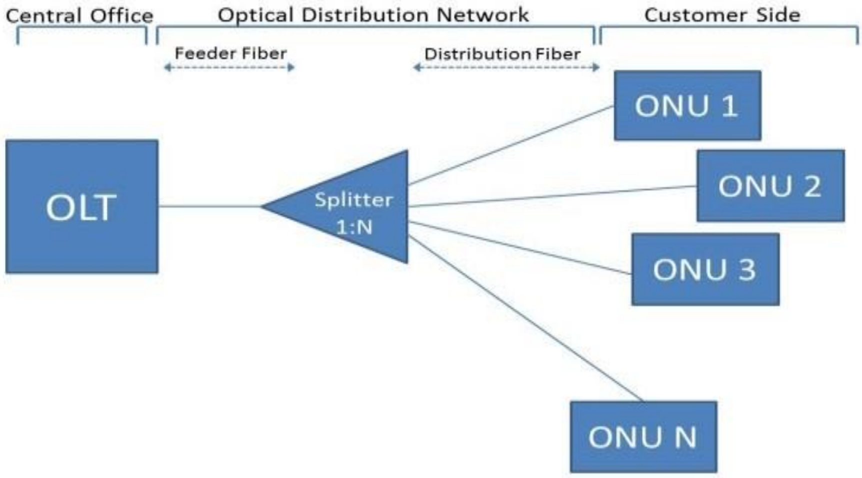

Figure 2. 3 Passive Optical Network Architecture(Steinke, 2020).

2.7 Passive Optical Splitter.

A Passive Optical Splitter is an optical distribution device that is capable of bidirectional transmission, with a single input and multiple outputs. It operates as a power divider and facilitates the transfer of optical signals from the input to the outputs (downlink), as well as from the outputs to the input (uplink). Passive Optical Networks (PONs), it is frequently employed to connect the optical port of an Optical Line Terminal (OLT) to multiple users(Alobaidan, 2017).

In a Passive Optical Network, the optical signal that enters through an input port travels from the Optical Line Terminal and is divided among multiple output ports, while the signal that arrives through an exit port travels from the Optical Network Terminal and is combined at the entry. An optical splitter is a critical component in a Fiber-to-the-Home (FTTH) PON, where a single optical input is divided into several outputs. This permits the deployment of a Point-to-Multi-Point (P2MP) physical fiber network, where a single OLT port can support multiple ONTs. The most common split ratios are 1:2, 1:4, 1:8, 1:16, 1:32, 1:64, and 1:128, although other custom split ratios are available at a higher cost.

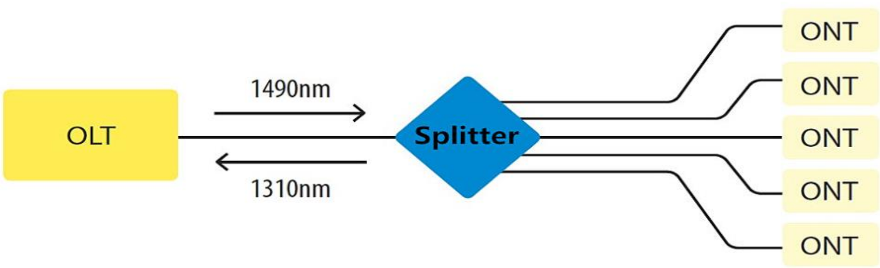

Figure 2. 4 power splitter(Paper et al., 2015)

Passive optical splitters do not require external power, making them cost-effective to deploy, use, and maintain. They only introduce optical power loss, which is a natural occurrence in transmission signals. The amount of loss introduced by the splitter is inversely proportional to the number of outputs it has. This means that the more outputs a splitter has, the greater the loss of optical power in the transmission signal.

$$Attenuation_{SPLITTER} = 10\log\frac{1}{N} \tag{2.1}$$

where N is the number of output ports on the splitter.

Therefore, a splitter with two outputs can experience a loss of 3 dB at each output.

2.8. Radio Over-fiber (RoF)

To offer wireless access, a technology known as Radio over Fiber (RoF) modulates light with a radio signal before delivering it through an optical fiber link. To provide customers with greater choice, convenience, and diversity, the next generation of access networks must integrate wired and wireless services. This means that triple-play voice, data, and video services must be delivered simultaneously. Due to the growing usage of optical access networks and the availability of cutting-edge and affordable technology, an integrated optical feeder network may enable the seamless integration of both broadband optical and wireless access networks. There are several uses for radio over fiber transmission in both GSM and WiMAX networks (Novak et al., 2016). Meeting the needs of contemporary communication systems can be made possible by the error-free transmission of data across an RoF system. RoF technology combines the mobility and flexibility of wireless systems and access network systems with the high bandwidth of optical communications systems(Chen et al., 2009).

Hybrid fiber-radio (HFR) networks, which use RoF technology, are highly effective for distributing telecommunication standards over optical fiber cables. To meet the growing demand for high-bitrate communication services in modern access networks, HFR networks have been increasingly adopted over the past decade. HFR transmission is achieved by directly modulating lasers or externally applying the analog radio frequency signal to the lasers. On the receiver side, a photodiode is used to recover the transmitted signal.

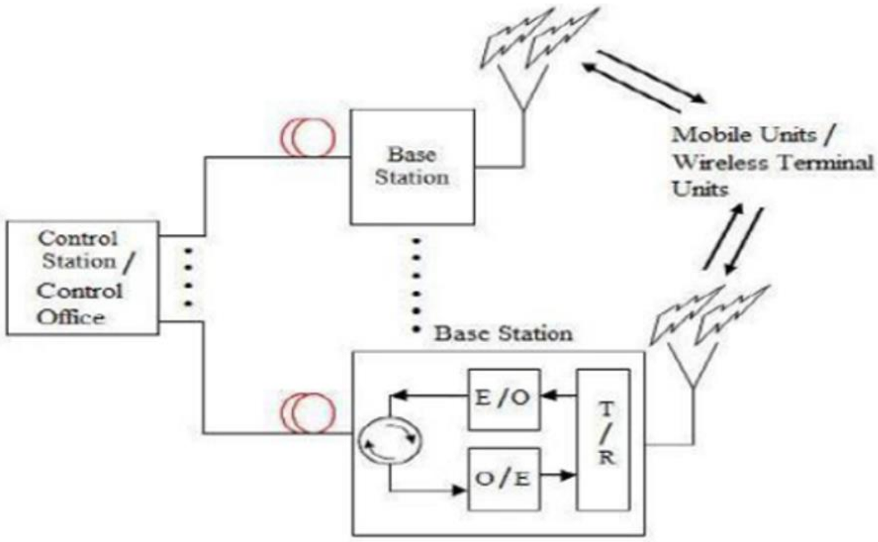

Figure 2. 5 General RoF architecture (Quilindo-méndez et al., 2020)

RoF technology utilizes the modulation of light with the desired RF signal for the transmission of information over optical fibers. The distribution of RF signals from a central office to a Base Station (BS) over a fiber optic link mixes wireless and fiber optic networks. The BS then sends the data to any fixed or mobile terminals that are in its coverage area. The optical transmitter, the optical access network, the BS, and the fixed end are the four main parts of a conventional RoF system. RoF systems have gained significant attention due to the numerous advantages that optical fibers offer, including low loss, large bandwidth, and transparent transmission characteristics for radio signals. RoF technology is highly efficient for delivering various RF transmissions, such as cellular and WLAN signals, to densely populated regions or outdoor areas that require extended coverage.

2.8.1 Modulations in RoF

Radio over Fiber (RoF) technology uses modulation techniques to convert radio frequency (RF) into optical signals that are transmitted over an optical fiber network. There are two different approaches used for the optical modulation process where the optical power emitted by a semiconductor laser is assorted following the characteristics of the modulating signal.

Direct Intensity Modulation: In Direct Intensity Modulation, the semiconductor laser is modulated directly, by modulating the excitation current (Munshid et al., 2018). This method varies the driving current to a semiconductor laser that is directly modulated following the information that needs to be transmitted. A linear operation of the system is possible using the intensity modulation direct detection technique. The power output of light intensity is:

$$p = p_0 + p(t) \tag{2.2}$$

$$I = I_0 + I(t) \tag{2.3}$$

where, (p_0, I_0) are bias points of the semiconductor laser.

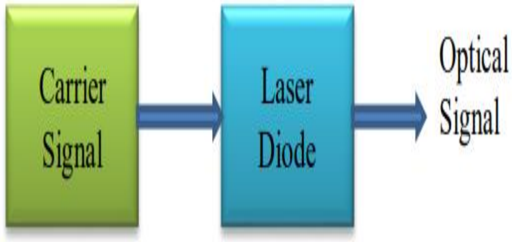

Figure 2. 6 Direct Intensity Modulation (Munshid et al., 2018)

Direct modulation is a straightforward optical modulation scheme. But it is not easy to use for high-frequency applications because of limited bandwidth, and laser non-linearity. This SCM technique can be used to improve the performance of the communication system.

External Intensity Modulation:

In the case of external intensity modulation, the optical output is generated by modulating the carrier signal produced by the CW laser in response to an electrical signal, as illustrated in the figure below.

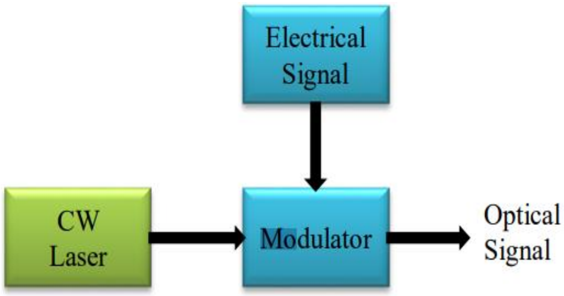

Figure 2. 7 External Intensity Modulation (Munshid et al., 2018)

The use of LiNbO3 external modulator gives higher performance for wide bandwidth and high-speed optical communications. External modulation frequently employs Mach-Zehnder and Electro Absorption Modulators. Mach-Zehnder Modulator is based on the change in refractive index in response to an external electric field, while Electro Absorption Modulator is based on the absorption of a semiconductor material(V. Sharma et al., 2011). The performance of external modulation technology is superior to direct modulation technique and it can function at high frequencies. The modulation process can make use of cutting-edge digital modulation techniques including Quadrature Phase Shift Keying (QPSK), Differential PSK (DPSK), and Quadrature Amplitude Modulation (QAM)(Vyas & Agrawal, 2017).

2.8.2 Architecture of RoF system

Radio over Fiber is a system that allows the transmission of radio frequency signals over optical fiber links. The RF front-end and the optical back end are typically the two primary parts of a RoF system's basic architecture. The creation of the RF signal that will be transmitted via the optical fiber is the responsibility of the RF front end. The baseband signal is often converted into a high-frequency RF signal using a radio frequency transmitter, such as a modulator. Amplifiers and filters may also be a part of the RF front end to enhance the signal's quality and guarantee that it is within the intended frequency range. The RF signal must be sent via the optical fiber link by the back-end optical system. Usually, this consists of an optical transmitter that transforms the RF signal into an optical signal and an optical fiber link that sends the optical signal to the receiver. At the receiver end, an optical receiver is used to convert the optical signal back into an RF signal. In addition to these basic components, an RoF system may also include various other components to improve its performance and functionality. These may include optical amplifiers to boost the optical signal strength, mode division multiplexing (MDM) to combine multiple optical signals onto a single fiber, and optical filters to remove unwanted noise and interference.

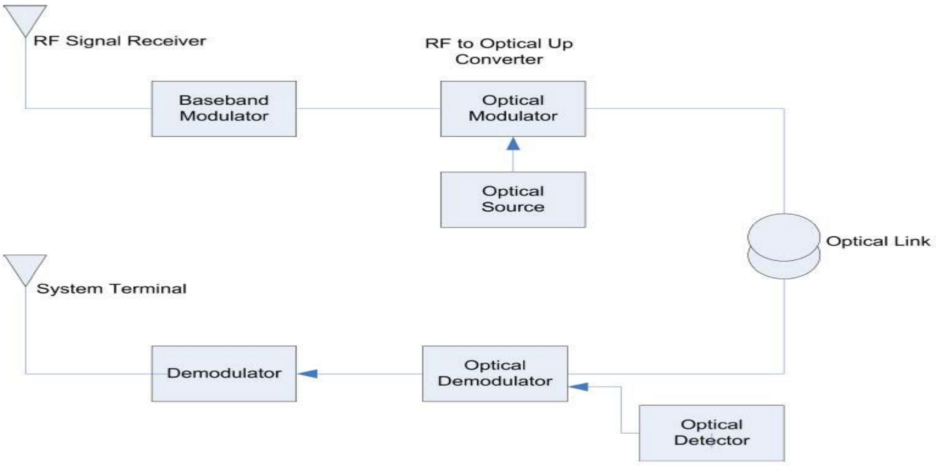

Figure 2. 8 Architecture of RoF system(Symposium et al., 2016)

2.8.3 Advantages of RoF

Radio over fiber has several advantages over traditional wireless communication systems are given below:

Low signal loss: RoF systems use optical fibers to transport RF signals, which have much lower signal loss than traditional copper or coaxial cables used in wireless communication systems. This allows for the transmission of signals over much longer distances without degradation of signal quality.

High bandwidth: RoF systems can support much higher bandwidths than traditional wireless communication systems, allowing for the transmission of high-speed data and video signals.

Improved signal quality: Optical fibers used in RoF systems are immune to electromagnetic interference, resulting in improved signal quality and reduced noise.

Enhanced security: RoF systems can provide enhanced security since optical fibers are difficult to tap or intercept, making it more difficult for unauthorized users to access the transmitted data.

Distributed antenna systems: RoF systems can be used to transport RF signals from a central location to remote antenna sites, enabling the use of distributed antenna systems (DAS) in large buildings or outdoor areas.

Lower power consumption: RoF systems can be more power-efficient than traditional wireless communication systems, reducing energy consumption and operating costs.

Immunity to Radio Frequency Interference: The immunity of optical fiber to Radio Frequency Interference (RFI) is a highly beneficial property that also enhances privacy and security.

2.8.4 Applications of ROF

Some applications of Radio over fiber (RoF) technology in PONs:

Last-mile connectivity: RoF can be used to provide high-speed wireless connectivity to end-users in PONs, extending the reach of the network and providing a reliable and cost-effective solution for last-mile connectivity.

Rural broadband: RoF can be used to provide wireless broadband connectivity to rural areas where laying traditional fiber optic cables may not be feasible or cost-effective.

Smart cities: RoF can be used to support various smart city applications, such as intelligent transportation systems, environmental monitoring, and public safety, by providing high-speed and reliable wireless connectivity to sensors and devices.

Disaster recovery: RoF can be used as a backup solution for PONs in case of natural disasters or other events that may damage the fiber optic cables, providing a resilient and reliable communication link for emergency response.

5G networks: RoF can be used to support 5G networks by providing high-speed and low-latency wireless connectivity to base stations and small cells, enhancing the coverage and capacity of the network.

Network operators can offer a dependable and affordable solution for next-generation communication services by combining the benefits of RoF and PONs.

2.8.5 Limitations of ROF Technology

Chromatic dispersion can reduce the fiber connection lengths in SMF-based RoF systems and result in phase de-correlation, which increases RF carrier phase noise. In contrast, modal dispersion in multi-mode fiber based RoF systems can dramatically reduce the link bandwidth and range. Although RoF transmission is analog, it should be noted that the radio system being disseminated need not be analog and may instead use digital technology with cutting-edge modulation schemes like QAM or OFDM. Due to its analog modulation and light detection, RoF is largely an analog transmission system. As a result, signal distortions like noise and distortion, which can be severe in analog communication systems, are also present in RoF systems. These distortions frequently impose restrictions on the noise figure (NF) and dynamic range (DR) of RoF links. The power received at the base station (BS) from the mobile units (MUs) can vary significantly depending on their location, with adjacent MUs having substantially more RF power than those several kilometers away in the same cell. This makes DR a crucial parameter for mobile (cellular) communication systems like GSM.

2.9 Related Works

A brief survey of literature in the area relevant to this work is as follows.

The authors of (Kavitha et al., 2020) have provided Radio over fiber on a gigabit passive optical network using a Quadrature Phase Shift Keying modulation scheme. In this study, they use 2.4 GHz quadrature phase shift keying modulation to develop and evaluate the Radio over Fiber Technique of 10 GB/s GPON network architecture. According to the simulation results, a hybrid WDM/TDM GPON with 2.5 Gbps, 2.4 GHz QPSK, and a range of 50 km fiber length offers good performance for end users of near 64. by using optisystem software, the performance evaluation was assessed using metrics such receiver power, eye diagrams, and optical to signal ratios. The results of this study indicate a low bit error rate is necessary to attain a good signal-to-noise ratio. This offers a practical response to the demands for high bandwidth for modern communication and the rapid increase in the number of wireless Internet users. In this paper, only one type of modulation technique QPSK, was selected and focused only on radio over fiber, not passive optical networks, or mode division multiplexing.

In the literature (Fazea, 2019), the author of this paper proposed a dense wavelength division multiplexing-passive optical network (DWDM-PON) architecture. This study examines the mode division multiplexing of Laguerre-Gaussian (LG) modes using vertical cavity surface emitting laser (VCSEL) arrays. For 200 m to 1 km, a total data rate of 25 GB/s was attained. Utilizing the spatial electric field, electric signal, eye diagram, and bit error rates (BER), the modal performance has been analyzed. The Laguerre Gaussian modes can be used to supply different services such as data, audio, video streaming, and surveillance monitoring to a single household, and this architecture is therefore appropriate for small private homes where each wavelength may serve a single optical network unit. They do not use Radio over fiber technology to transmit high-efficacy data.

In (M. Sharma & Kakkar, 2020) Compressed spectrum return to zero was proposed for the performance analysis of mode division multiplexing passive optical networks. In this paper, a mode division multiplexing-based passive optical network system is considered at 50 Gbps over 2.8 km of MMF, and 25 users were serviced. The resultant performance was taken between the compressed spectrum return to zero and non-return to zero. Because CSRZ has a high dispersion tolerance, works for 2800 m within an acceptable BER range of 10–10, and has an efficient spectrum, it has been predicted to perform more effectively than NRZ. Due to anticipated increases in bandwidth demand, the proposed system can be used with the WDM PON system now in place to increase capacity.

In (V. Jain & Bhatia, 2020), Performance improvement techniques for radio over fiber systems are presented. Several techniques are utilized in this study to enhance the performance of a radio over fiber technology link as well as present the fundamental architecture of radio over fiber. The author explains the principles of radio over fiber technology by introducing an optical transmitter, an optical fiber, and an optical receiver. In addition to this, they also covered a variety of RoF link performance optimization approaches, summarizing their benefits and drawbacks. Additionally, concluded that there are a large number of promising areas for more research in ROF. They also use phased array antennas, multimode fibers, and plastic optical fiber in a radio-over-fiber system.

The authors (Kathpal & Garg, 2019), proposed an analysis of the radio over fiber system for mitigating the four-wave mixing effect. The effectiveness of the proposed (8/32 RoF-BF) system has been examined with channel spacing, power level, and channel number. According to simulation results, they observed that by decreasing the power level of the signal source and increasing the channel spacing, the four-wave mixing effect decreases.

According to the simulation results, keeping the channel spacing at 75 GHz and the input power level at 0 dBm for an eight-channel system reduces the effects of four-wave mixing. The authors also presented the Four-Wave Mixing side band by reducing power to 4 dBm by adding a Bessel filter. Finally, they conclude that the effect of nonlinearity in radio over fiber will be reduced by using adaptive modulation formats and employing external modulation for the deployment of radio over fiber systems in future transport networks.

In (Horvath et al., 2020)**,** Passive optical network progress is presented in this paper. The authors of the study discussed various cost-effective technologies that can meet the needs of businesses. They also examined data communication between passive optical network elements such as optical line terminals (OLT) and optical network units (ONU). The study evaluated a power peak of 7 mW using on-off keying (OOK) modulation, 100 ps pulse duration, and a power level of approximately 5 dBm. The laser phase is a crucial factor in high-speed transmission systems, particularly in high-order modulation formats. The study concluded that using the OOK modulation technique can help eliminate phase noise and enhance system performance.

In (Hamza et al., 2021), A model for a bidirectional transmission system using sub-carrier multiplexing, wavelength division multiplexing, and radio over fiber is presented. The proposed system used 1270 nm wavelengths for uplink transmission and 1577 nm wavelengths for downlink transmission. The author evaluated the system using the Optisystem 15 software. The simulation results of the proposed SCM/WDM-XGPON-RoF system was evaluated using various measuring components such as optical spectrum analyzers and electrical spectrum analyzers, BER analyzers, and Q-factors. The main focus of this paper is evaluating the performance of the system with and without the Square Root Method (SRM) at the receiver side and comparing the values of bit error rate and Q-factor on both sides. According to simulation results, the use of the Square Root Method improved the performance of the system, and the bit error rate (BER) was less than the acceptable level at 80 km of optical fiber length, which was 1.00E-09, but without the Square Root Method, it was higher than 1.00E-09, which is equal to 1.00E-6. The Q-factor was also reduced without the Square Root Method, and at a length of 50 km, its value is 6.4, compared to 9.15 with the SRM Square Root Method.

In (Ait Ahmed et al., 2019)**,** The use of radio over fiber (RoF) systems in integrating optical and wireless networks. The author discusses the use of wavelength division multiplexing (WDM) to improve the performance of RoF systems, the effects of attenuation and dispersion on RoF systems, and the use of an EDFA amplifier to limit these effects. Also It studies the impact analysis of modulation types like quadrature amplitude modulation (QAM) and differential phase shift keying (DPSK). They conclude that Differential Phase-Shift Keying (DPSK) modulation has a better distribution than Quadrature Amplitude Modulation (QAM) modulation. According to simulation results, the proposed method considers constellation diagrams, received optical power, fiber dispersion, channel spacing variation, and laser power to validate the study.

The design, implementation, and evaluation of a Giga Passive Optical Network (GPON) based on Fiber to the Home (FTTH) technology be given in (Abdellaoui, 2022). In this paper, the development of access networks, network elements, and broadband access technologies is presented. The proposed architecture is evaluated for residential and commercial solutions and discusses the challenges of designing and deploying FTTH access. The author explains the challenges of designing and deploying FTTH access networks, such as the bandwidth requirements per user type, maintaining cost, and quality of service. This challenge will be reduced by selecting the appropriate design architecture and planning for FTTx by employing wave division multiplexing via a passive optical network, ensuring security through a single splitter. This study also illustrates the performance and reliability of the network's Giga passive optical network data transfer at 1.24 Gbps upstream and 2.44 Gbps downstream. Finally, the author considers a Giga passive optical network as the best option for broadband FTTH applications due to its increasing bandwidth because many terminal operators always need bandwidth.

In this paper, a review of wavelength-division-multiplexed passive optical network (WDM-PON) technologies for broadband access was presented. The author discusses the advantages of WDM-PONs over traditional PONs, including higher bandwidth and the use of multiple wavelengths for transmission. The authors conclude that WDM-PONs will revolutionize broadband access technology by providing high bandwidth to end users (Banerjee et al., 2005).The author can not consider any modulation technique in order to transmit data along high band width.

This paper presents a study on the performance of various linearly polarized (LP) modes in a two-channel mode division multiplexing (MDM) passive optical network. The research findings indicate that LP modes 1, 3, and 5 exhibit superior performance with reduced mode crosstalk when compared to other LP modes. Additionally, the paper discusses the benefits of passive optical networks, including their scalability, low power usage, and ease of maintenance. Furthermore, the authors highlight the use of optical fiber technology in high-speed internet and suggest that MDM-PONs utilizing LP modes in multi-mode fibers could be a promising solution for future high-speed and high-capacity optical networks (Singh, 2016).

In (Mohsen et al., 2021) , Design and Implementation of 1.28 Tbps DWDM based RoF system with External Modulation and Dispersion Compensation Fiber was presented. This paper presents a research system that utilizes 32 channels with a bit rate of 40 Gbps, resulting in a total bit rate of 1.28 Tbps. The system's performance is evaluated at different distances, including 60, 120, and 180 km, using parameters such as eye diagram, Q-factor, and minimum bit error rate (Min BER) obtained using Optisystem 17.1 software. The results show that the eye diagram quality indicates higher quality signals received over varying distances. An increase in transmission distance is found to be directly proportional to the Min BER, which results in a higher error rate within the transmitted bits. However, the Q-factor shows an inverse relation with distance, as the transmitted signal quality is reduced with increasing distance. To optimize the proposed system and mitigate the effects of dispersion compensation, both Erbium-doped fiber amplifier (EDFA) and dispersion compensation fiber (DCF) are used.in order to improve the system they used amplifier only rather than using Different Modulation Technique.

In(Ali & Farhood, 2019) Design and Performance Analysis of the WDM Schemes for Radio over Fiber System With Different Fiber Propagation Losses is presented. The author concludes that to modulate optical sources, an electrical signal was utilized, and the modulated signal was transmitted through an optical fiber to the receiver side. This direct modulation of the signal to the optical fiber resulted in a reduction in power consumption, while maintaining a high radio carrier frequency at the BS antenna side. Additionally, power consumption was minimized with a simple radio station, and complex devices and equipment were kept at the CS.The WDM-RoF system was evaluated for different fiber lengths, and the results indicated a BER of 1.10 x 10^-10, a Q-factor of 6.30, and a sample eye diagram of 2.585 x 10^-5. This system achieved excellent results, as the BER was less than 10^-9, and the Q-factor exceeded 6.
From the above literature, researchers have increased the passive optical network by using different multiplexing techniques and modulation types/al algorithms. Unlike those papers, this thesis focuses on mode division multiplexing passive optical networks and radio over fiber to increase the bandwidth and transfer high-capacity data rates. Increasing the

bandwidth of passive optical networks is performed by considering advanced modulation techniques such as M-array differential phase shift keying and M-array quadrature amplitude modulation.

Table 2. 1 Some summary of related work

Authors	Year	Title	Contribution/ Concept Covered.	Gaps
Kavitha et al.	2020	Radio over fiber on gigabit passive optical network using Quadrature Phase Shift Keying modulation scheme.	The radio-over Fiber Technique was evaluated by applying QPSK and WDM.	This paper focuses only on QPSK using WDM.not include other types of modulation like QAM and MDM.
Fazea...	2019	Mode Division Multiplexing and Dense WDM-PON for Fiber-to-the-Home.	Dense WDM-PON is studied.	Even though it uses MDM, Radio over fiber technology is not considered.
Ait Ahmed et al.	2019	Radio over fiber (RoF) systems in integrating optical and wireless networks.	DSPK and QAM Modulation techniques are considered with RoF.	Mode division multiplexing is not considered.
Horvath.	2020	Passive optical network progress overview.	On-off keying (OOK) modulation and elements of PON, ONU, and ONT are described.	Not focus Advance modulated DPSK and QAM.
Hamza et al.	2021	Performance Enhancement of SCM/WDM-RoF-XGPON System for Bidirectional Transmission With SRM.	WDM, RoF, and SCM are covered in this study.	Mode division multiplexing is not considered.
Ali& Farhood	2019	Design and Performance Analysis of the WDM Schemes for Radio over Fiber System with Different Fiber Propagation Losses	WDM and RoF	Noused advanced modulation such as QAM and DPSK.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter is mostly concerned with the methods used in this thesis. In this thesis, different related papers and articles are reviewed from Books, and various journals such as Elsevier, EEE, that are related to passive optical networks, Mode division multiplexing, and radio over fiber technology are highlighted.

3.2 Materials

In the thesis, Optisystem software is used for all simulations. Optisystem is a platform used for planning, designing, testing, and simulating optical links at the transmission distance of high data rates of optical networks. The platform enables the integration of diverse optical fiber and wireless for the development of optical networks. This is a cost-effective and time-efficient approach to help researchers work more productively.

3.3 Methodology

To meet the objectives of the thesis the following formal methodologies are followed.

Literature Review: This thesis work is closely related to previous research on the subject by scholars. As a result, the literature review entails reading books, articles, papers, and journals as well as browsing the internet from different sources for information on related topics (such as the passive optical network, mode division multiplexing technique, and radio over fiber).

Problem Identification: based on the paper reviewed from different papers the research gaps are identified for a research study.

System Designing: after the identification of the research gap the systems are designed for the proposed work.

Simulation of designed System using Optisystem: After designing the proposed system, the simulation is done using Optisytem tools.

Result and Discussion: Depending on the simulation results, discussions are performed on the results.

The procedure used throughout this thesis study can be summarized in Figure 3.1, which shows the workflow.

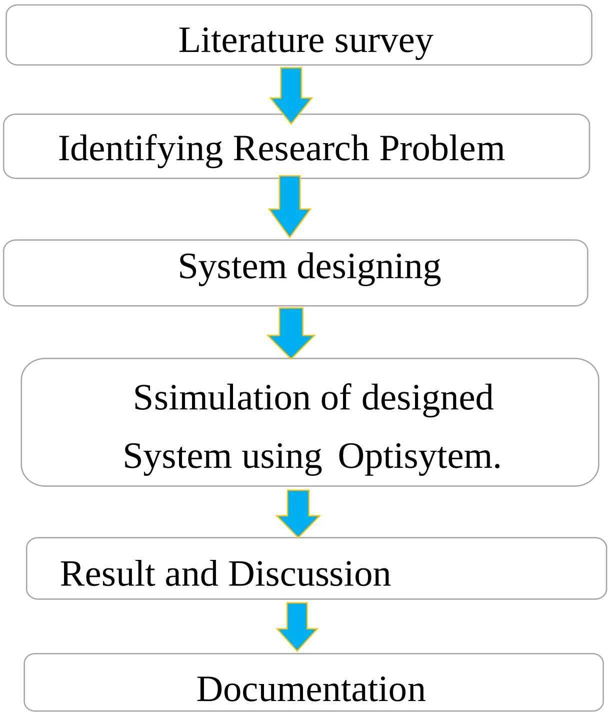

Figure 3. 1 Methodology

3.4 System Model for Passive Optical Network

Passive Optical Networks are consisting of an Optical Line Terminal which is located at the service provider's central office and Optical Network Units situated at the end-users' premises. The signals are distributed using optical splitters, some common split ratios are 1:4, 1:8, 1:16, 1:32, 1:64, and 1:128. The maximum distance passive optical network between CO and the user is 20 km. The OLT is used to interface with the metropolitan network and convert the incoming traffic from the metropolitan rings into the PON transport layer. The ONU serves as the interface between the user equipment and the PON.it is situated outside the customer's premises, as shown in Figure 3.2 below.

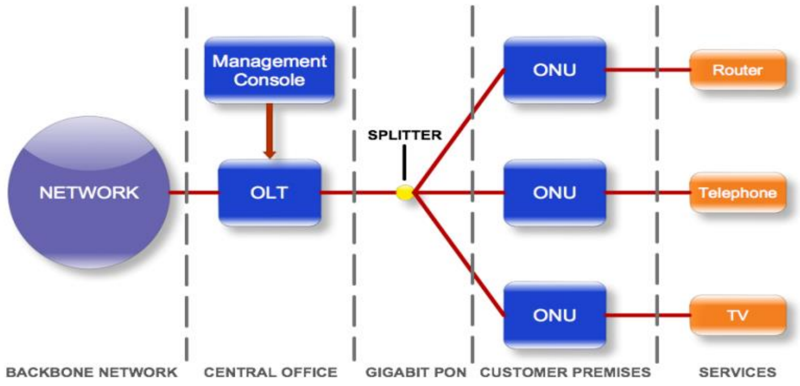

Figure 3. 2 Architecture Passive Access Network(Arturo & Lopez, 2012).

The fundamental benefit of this strategy is that it is inexpensive due to the significant use of passive devices that operate without power, resulting in zero power consumption.

Downstream

In a Passive Optical Network (PON), downstream traffic flow shows the direction of data transmission from the optical line terminal to the optical network units. In a PON, the downstream traffic is broadcasted from the OLT to all the ONUs on the network. The downstream traffic typically carries data such as internet, TV, and voice services from the service provider to the customer premises. The downstream traffic flow is in a PON and typically operates at a higher data rate than the upstream traffic flow. This is because the downstream traffic is intended to serve multiple customer premises, while the upstream traffic flow is intended for individual customer premises to send data back to the service provider. The downstream traffic in a PON is typically modulated using a high-speed optical modulation scheme, such as wavelength-division multiplexing and Mode division multiplexing, to achieve high data rates and efficient use of the available optical bandwidth.

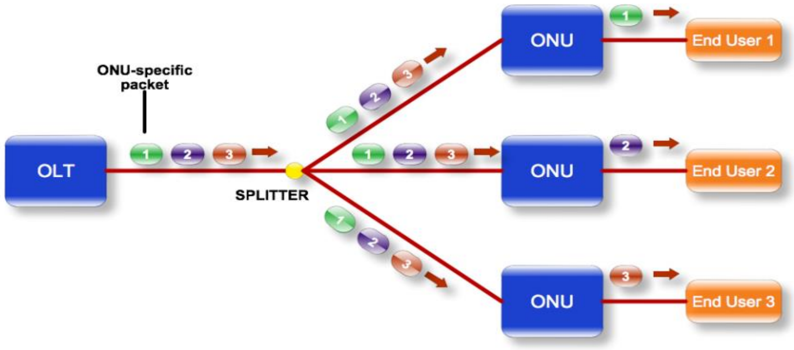

Figure 3. 3 Downstream Traffic Flow in a PON(Arturo & Lopez, 2012)

Upstream

In a Passive Optical Network (PON), upstream traffic flow refers to the direction of data transmission from the ONU at the customer premises to the OLT at the service provider's central office. In a PON, the upstream traffic is transmitted from individual ONUs to the OLT. The upstream traffic typically carries data such as user requests, acknowledgments, and other control information back to the service provider. The upstream traffic flow in a PON operates at a lower data rate than the downstream traffic flow. This is because the upstream traffic flow is intended for individual customer premises to send data back to the service provider, and the amount of data generated by each customer is typically much lower than the amount of data sent by the service provider.

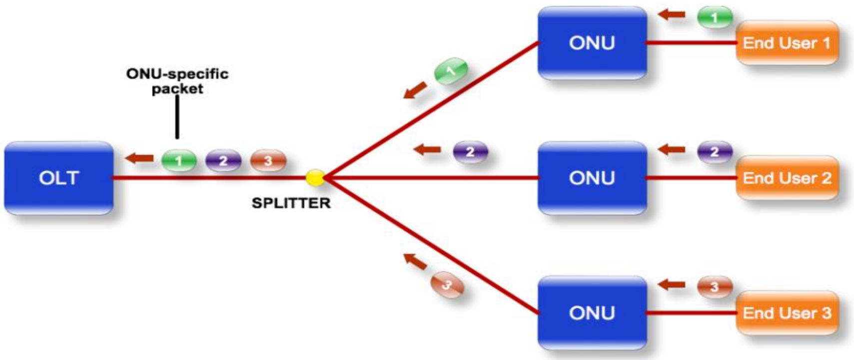

Figure 3. 4 Upstream Traffic Flow in a PON(Arturo & Lopez, 2012)

3.5 System Model for Proposed Mode Division Multiplexing Passive Optical Network.

This section shows a brief overview of the simulation in OptiSystem, where all essential parameters are based on the standardized properties of the Passive Optical Network.

The parameter Required for the Modeling of the proposed system is Optical Line Terminal (OLT) at Central Office (CO), Single-mode fiber, mode Multiplexing and demultiplexing, ODN, Passive Optical splitter, and ONU.

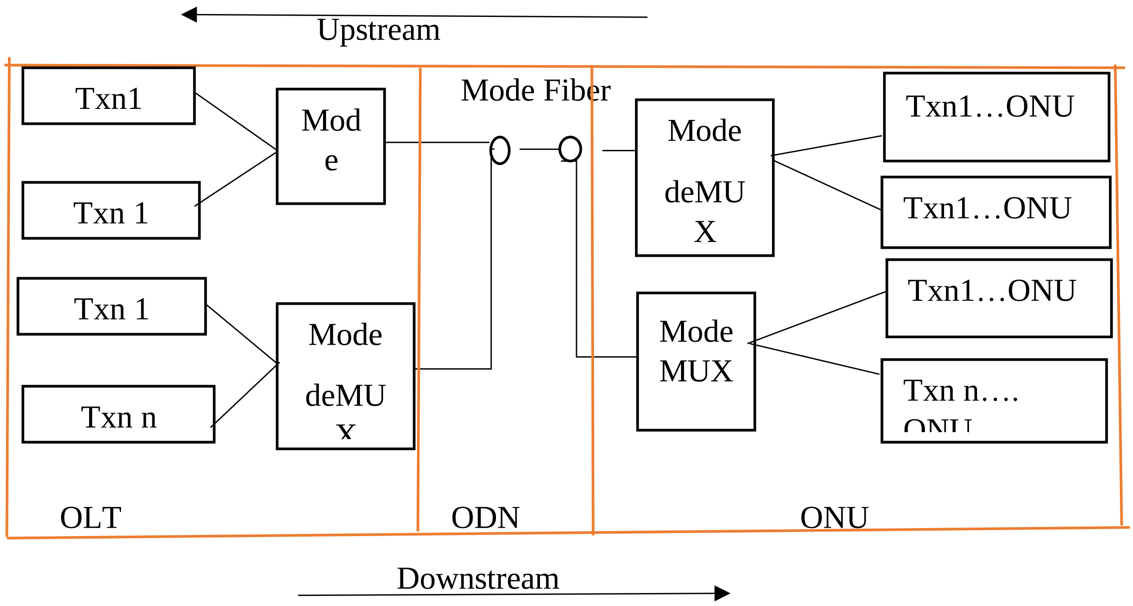

Figure 3. 5 Proposed Block diagram of MDM PON

In the proposed block diagram or simulation, a single transmitter and receiver are employed at the Optical Line Terminal (OLT), and the signals were distributed to eight Optical Network Units (ONUs) through a 1x8 passive optical splitter. Optical circulators were utilized to separate downstream and upstream signals, and the optical delay was employed to ensure proper timing of circulation.

3.6 System Design of Mode Division Multiplexing Passive Optical Network.

A single transmitter and receiver are utilized at the Optical Line Terminal (OLT) to distribute signals to 8 Optical Network Units (ONUs) via a bidirectional passive optical splitter with a capacity of 1x8. An optical circulator is employed to separate downstream and upstream signals, while an optical delay is employed to ensure the accurate timing of circulation.

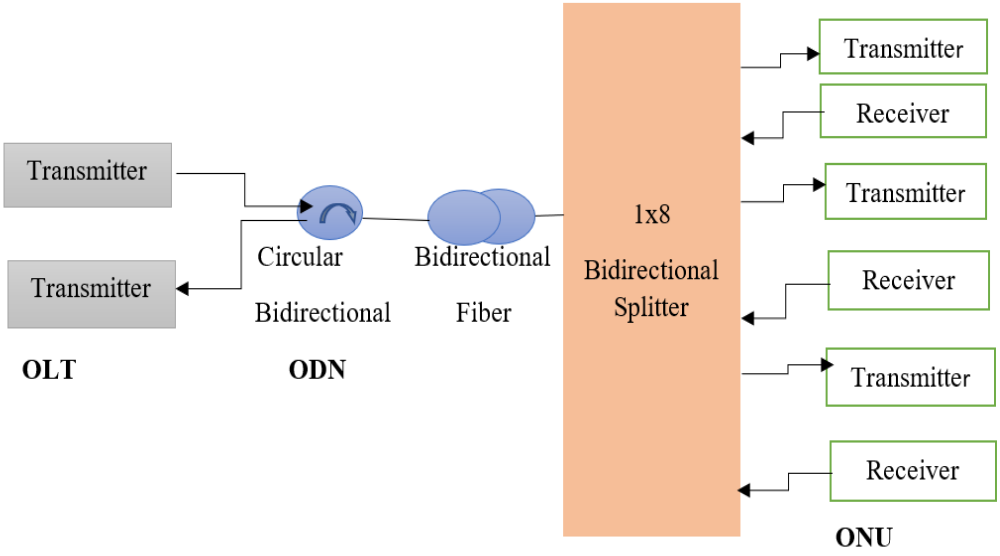

Figure 3. 6 System Design of Mode Division Multiplexing Passive Optical Network.

3.7 Mode Division Multiplexing Layout Simulation by using Optisystem v20

Mode Division Multiplexing (MDM) is a technique used in optical communication systems to increase the capacity of optical fibers by transmitting multiple modes of light. Below two Figure 3.6 and Figure 3.7 indicated block diagrams of the transmitter side and the receiver side, respectively.

3.7.1 Transmitter Section

The Passive Optical Network (PON) transmitter element is a simulation component of the OptiSystem software that simulates the transmitter part of a PON system. The Optical Network Units (ONUs) at the client premises are connected to the optical fiber via the PON transmitter element, which also produces the upstream and downstream optical signals. The Optical Transmitter part consists of Pulse Generator, Pseudo Random Bit Sequence, Modulator, Optical Signal, and CW laser

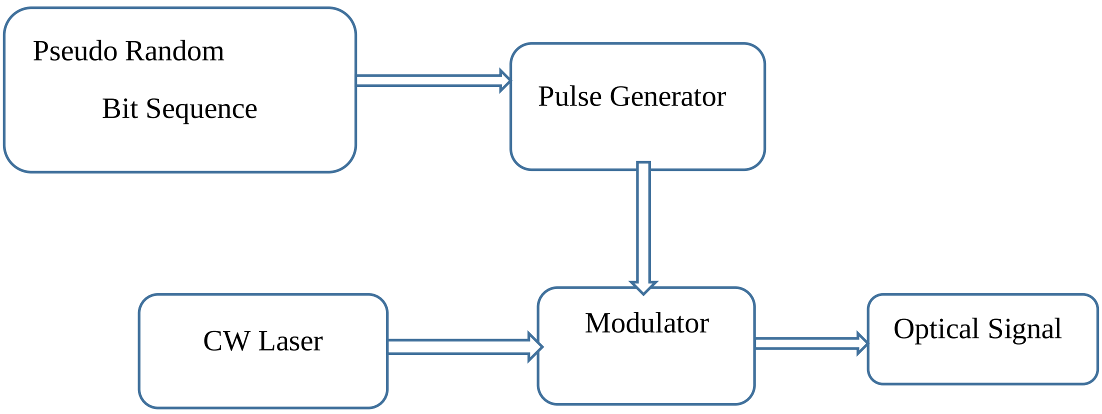

Figure 3. 7 Block diagram of Transmitter section

Pseudo-Random Bit Sequence.

It generates a binary sequence using a deterministic algorithm and is sequenced following customer preferences by the service provider. The duty cycle of this signal is consistent with that of a continuous-time signal. The term refers to an algorithm that employs mathematical formulas to generate a series of random numbers that exhibit properties similar to those of random data. The algorithm produces a sequence of numbers that approximates the characteristics of random data(Press, 1991). The N bits sequence is generated by this model.

$$N = T_w B_r \tag{3.1}$$

$$N_G = N - n_l n_t \tag{3.2}$$

where N is a sequence number of bits, T_w is the global Time window, B_r is the parameter of the Bit rate, N_G is the number of bits n_l the number of leading zeros, and n_t the number of trailing zeros.

The algorithm used to generate the bit sequence is determined by the operation mode. In the Probability mode, a random number generator is used, and the Mark probability parameter specifies the probability of ones appearing in the sequence. The Alternate mode generates a sequence of alternating ones and zeros, while the One's mode generates a sequence of ones. Similarly, the Zeros mode generates a sequence of zeros in order.

Pulse Generator

The pulse generator is converting the binary data into electrical pulses.

Continuous wave (CW) laser:

A Continuous Wave laser produces a continuous emission of light in one or more modes. Its output power remains constant over long periods (Verma et al., 2017). A type of laser known as a continuous wave (CW) laser continuously emits a beam of light at a single wavelength. It continuously emits a stream of light that can be controlled to transmit data. A wide variety of wavelengths of light, from the infrared to the ultraviolet, can be produced using CW lasers. The Gaussian noise is modeled using the probability density function (Ait Ahmed et al., 2019).

$$f(x) = \frac{1}{\delta\sqrt{2\pi}} * e^{-\frac{1}{2}\left(\frac{x-\eta}{\delta}\right)^2} \tag{3.3}$$

Where $f(x)$ is the Probability density function, η mean and δ Standard deviation.

Modulator

The modulator is used to vary the intensity or phase of the light source to encode the information onto the optical signal. Also, it is a method of encoding information onto a carrier wave in a digital communication system. In modulation, a digital signal containing information is used to vary the properties of a carrier wave, such as its amplitude, frequency, or phase, in a way that represents the information being transmitted. The modulation format determines the specific way in which the carrier wave is modulated and demodulates the signal at the receiver.

Quadrature Amplitude Modulation (QAM): It is a digital modulation technique used in communication systems to transmit digital data over a communication channel. It combines the principles of amplitude modulation (AM) and phase shift keying (PSK) modulation. In QAM, the digital data is encoded onto a carrier wave by varying both the amplitude and phase of the wave. This modulation is applied to two orthogonal carrier waves, called the in-phase (I) and quadrature (Q) components. Both I and Q components are typically plotted on a two-dimensional graph, known as a constellation diagram, which shows the amplitude and phase of the signal. The number of points on the constellation diagram determines the number of bits that can be encoded onto the carrier wave. For example, a 4-QAM constellation diagram has four points, which can represent two bits of data per symbol.

Differential Phase Shift Keying (DPSK): Differential Phase Shift Keying (DPSK) is a digital modulation technique employed in communication systems to transmit digital data over a communication channel. It is a variation of the Phase Shift Keying (PSK) modulation technique, where the phase of the carrier wave is altered to represent the digital data being transmitted. DPSK modulation is executed utilizing two orthogonal carrier waves, namely the in-phase (I) and quadrature (Q) components. The digital data is encoded by shifting the phase of the I component relative to the previous bit, while the Q component stays constant and is utilized as a reference for demodulation at the receiver.

Optical Signal

The optical signal is used to transmit information over long distances using fiber optic cables. The information is encoded into the light waves using modulation techniques the light waves are then transmitted through the fiber optic cable, which acts as a waveguide and guides the light waves over long distances with low attenuation and minimal signal distortion.

3.7.2 Receiver Section

The receiver section of a Passive Optical Network (PON) is responsible for receiving optical signals transmitted from the Optical Line Terminal (OLT) and converting them into electrical signals that can be processed by the customer's equipment. The receiver section typically consists of the following components:

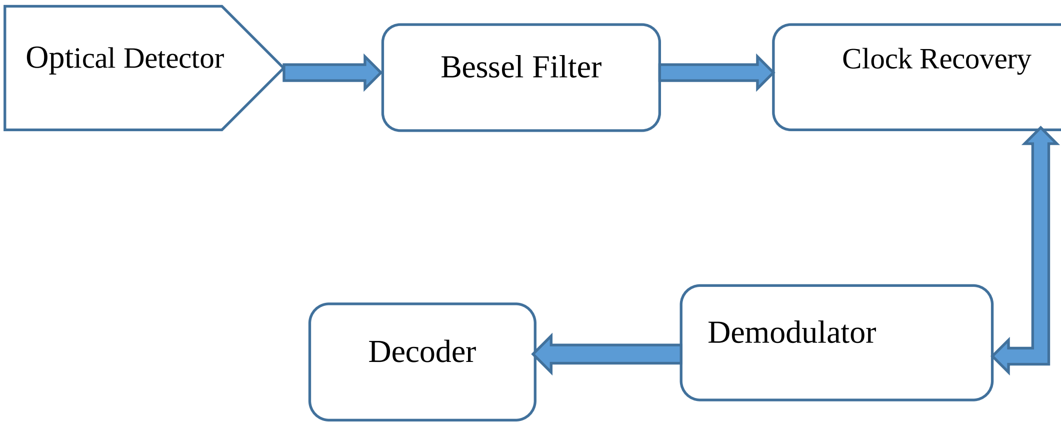

Figure 3. 8 Block diagram of Transmitter section

Optical Detector

An optical detector is a device that detects and converts optical signals into electrical signals. The optical detector consists of a photodiode that converts the optical signal into an electrical signal by the process of photoelectric effect. The photodiode is typically made of semiconductor material, such as silicon or germanium, and is designed to have a high sensitivity to light in a specific wavelength range.

Bessel Filter

A Bessel filter is a type of linear, analog electronic filter that has a flat group delay response. In OptiSystem, the Bessel filter is used as a digital filter to process signals in a simulation. The Bessel filter can be used for various applications, such as smoothing and noise reduction, and it is especially useful in applications where the preservation of the signal's waveform is critical. OptiSystem allows users to specify the order of the Bessel filter, and users can choose from a range of orders depending on their specific needs. Additionally, users can adjust the cutoff frequency of the Bessel filter to achieve the desired frequency response, and used to boast the weak electrical current, we add an amplifier. After being amplified the signal passes through a Bessel Filter to reduce the noise outside the signal bandwidth.

Clock Recovery

Clock recovery is the process of extracting a clock signal from a data stream that is being transmitted over a communication channel. In digital communication systems, the clock signal is used to synchronize the transmitter and receiver and to ensure that the data is sampled at the correct time.

Demodulator

A demodulator is a device that extracts the modulating information from a modulated carrier signal. The demodulator is used to recover the original modulating information from the modulated carrier signal. Two common types of modulated signals are Quadrature Amplitude Modulation (QAM) and Differential Phase Shift Keying (DPSK).

Quadrature Amplitude Modulation demodulator

To extract modulating information from a QAM-modulated signal, a Quadrature Amplitude Modulation demodulator is employed. QAM is a modulation technique that employs amplitude and phase modulation to transmit data over a communication channel. The QAM demodulator comprises a carrier recovery circuit, a symbol synchronization circuit, and a demodulation circuit. The carrier recovery circuit is responsible for recovering the carrier signal, while the symbol synchronization circuit is responsible for synchronizing the timing of the received signal with the demodulator.

Differential Phase Shift Keying Demodulator

A Differential Phase Shift Keying demodulator is used to extract the modulating information from a DPSK-modulated signal. DPSK is a type of digital modulation that changes the phase of the carrier signal to represent digital data. The DPSK demodulator typically consists of a delay line, a phase detector, and a low-pass filter. The low-pass filter is used to remove any high-frequency noise in the signal and to extract the demodulated data.

Decoder

A decoder is a device that converts an encoded signal into its original form. The encoded signal can be in the form of digital data or analog signal that has been modulated using a specific modulation scheme. The decoder is used to recover the original information from the encoded signal. The decoder typically consists of a demodulator and a decoding algorithm. After demodulation, the encoded signal is converted

Into a digital or analog signal that can be processed by the decoding algorithm. The decoding algorithm is used to convert the encoded signal into its original form.

3.8 Simulation Design of MDM with QAM and DSPK

This section briefly describes the simulation setup by using the optic system considering all necessary parameters based on mode division multiplexing.

3.8.1 Simulation Set up of Mode division multiplexing with 16-QAM

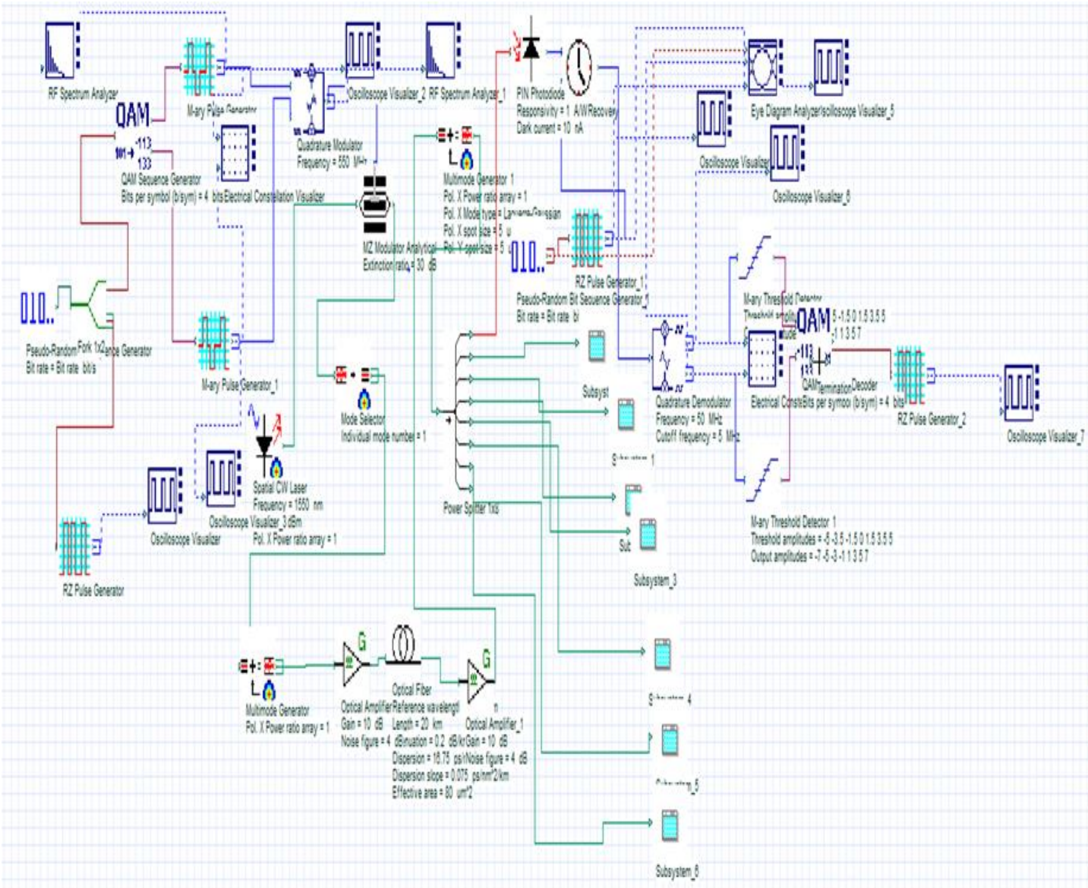

Figure 3. 9 Simulation design of MDM with 16-QAM

Table 3. 1 General parameter used during Simulation for 16-QAM

parameters	Value
RoF operation frequency	550 GHz
Type of encoding	16-QAM
Bitrate (Gbps)	2.5/5
Symbol Rate (Gbps)	Bitrate/4
Sequence length	256
Sample per bit	64
Fiber Length	20km
Reference wavelength(nm)	1550nm

3.8.2 Simulation Set up of Mode division multiplexing with 8-DPSK

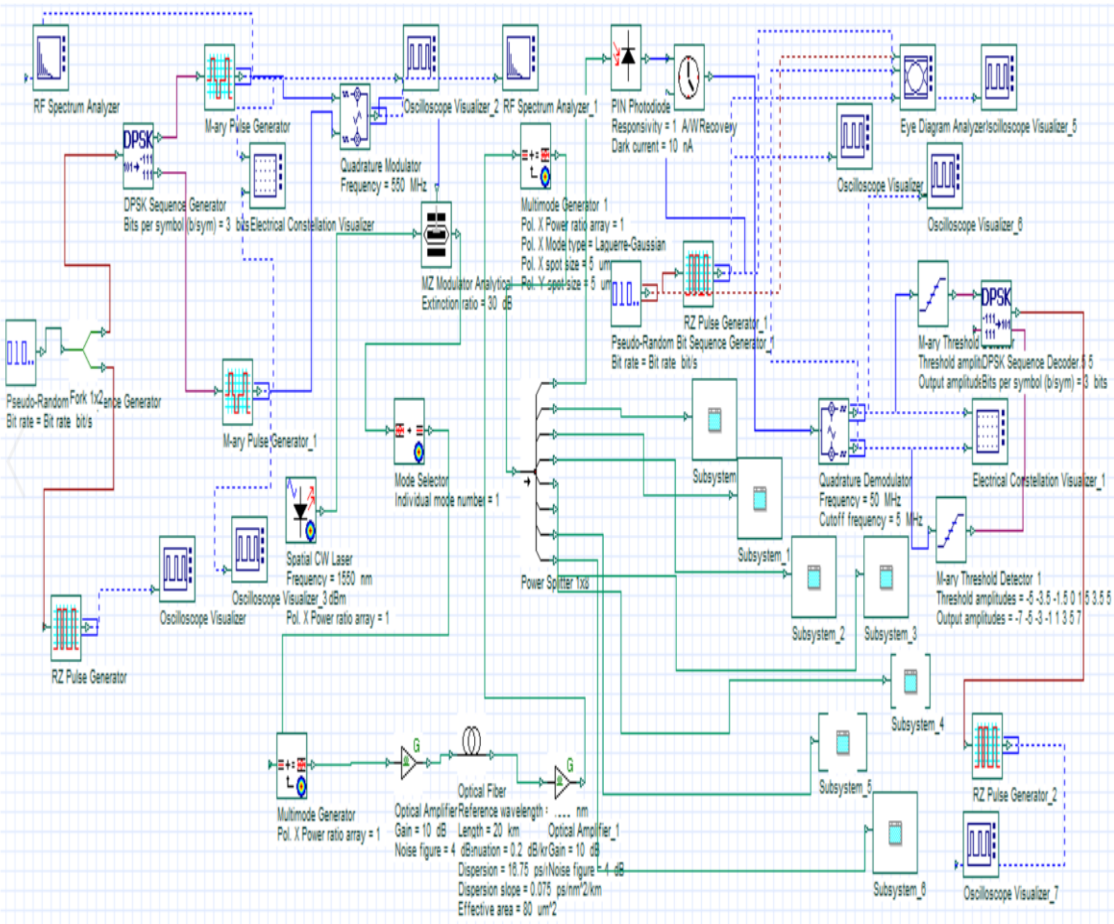

Figure 3. 10 Simulation Design of MDM-8-DPSK

The bellow Table 3.2 shows the parameter used during simulation of 8-DPSK.

Table 3. 2 General parameter used during Simulation of 8-DPSK

parameters	Value
RoF operation frequency	550 GHz
Type of encoding	8-DPSK
Bitrate (Gbps)	2.5/5
Symbol Rate (Gbps)	Bitrate/3
Sequence length	256
Sample per bit	64
Fiber Length	20km
Reference wavelength(nm)	1550nm

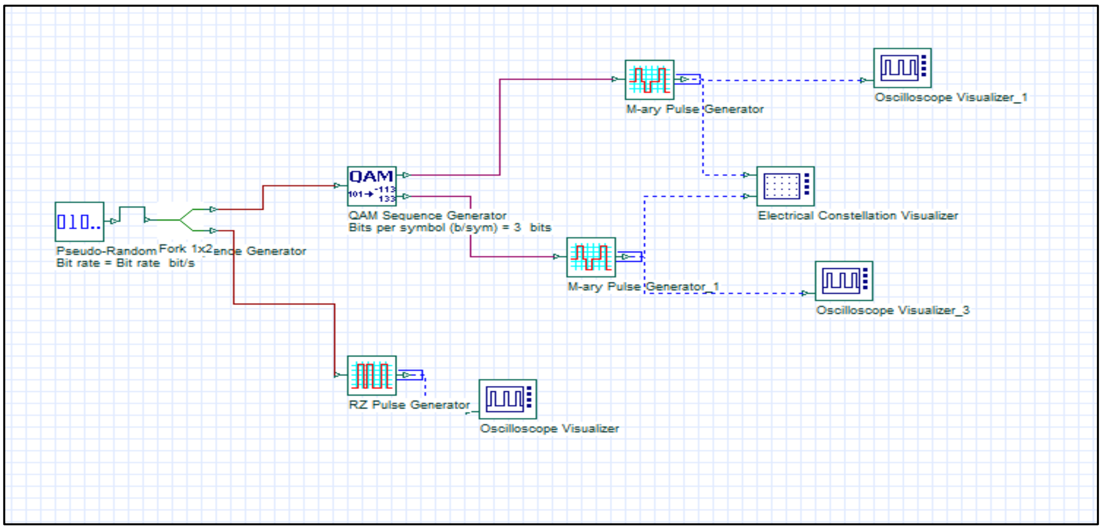

Figure 3. 11 Pulse generation of DPSK/QAM

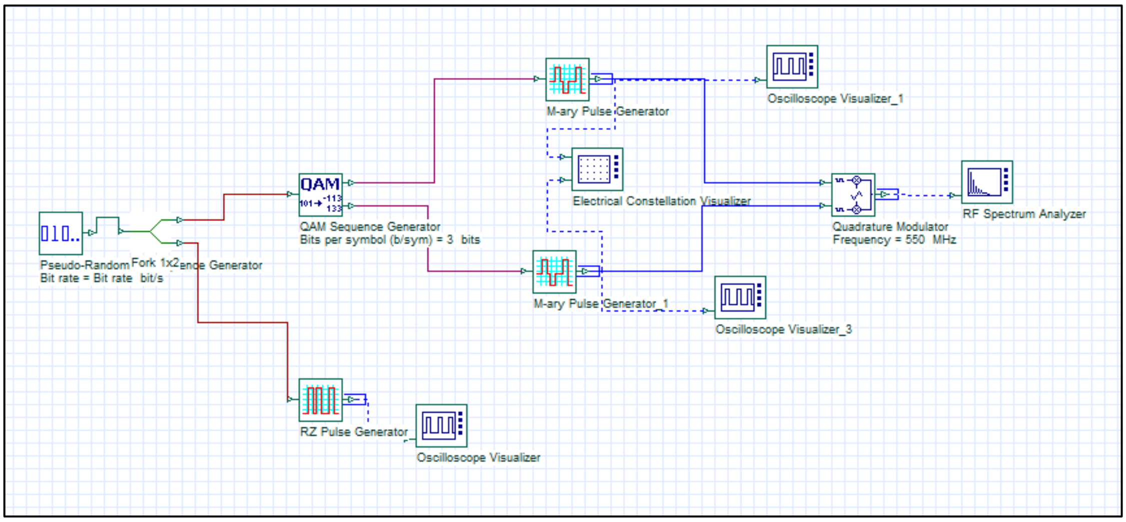

Figure 3. 12 DPSK/QAM Transmitter

3.9 Simulation Design of MDM for Noise Removal Systems

During the design of mode division multiplexing for noise removal systems, we used some parameters such as spatial CW laser, QAM, DPSK, mode selector, RZ pulse generator, and PIN photodiode are considered.

Table 3. 3 Component used during Design and their Description.

Component	Description
PRBS Generator	Generates PRBS according to different modes of operation
NRZ Pulse Generator	Generates NRZ-coded signal
RZ	Generates RZ code signal
CW Laser	Generates a continuous wave optical signal
Circulator Bidirectional	Separates upstream and downstream signals
Optical Null	Creates a zero optical signal
1xN Splitter Bidirectional	Splits the signal into the required number of signal streams (N= 8) to transmit it to ONUs
Bidirectional Optical Fiber	Allows optical signals to travel in both directions at the same time
PIN Photodetector	Convert an optical signal to an electrical signal
Bessel Filter	Filters the signal with a Bessel frequency transfer function
Buffer Selector	Selects the signal data associated with a specified iteration in a series of iterations
3R Regenerator	Regenerates the optical signal
BER Analyzer	Measures the performance of the system based on the signal before and after the propagation

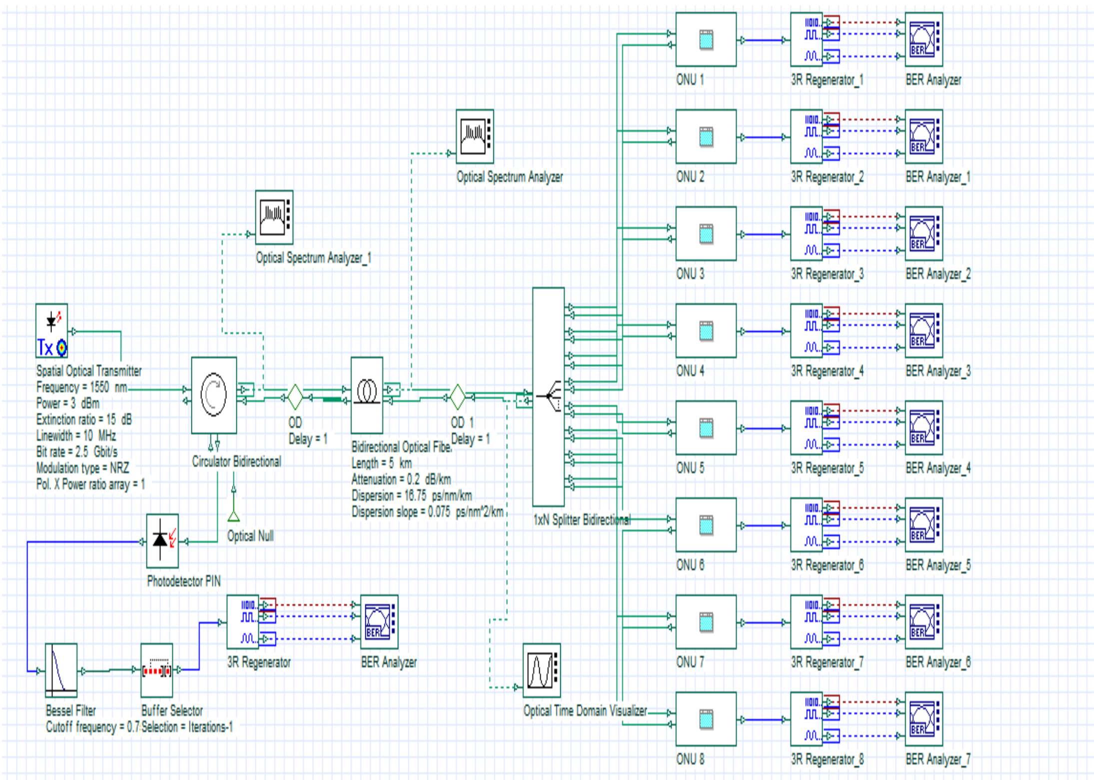

Figure 3. 13 Simulation Design of MDM for Noise Removal Systems

Table 3. 4 Simulation setups of bidirectional PON parameter values during Noise removal

Component	Parameter	Value
PRBS generator	Downstream bit(Gbps)	1550nm
	Upstream bit (Gbps)	1310nm
CW laser	Downstream bit(Gbps)	1550nm
	Upstream bit (Gbps)	1310nm
	Power	3dB and 5 dB
	Line Width	10MHz
RZ/NRZ pulse generator	Amplitude	1au
	Rise time	0.05 Bit
	Fall time	0.05 Bit
Single Optical fiber	Fiber Length	5km,10km,15km,20km, 30,and 50km
	Attenuation constant	0.2d B/km
	Dispersion(ps/nm/km)	16.75
	Dispersion Slope (ps/nm/km)	0.75
Splitter	No output port	8
Circulator bidirectional	Insertion Loss	0dB
Bessel filter	Dark current	10nA
	Cut of frequency	0.75*Bit rate Hz
PIN photodetector	Responsivity	1A/W

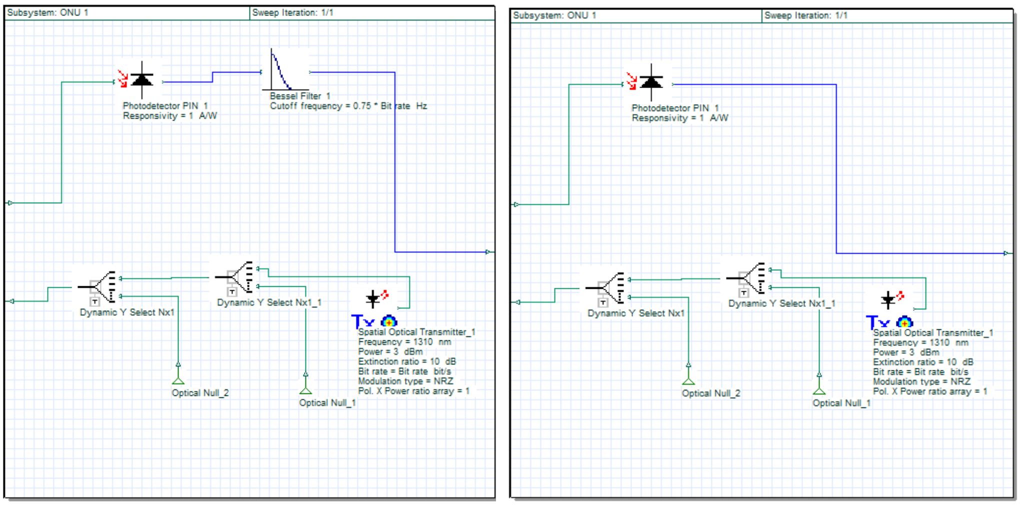

Figure 3. 14 ONU sub system with and without Bessel filter

3.10 Parameters used in Mode division multiplexing

The multi-mode component that we used in Optisytem software is Transmitters, Optical Fibers, Pulse Generator, Mode Generators, Receivers, passives, and Visualizer.

Differential phase shift keying (DPSK)

Differential Phase Shift Keying (DPSK) is a digital modulation technique used both in wireless and wire communication systems to transmit digital data over radio waves. DPSK encodes data by changing the phase of the carrier wave. The DPSK modulation format uses the relative carrier phase values of adjacent symbols before and after to indicate the modulation format for digital information, a hot topic in recent years due to advancements in optical transmission technology and some experimental systems' superior performance (Wenhao et al., 2015).

DPSK modulation and demodulation

DPSK (Differential Phase Shift Keying) is a type of PSK (Phase Shift Keying) modulation format that depends on the relative phase between adjacent symbols that carry digital information "1" or "0". It is commonly known as DPSK, where a phase of 0 or π indicates the transmitted information.

Non-Return-to Zero

The Non-Return-to-Zero (NRZ) technique is a digital data transmission method that employs constant direct current (DC) voltages to transmit binary low and high states, represented by the numerals 0 and 1. This modulation format is preferred over the Return to Zero (RZ) format due to its simplicity, superior quality, and ability to cover greater distances.

Non-Return-to-Zero (NRZ)

In the NRZ (Non-Return-to-Zero) method, the binary data obtained from the pseudo-random bit sequence (PRBS) is transformed into electrical pulses that do not return to zero to produce a baseband signal. This signal modulates the digital data, where binary low and high states are represented by the numerals 0 and 1 and transmitted using constant direct current (DC) voltages. The NRZ modulation format is preferred due to its simplicity, superior quality, and ability to transmit data over greater distances(D. Jain & Iyer, 2021).

Mach-Zehnder Modulator (MZM)

The Mach-Zehnder technology is based on the electro-optical effect, which involves altering the optical path length by applying an external voltage. A Mach-Zehnder modulator manages the amplitude of an optical wave by dividing the input waveguide into two waveguide arms. When a voltage is applied to one of the arms, it causes a phase shift in the light wave as it passes through that arm(Chughtai, 2012). The two waveguide arms of the Mach-Zehnder modulator recombine the optical signal, and the resulting phase difference between the waves in the arms causes amplitude modulation. As the optical signal passes through both arms, the phase difference between the waves is converted into an amplitude-modulated waveform. The bias voltage applied to the electrode controls the optical phase in each arm.

The optical carrier signal generated by one of the arms of the Mach-Zehnder modulator can be expressed (Ali & Farhood, 2019).

$$E_{out} = E_0 \cos\left[\frac{\pi \times V(t)}{2 \times V\pi}\right]\cos(\omega_c t) \tag{3.4}$$

Where E_0 is the amplitude of the carrier, ω_c is the input carrier frequency, $V\pi$ is the half-wave voltage of MZM, and $V(t)$ is the applied voltage.

$$\Delta\varphi = \begin{cases} 0\,code & 0 \\ \pi\,code & 1 \end{cases} \tag{3.5}$$

$$V(t) = V_{bias} + V_{\mathrm{m}}\cos(\omega_{RF} t) \tag{3.6}$$

where V_{bias} is the DC biased voltage, V_m is modulation voltage, and ω_{RF} is the angular frequency of the driving signal.

PIN diodes are used at the receiver to facilitate fiber optic network communication because they provide extremely high-speed internet access. Even if the ADP diode is more suitable for continuous wave lasers, it does not cover more than 60 km due to its nonlinearity. As the distance increases, the noise also increases, but PIN diodes cover a larger range compared to ADP. The advantages of a PIN photodiode include high light sensitivity, fast response speed, wide bandwidth, low implementation cost, low noise generation, low-temperature sensitivity, small size, and better longevity compared to standard diodes.

3.11 Performance Parameters Used in PON Network

The modulation system is one of the primary elements that influence communication quality(Naing & Htet, 2014). The quality of the service offered by the optical communication network is measured by certain parameters. The following is a list of parameters that can be utilized in our study to evaluate and assess each optical communication performance.

Quality Factor

The Q factor is a parameter that directly reflects the quality of an optical communication system. The higher the Q factor better is the quality of the optical signal. The Q factor is a measure of signal energy loss, with a higher Q factor indicating less energy loss. It is a useful metric for assessing the quality of a system, especially when combining two signal-to-noise ratios (SNRs) into a single quantity. In binary digital communication systems, there are only two signal levels, each with a unique average noise level. Thus, there are two discrete SNRs, one electrical and the other optical, associated with the two signal levels. To accurately calculate the overall probability of bit error, both SNRs must be considered(C. Engineering & Ambaye, 2021).

$$Q = \frac{E_{Eye}}{\sqrt{\left|\sigma_0^2 - \sigma_1^2\right|}} \tag{3.7}$$

Where, Q is the Quality factor., σ_0 and σ_1 standard deviations for bit 0 and bit 1 respectively and E_{eye} Eye diagram.

Bit Error Rate (BER).

In telecommunication transmission, the Bit Error Rate (BER) is a measure of the percentage of bits that have errors about the total number of bits received during transmission. A high BER indicates that data may need to be retransmitted frequently due to errors. To improve the BER, one can choose a strong signal strength (unless it causes cross-talk and more bit errors), a slow and robust modulation or line coding scheme, or apply channel coding schemes like redundant forward error correction codes (Shah et al., 2006). Error rates in communication systems refer to the number of bit errors resulting from noise, interference, or distortion in the received bits of data. The BER is calculated as the percentage of bits with errors relative to the total number of bits transmitted(Shah et al., 2006).

$$BER = \frac{number\ of\ erroneous\ bits}{number\ of\ total\ bits} \tag{3.8}$$

$$BER = \frac{E}{N} \tag{3.9}$$

where E is the Errors and N is the Total Number of bits transmitted.

BER can also be defined in terms of the probability of error (POE).

$$POE = \frac{1}{2}(1 - erf)\sqrt{\frac{E_b}{N_O}} \tag{3.10}$$

$$BER = \frac{1}{2}(1 - erf)\sqrt{\frac{E_b}{N_O}} \tag{3.11}$$

where erf is the error function, E_b is the energy in one bit, and N_O is the noise power spectral density (noise power in a 1 Hz bandwidth)(Breed, 2003).

The Q-factor and BER are inversely related to each other. The Q-factor measures the quality of the signal in a communication system, with a higher Q-factor indicating better signal quality and a lower BER. Conversely, a lower Q-factor indicates poor signal quality and a higher BER. Therefore, the Q-factor is often used to predict the BER in a communication system.

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \approx \frac{\sim 1}{\sqrt{2\pi Q}} \exp^{\left(\frac{-Q^2}{2}\right)} \tag{3.12}$$

where Q is the Quality factor.

BER is usually too small to quantify in the case of optical domain thus Q-factor is mostly used as a quantifying parameter for the analysis.

$$BER = \frac{1}{2\left(\frac{erfcQ}{2}\right)} \tag{3.13}$$

$$Q = \frac{I_O - I_1}{I_0 + I_1} \tag{3.14}$$

Eye Diagram

During transmission, a quick and effective way to assess the quality and integrity of the electronic signal (after it has been converted from optical to electrical) is to generate an eye diagram. An eye diagram is created by superimposing bit periods on an oscilloscope to give a visualization of the signal's quality. If the signal is relatively noise-free and has sufficient amplitude to be recognized as a "one" or "zero", the eye diagram will show an "open eye". However, if there is noise or other interference, the eye diagram will appear "fuzzy" or unclear.

The eye diagram is a visual representation of the superposition of all overlapping bits in a communication signal, and it provides information on the differentiability between logic one and logic zero. The wider the opening of the eye, the greater the differentiation between the two logic levels, which indicates a better signal-to-noise ratio. As a result, an eye diagram is an essential tool for evaluating the quality of a signal and for detecting any problems that may be affecting its integrity.

Eye height: It provides the measure of the presence of additive noise in the circuit.

Eye closure: It provides the measure of inter-symbol interference.

Eye overshoot / undershoot: It shows the peak distortions due to interruptions in the path of propagation of the signal.

Eye width: It gives information about timing synchronization and jitter effects.

Eye fall and rise time: Eye fall time is the mean time between the high and low threshold values. Eye rise time is the mean time between the low and high threshold values.

The Eye-diagram analyzer is utilized to evaluate signal quality through metrics such as the quality factor and bit error rate. The received pulse shape, or eye diagram at the receiver, can be analyzed to assess the signal quality and identify sources of distortion and attenuation. By analyzing the eye diagram, it is possible to obtain significant insights into the received digital signal. The opening of the eye can be calculated using the following formula (Badraoui & Berceli, 2018). I_0 and I_1 denote the mean values, and σ_0, σ_1 denote the standard deviations of the probability density function (PDF) for bit 0 and bit 1 respectively.

$$E_{eye} = I_1(\min) - I_0(\max) \tag{3.15}$$

Where 0 $I_1(\min)$ the Minimum current threshold for logic 1 and $I_0(\max)$ is the max maximum current threshold for logic 0.

The BER is defined as,

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{3.16}$$

where erfc is the error function.

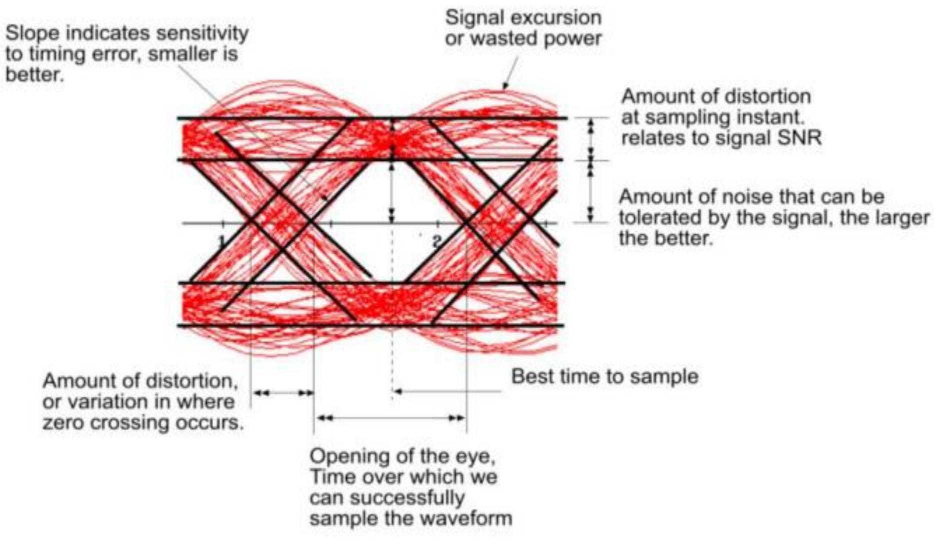

Figure 3. 15 Eye Diagram Interpretation(E. Engineering & Engineering, 2017)

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, the simulation and analysis of the system model are presented. The simulation results of each model design are obtained and analyzed by using Optisystem simulation software.

4.2 performance analysis of the eye diagram, Q-factor, and BER during noise removal

An appropriate way to measure the performance of the system is by using an eye diagram, as shown below in Figure 4. 1 to Figure 4. 12. The performance analysis of the eye diagram, is considered at 3dBm, 2.5Gbpsin part one, and in part two 3 dBm and 5Gbps as reference. The performance evaluation of each eye diagram is taken by considering the Q-factor and BER during noise removal at different fiber lengths (km), such as 5 km, 10 km, 15 m, 20 km, 30 km, and 50 km.

4.2.1 Eye diagram and min BER at a data rate of 2.5 Gbps and 3 dBm

From the below Figure 4.1, the analysis of the eye diagram with a maximum Q-factor of 30.182 and a minimum BER of 2.03832e-200 at 2.5Gbps and 3dBm indicates that high signal quality and a low BER. The high Q-factor indicates that the system is operating with low noise and high signal quality which shows the eye diagram has a wide eye-opening.

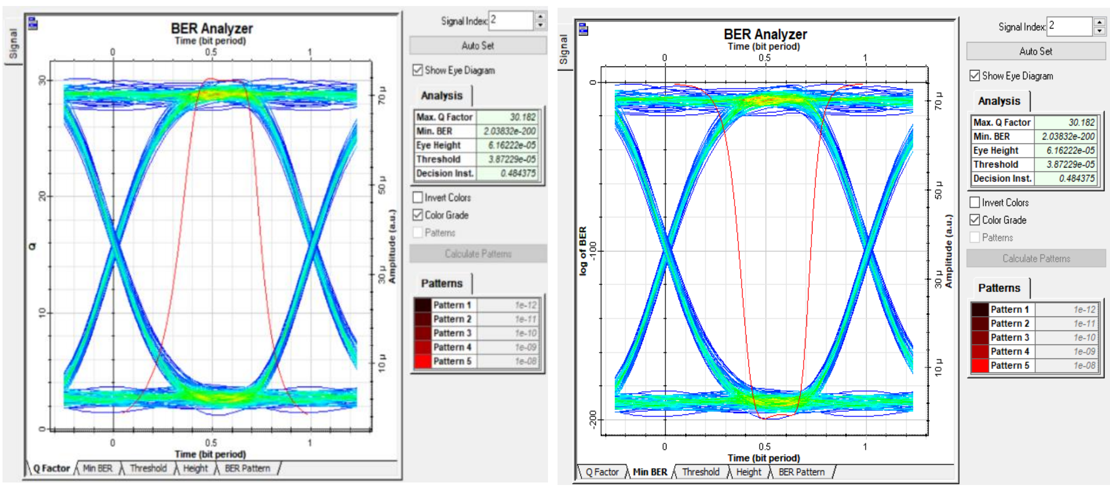

Figure 4.1 Eye diagram of 5 km, with 3 dBm and 2.5 Gbps at Q-Factor and Min BER

The maximum Q-factor of 21.0661 shows that the system is still functioning with low noise and excellent signal quality, despite the attenuation, at a power level of 3 dBm, and data Rate of 2.5Gbps which can help to maintain a high SNR and limit the impact of noise on the signal. The system is successfully identifying and correcting errors due to the data transfer is reliable, according to the minimal BER of 1.499302e-62.

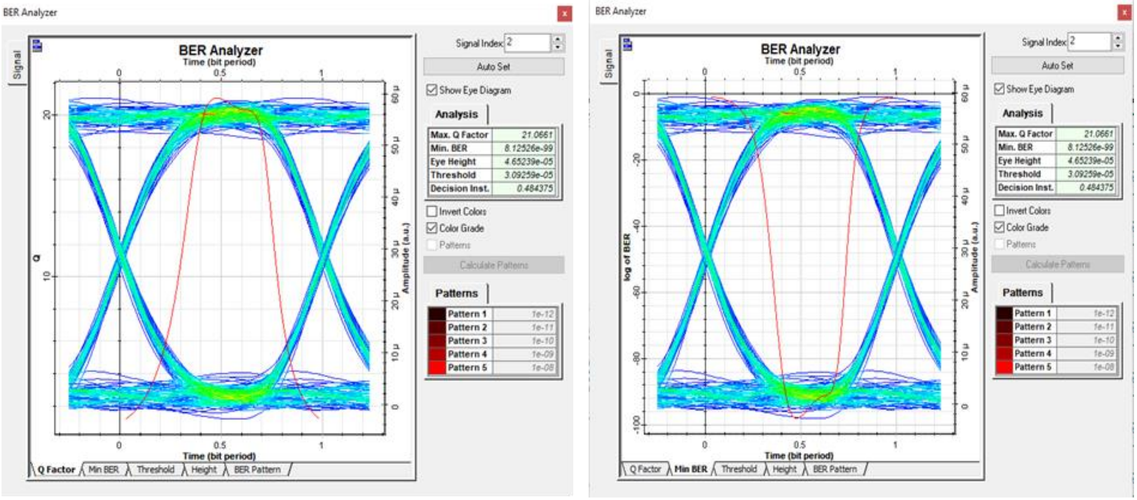

Figure 4.2 Eye diagram of 10 km, with 3 dBm and 2.5 Gbps at Q-Factor and Min BER

The below Figure indicated the values of a high Q factor and a minimum BER indicating good signal quality and a high data rate. so that a high signal quality shows the eye diagram has a wide eye-opening, and a low BER shows a good signal quality.

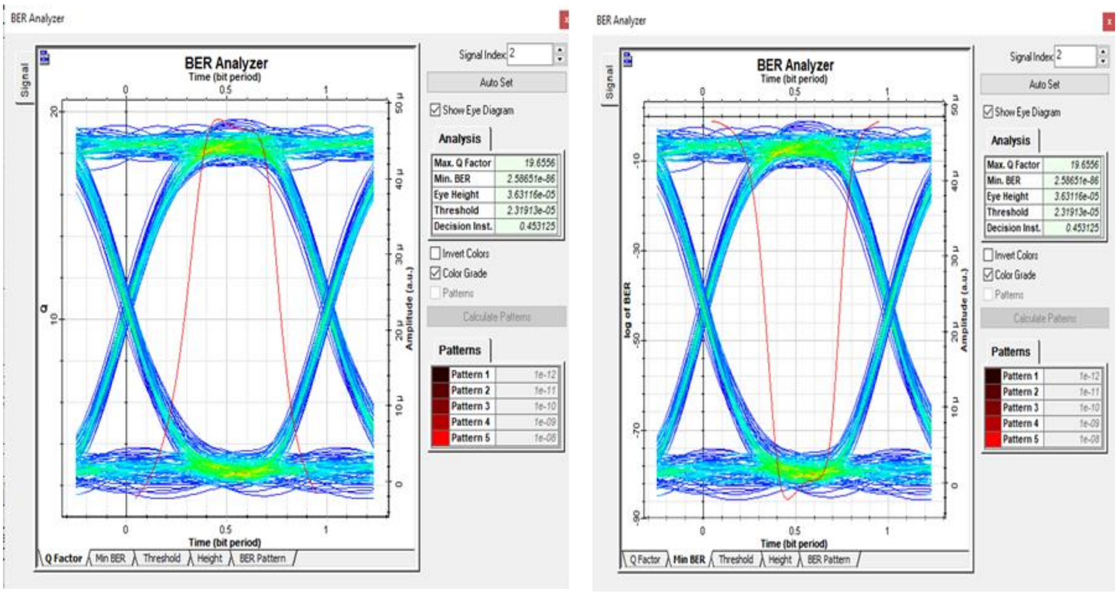

Figure 4.3 Eye diagram of 15km, with 3 dBm and 2.5 Gbps at Q-Factor and Min BER

The eye diagram Mat 20km indicates a narrower eye-opening, signifying a poorer signal. The system is still successful in detecting and correcting errors, indicated by the low BER, but the data transfer might be less reliable than it would be for transmission at a shorter distance with a higher Q-factor and lower data rate.

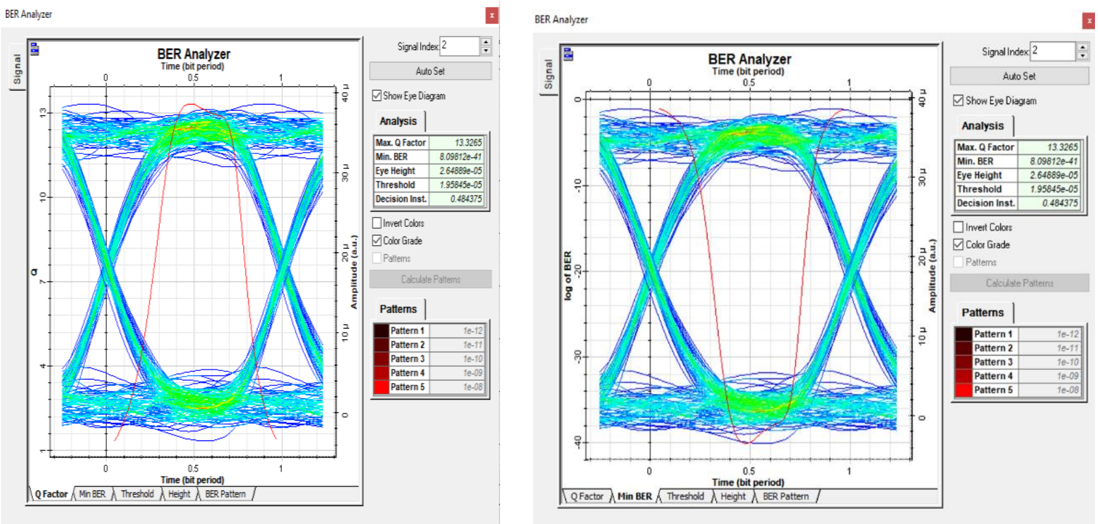

Figure 4.4 Eye diagram of 20km, with 3 dBm and 2.5 Gbps at Q-Factor and Min BER

Analyzing the eye diagram at 30 km, 3dBm, and 2.5 Gbps with a maximum Q-factor of 8.41743 and a minimum BER of 1.1817e-17 indicates that the signal quality is significantly degraded due to the distance, and the communication system is not operating at optimal performance.

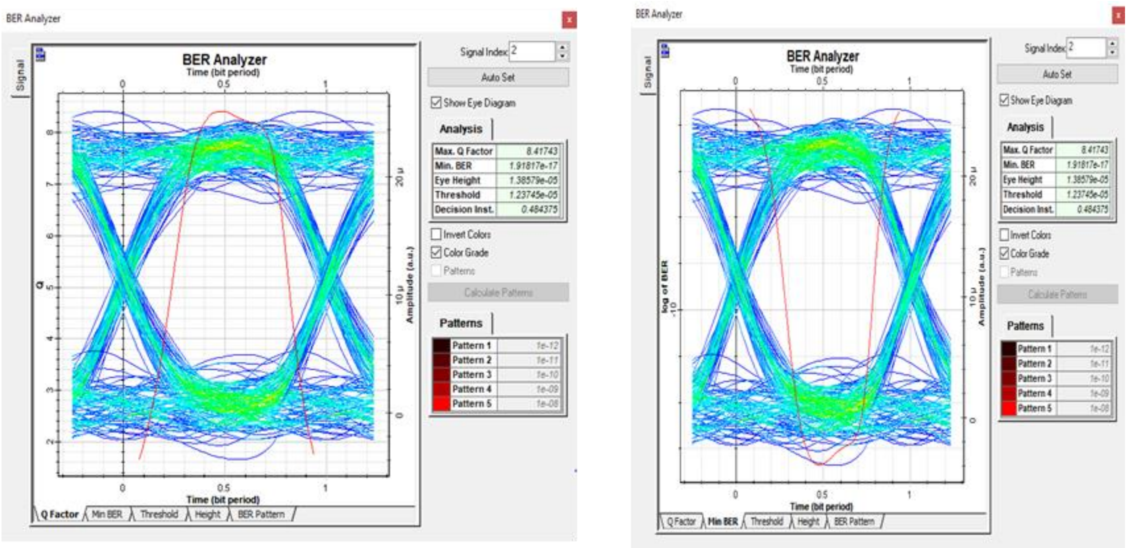

Figure 4.5 Eye diagram of 30km, with 3 dBm and 2.5 Gbps at Q-Factor and Min BER

From the below Figure 4.6 at a data rate of 2.5 Gbps with 50km, the signal has a high bandwidth, which can lead to a narrower eye-opening on the eye diagram.

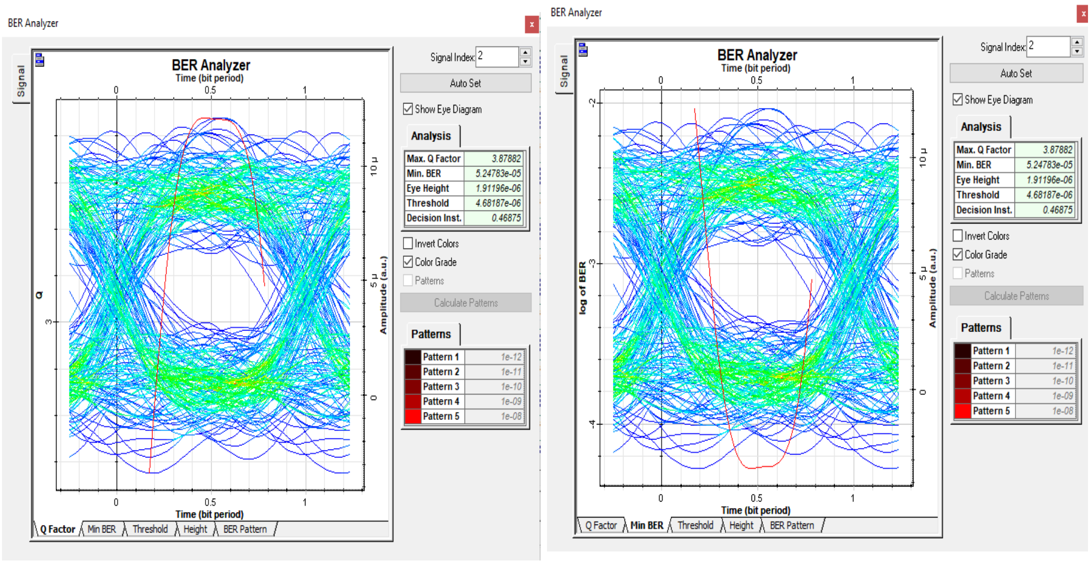

Figure 4.6 Eye diagram of 50km, with 3 dBm and 2.5 Gbps at Q-Factor and Min BER

The maximum Q-factor of 3.87882 indicates that the system is operating with high noise and reduced signal quality, also the minimum BER of 5.24783e-05 indicates that the system is not effectively detecting and correcting errors, and the data transmission is not reliable.

Table 4. 1 Results of Min BER and Max Q Factor at different km, 3 dBm, and 2.5Gbps

Fiber length(km)	Q-factor	Min. BER	Eye Height
5	30.182	2.03832e-200	6.16222e-05
10	21.0661	8.12526e-99	4.65239e-05
15	19.6556	2.58652e-86	3.63116e-05
20	13.3265	2.64889e-41	2.64889e-05
30	8.41743	1.1817e-17	1.38579e-05
50	3.87882	5.24783e-05	1.91196e-06

4.2.2 Eye diagram and min BER at a data rate of 5Gbps and 3 dBm

Under this, the performance analysis of the eye diagram is considered at 3 dBm and 5 Gbps is analyzed by considering different lengths starting from Figure 4.7 to Figure 4.12.

In Figure 4.7 the combination of a high Q-factor and a low BER indicates that the signal quality is good and operating at optimal performance. The eye diagram shows a wide eye opening, indicating a high signal quality. Due to this and the low BER, the system does not require additional measures to improve the signal quality and reduce the BER.

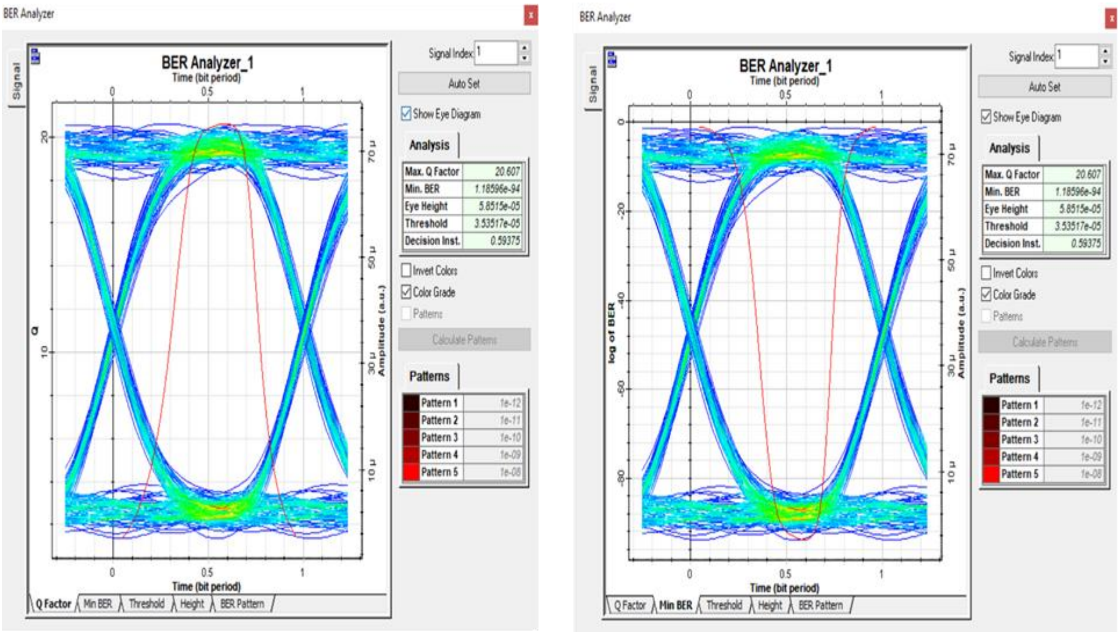

Figure 4. 7 Eye diagram of 3 dBm, 5km and 5Gbps at Max Q Factor and Min BER.

Figure 4.8 below shows the combination of a high Q-factor and a low BER which indicates good signal quality is excellent, and the communication link is operating at optimal performance. The eye diagram shows a wide eye opening, indicating a high signal quality. Due to this and the low BER, the system does not require additional measures to improve the signal quality and reduce

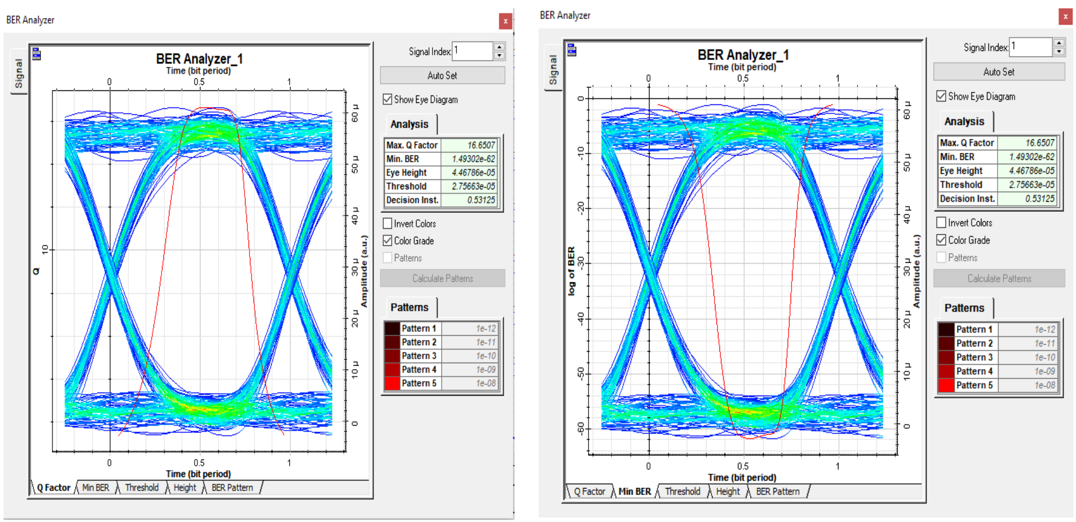

Figure 4. 8 Eye diagram at 3 dBm, 10km, and 5Gbps at Max Q Factor and Min BER.

Figure 4.8 below shows the combination of a high Q-factor and a low BER which indicates good signal quality is excellent, and the communication link is operating at optimal performance. To improve the signal quality and reduce the BER.

The below Figure indicates that at 15 km, the eye diagram indicates that the Q factor of good signal quality is due to a high Q factor and a minimum BER.

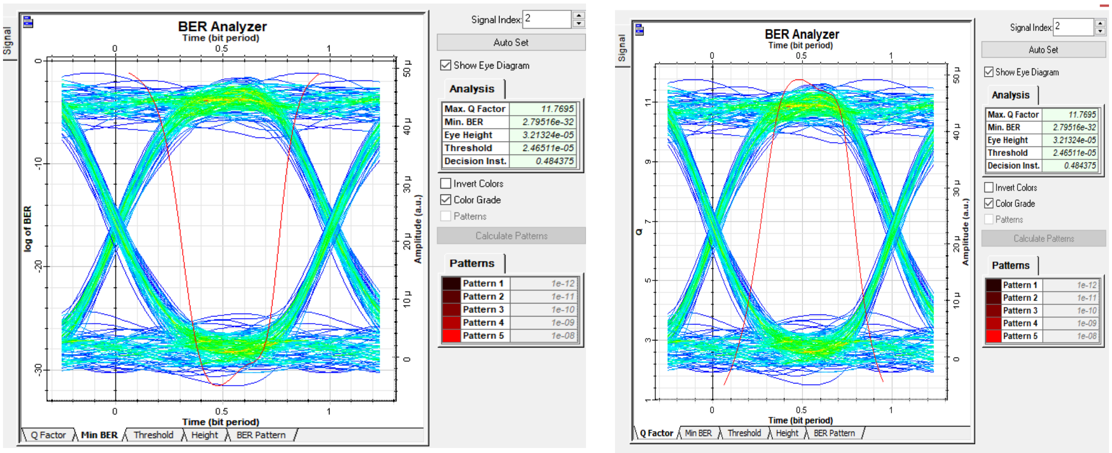

Figure 4. 9 Eye diagram at 3 dBm, 15km, and 5Gbps at Max Q Factor and Min BER

The eye diagram of the Q factor and Min BER of Figure 4.10 at 20km is somewhat good Signal quality, and the Eye is widely open.

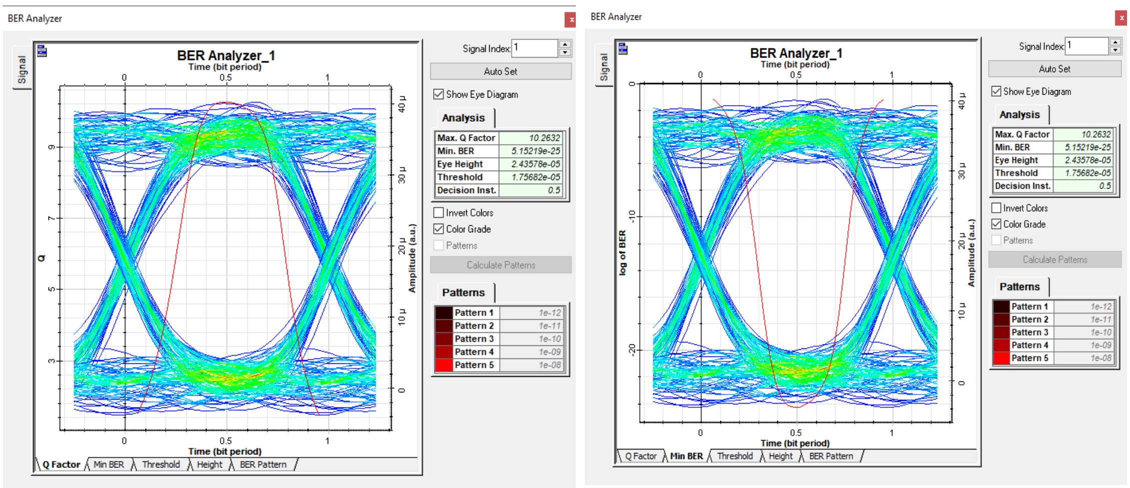

Figure 4. 10 Eye diagram at 3 dBm, 20km and 5Gbps at Max Q Factor and Min BER.

Analyzing the eye diagram at 3 dBm, 30 km, and 5 Gbps with a maximum Q-factor of 6.20218 and a minimum BER of 2.78198e-10 indicates that the signal quality is severely degraded due to the distance of 30km.

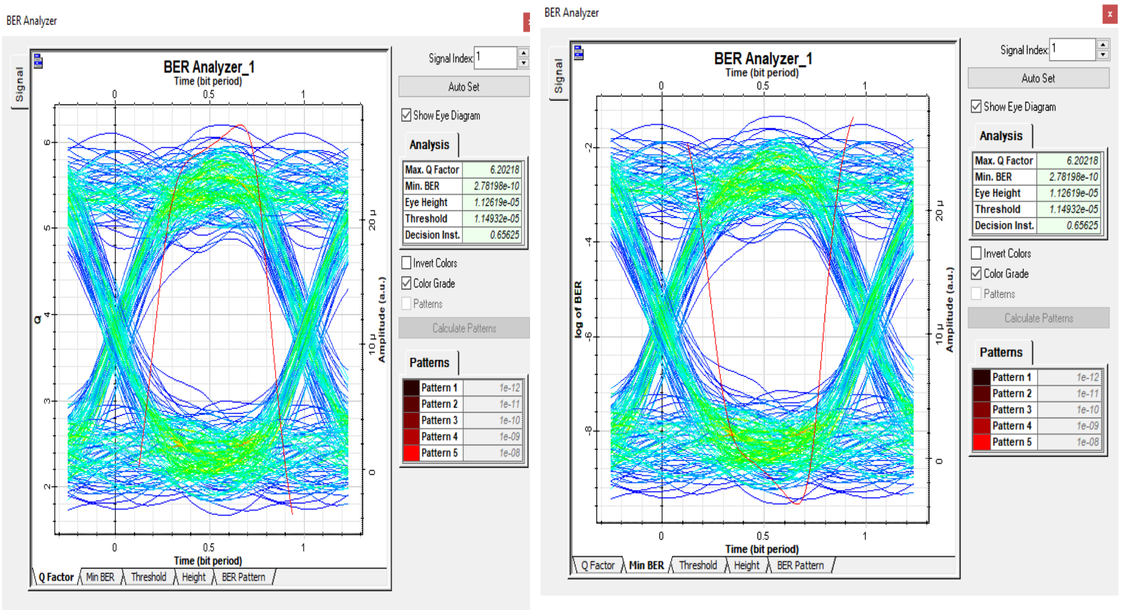

Figure 4. 11 Eye diagram at 3 dBm, 30km, and 5Gbps at Max Q Factor and Min BER.

The maximum Q-factor of 2.5 indicates that the signal quality is severely degraded due to the distance and the system may not be able to achieve reliable data transmission, and the minimum BER of 0.00506693 indicates that the system is not detecting and correcting errors, which shows that the data transmission is not reliable.

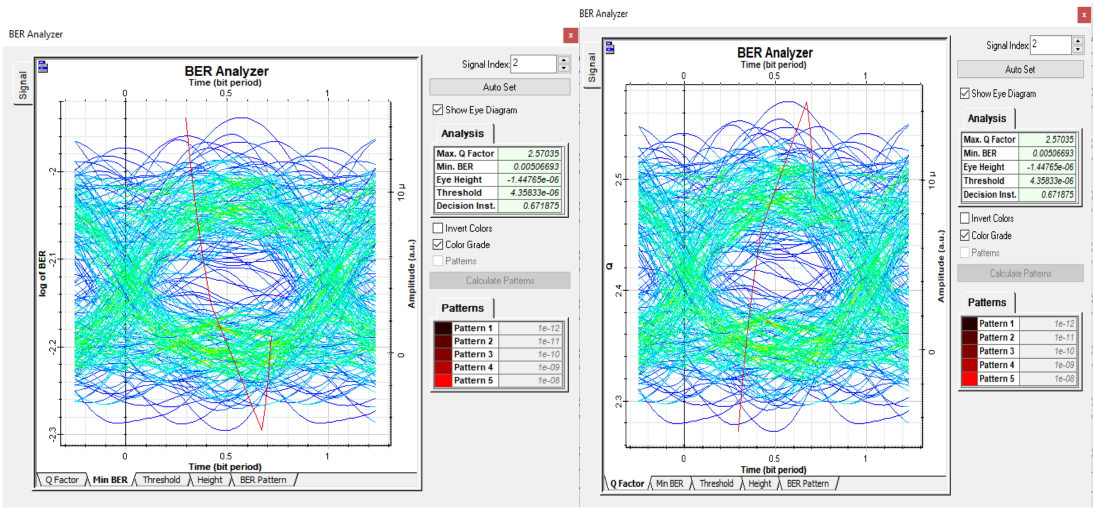

Figure 4. 12 Eye diagram at 3 dBm, 50km, and 5Gbps at Max Q Factor and Min BER

Therefore, when we see the performance of the eye diagram on the eye diagram and min BER at a data rate of 5 Gbps and 3 dBm, the eye diagram becomes narrower than 2.5 Gbps and 3 dBm because of increasing Data rate from 2.5Gbps to 5Gbps.

Table 4. 2 Results of Max Q Factor and Min BER at different km, 3 dBm, and 5Gbps

Fiber length(km)	Q-factor	Min. BER	Eye Height
5	20.607	1.18596e-94	5.8515e-05
10	16.6507	1.499302e-62	4.46786e-05
15	11.7695	2.79516e-32	3.213e-05
20	10.2632	5.152e-25	32.43578e-05
30	6.20218	2.78198 e-10	1.12619e-05
50	2.57035	0.00506693	-1.44765 e-05

Table 4.2 indicates the result of the Q-factor, Min BER Eye Hight of the system by varying the length of fiber in km at a comparable power of 3 dBm and a data rate of 5 Gbps.

4.3 Performance analysis of the eye diagram, Q-factor, and BER With Out Bessel Filter during noise removal

The performance analysis of an optical commutation system can be evaluated using various parameters such as the eye diagram, Q-factor, and bit error rate (BER). When noise is present in the system, these parameters can be affected, and it is important to remove the noise to improve the system's performance. One of the best techniques used to remove noise is the Bessel filter.

4.3.1 Eye diagram, Q-factor, and min BER at the power of 3dBm for both 2.5Gbps and 5 Gbps.

In Figure 4.13 the analysis of the eye diagram without a Bessel filter, with a Q-factor of 5.758 and a BER of 4.256e-09 indicate that the system performance is not good. Due to no filter being applied on the system noise can cause the eye opening to become narrower and increase BER.

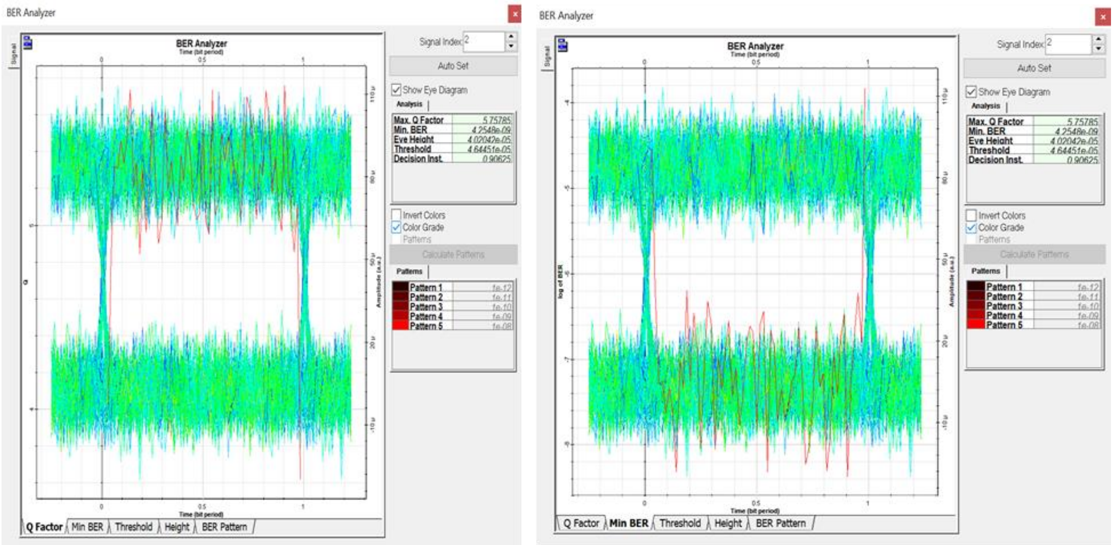

Figure 4. 13 Eye diagram without Bessel filter of 20km, 2.5Gbps at Q Factor and Min BER

Figure 4.14 below shows the Poor performance of the Eye diagram with Higher BER and Minimum Factor. The eye diagram is narrow which shows the poor performance of the system. In the absence of a Bessel filter, the eye diagram may exhibit a narrower eye-opening and indicate reduced signal quality.

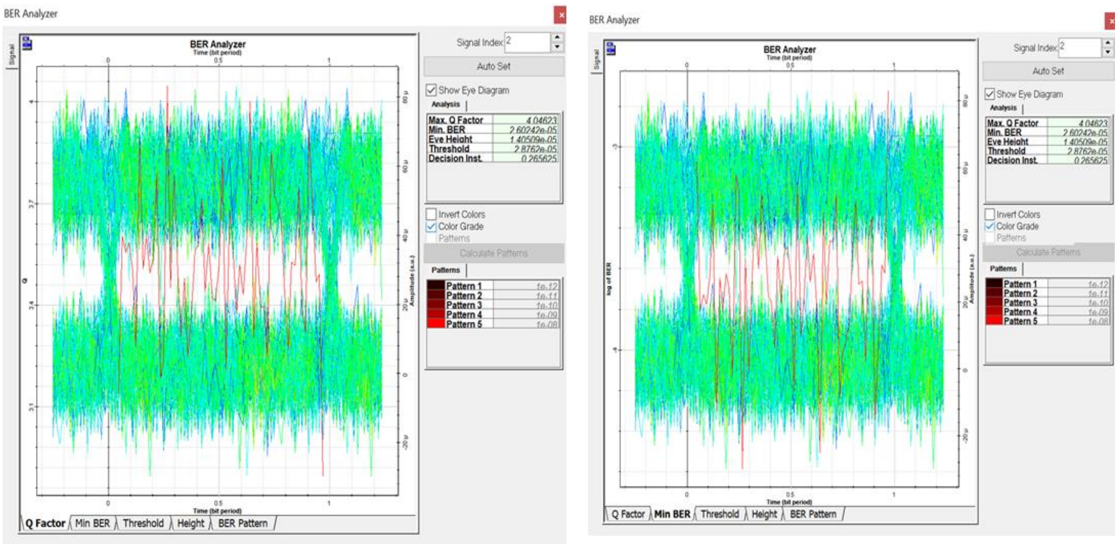

Figure 4. 14 Eye diagram without Bessel filter of 20km, 5Gbps at Q Factor and Min BER

Overall, the analysis of the eye diagram without a Bessel filter indicates that the system performance is affected by noise and other factors and that optimizing the system parameters and using a Bessel filter can improve the eye diagram and enhance the performance of the system. The below Table 4.3 indicate that the comparison parameter such as Q-factor, Eye diagram and Min BER by considering with Bessel filter and without Bessel filter.

Table 4. 3 Comparison of Performance parameter both with and without Bessel filter

Data Rate	Length	With Bessel Filter		Without Bessel Filter	
		Q factor	BER	Q factor	BER
2.5Gbps	20km	13.3265	2.6489e-41	5.757	4.25e-09
5Gbps		10.2632	5.152e-25	4.045	2.6024e-05

4.3 Simulation Result of MDM with 16-QAM

In Figure 4.15 a simulation of a 16-QAM optical communication system, an analysis of the RF spectrum was performed at different stages of the system. The M-array pulse generator was used to generate the electrical pulses that are modulated onto the optical carrier signal. The amplitude of the electrical pulses generated by the M-array pulse generator ranged from a maximum of 29.427 dBm to a minimum of -106 dBm. The RF spectrum analysis of the signal generated by the M-array pulse generator showed the presence of multiple frequency components at different amplitudes, corresponding to the different pulse amplitudes in the signal. After the M-array pulse generator, the signal was modulated onto the optical carrier using a quadrature modulator. The RF spectrum analysis of the signal after modulation showed a similar pattern of multiple frequency components at different amplitudes. However, the maximum amplitude of the signal after modulation was slightly lower at 28.144 dBm.

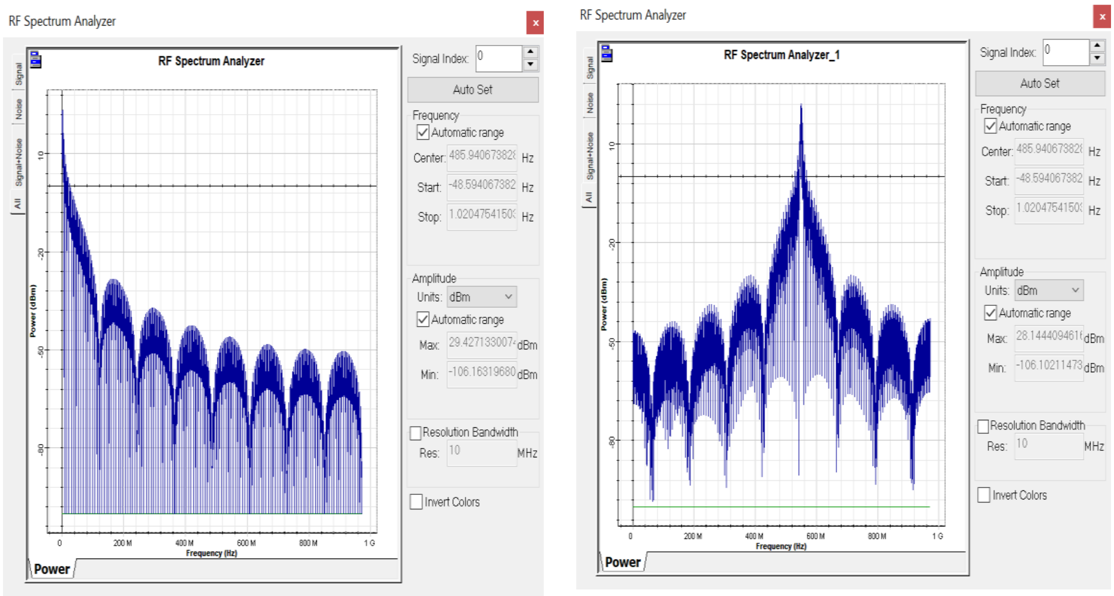

Figure 4. 15 Optical Spectrum analysis for 16-QAM

The below Figure 4.16 indicate an analysis of the electrical constellation at the M-array pulse generator was performed, with a maximum value of I=4 and a minimum value of Q=-4. The receiver uses this threshold to distinguish between the different signal states and to decode the transmitted information. The performance analysis of the electrical constellation and M-array threshold in a 16-QAM optical communication system provides valuable information for optimizing the system performance and achieving higher-quality transmission.

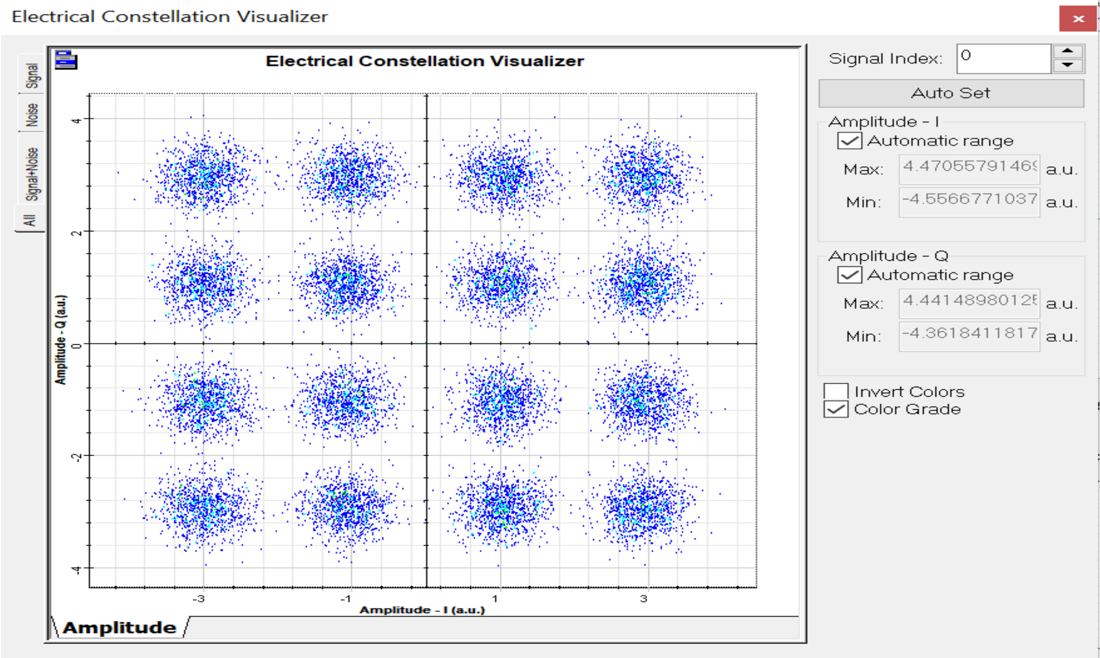

Figure 4. 16 Electrical Constellation of 16 QAM at M-ary

4.4 Simulation Result of MDM with 8-DPSK

In an optical communication system using 8-DPSK modulation, the RF spectrum analysis, and electrical constellation diagram are important tools for evaluating the performance of the system. In the below Figure 4.17 by using 8-DPSK modulation, the RF spectrum analysis is used to evaluate the performance of the system. The analysis of the RF spectrum with a maximum amplitude of 16.84 and a minimum amplitude of 15.89 suggests that the system is operating within the desired range.

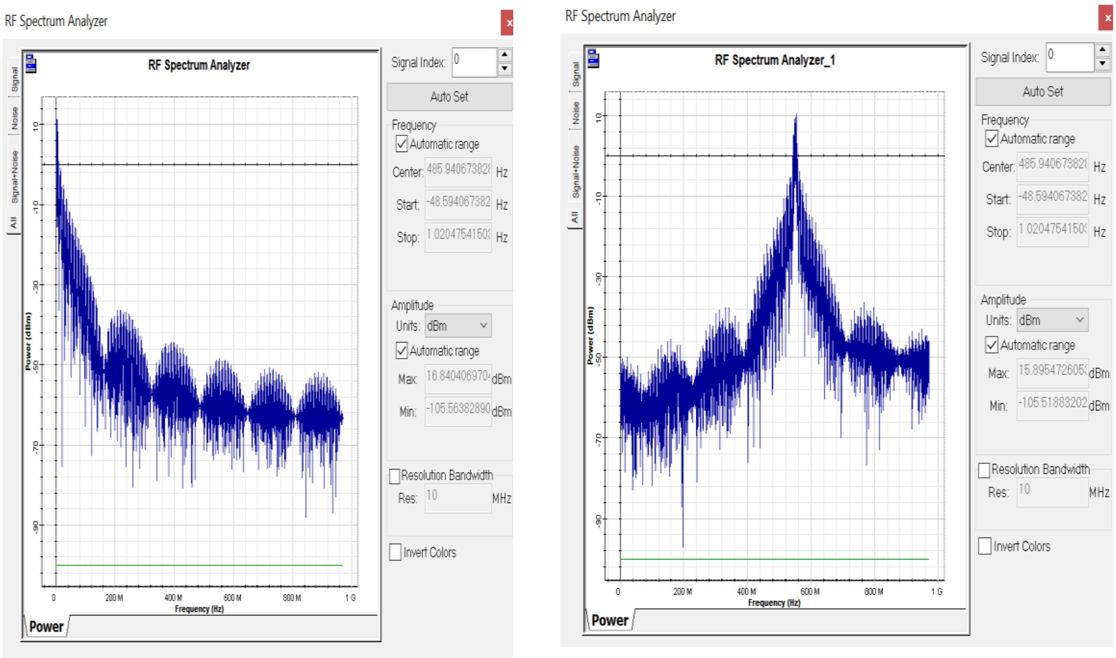

Figure 4. 17 Optical Spectrum analysis for 8-DPSK

The electric constellation is a graphical representation of the transmitted and received signals in a digital communication system. It provides a visual representation of the signal space, which can be used to analyze the performance of the modulation scheme and the effects of channel impairments. Analyzing the electric constellation at the M-array pulse generator and M-array threshold detector can provide valuable insight into the performance of a digital communication system. In an optical communication system using 8-DPSK modulation, the M-array threshold represents the decision threshold for the receiver to distinguish between different signal states and decode the transmitted information.

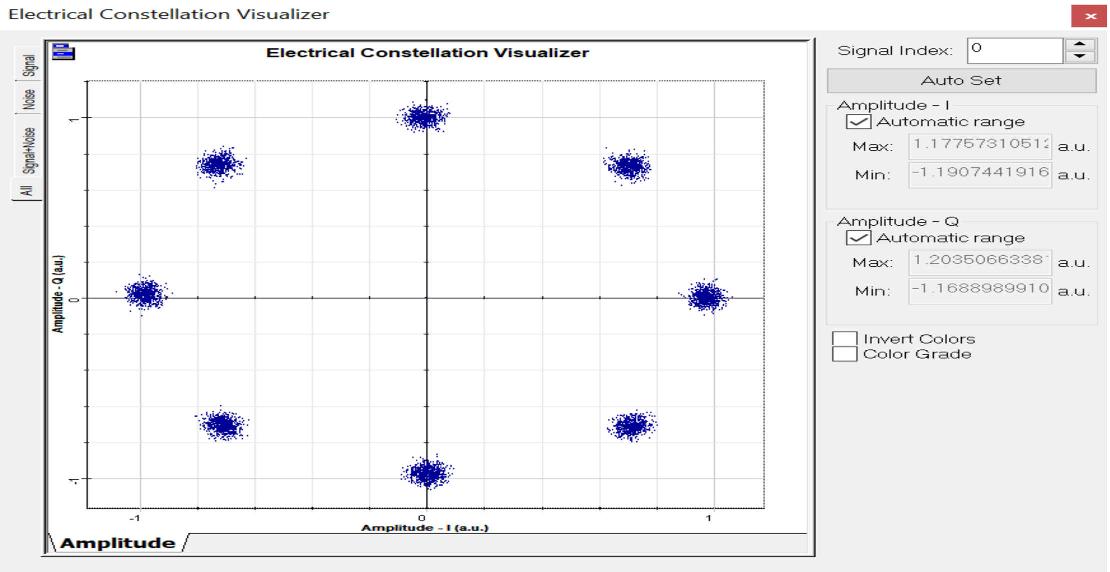

Figure 4. 18 Electrical Constellation of 8-DPSK at M-ary

4.5 Q-Factor Comparison with Variable Power and Different Length.

In this section, the comparison takes place between different power (0dBm, 3dBm, 5dBm, and 10dBm) and Different Length of (5km, 10km, 15km, 20km, 30km, and 50km) by considering setting Three Different Bite rates of 2.5Gbps, 5Gbps, and 10Gbps.

4.5.1 Q-Factor comparison with different lengths at 3dBm.

Below, Figure 4.19 indicates how the system's performance is impacted by distance by using different fiber length samples, and as fiber length increases, Q factor values decrease. The Q-factor continues to decline as the bidirectional optical fiber length grows and the signal quality degrades over 50 kilometers. Therefore, the below figure indicates that as fiber distance increases over fiber length, the Q factor decreases and at 5km we have the best Q factor.

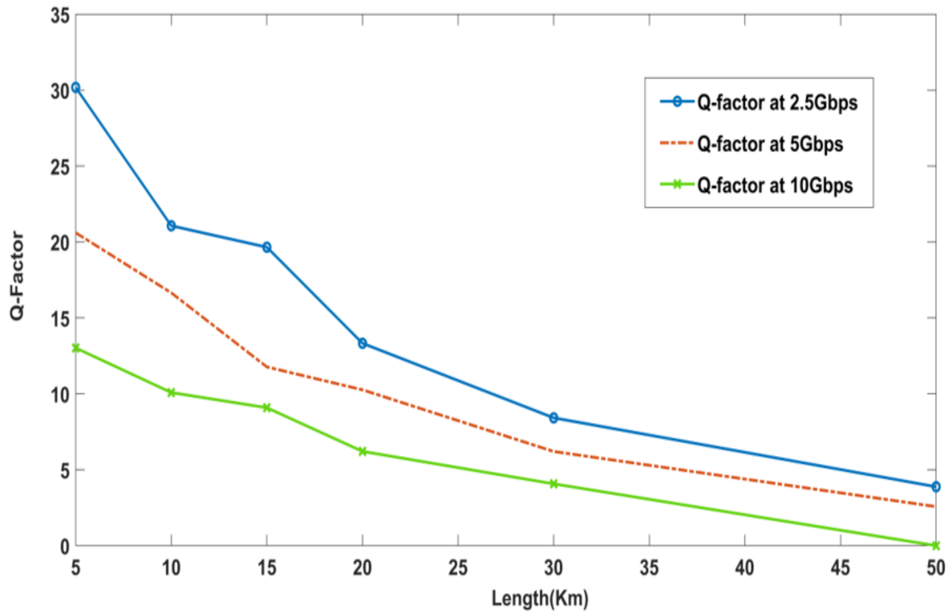

Figure 4. 19 Q Factor vs different Length

Table 4. 4 Results of Q Factor at 3dBm and different Length Values.

Fiber length(km)	Q-factor(2.5Gbps)	Q-factor(5Gbps)	Q-factor(10Gbps)
5	30.182	20.607	13.0217
10	21.0661	16.6507	10.0837
15	19.6556	11.7695	9.08429
20	13.3265	10.2632	6.20832
30	8.41743	6.20218	4.07044
50	3.87882	2.57035	0

Table 4.4 shows the value of different Q factors and Different lengths to compare them.

4.5.2 Q-Factor comparison with different Power at 10km

As we observed from below Figure 4.20, the value of Q factor 50.212vof 2.5 Gbps is the best compared to others. Because when we increase the data rate from 2.5Gbps to 10Gbps, the quality of the signal going to decreases.

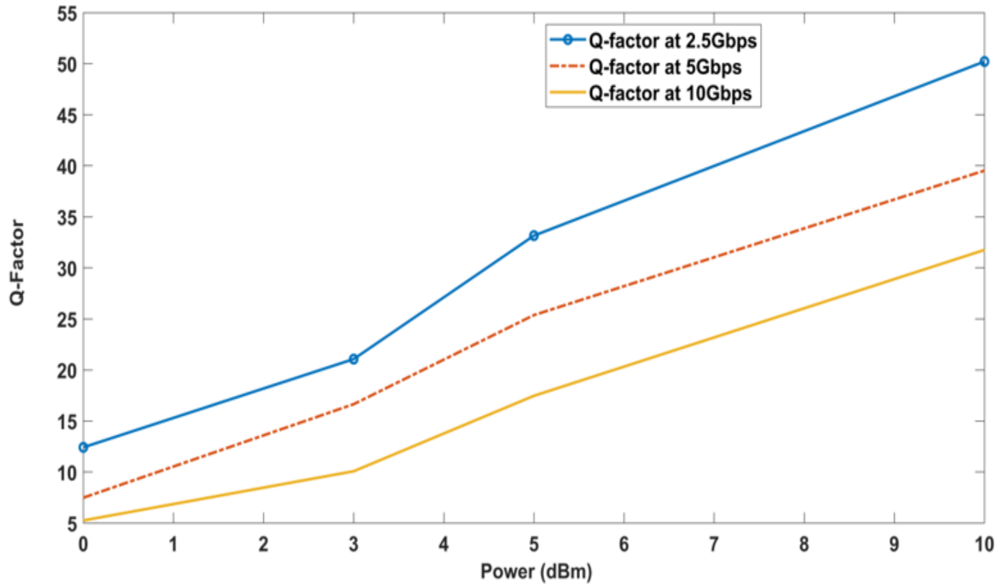

Figure 4. 20 Q-factor vs different power

Table 4.5 compares the Q factor by considering the power range from 0 dBm to 10 dBm at a fixed 10km.

Table 4. 5 Result of Q-factor at 10km and different power

Power(dBm)	Q-factor(2.5Gbps)	Q-factor(5Gbps)	Q-factor(10Gbps)
0	12.4227	7.48958	5.26045
3	21.0661	16.6507	10.0837
5	33.1597	25.3758	17.4704
10	50.212	39.5296	31.7599

4.6 BER Comparison with Variable Power and Different Length

With increasing power level and length, the BER increased as the biting error rate decreased. This indicates that as optical fiber length increases, dispersion also increases.

4.6.1 BER comparison with different power at 10km.

According to below Figure 4.21, it can be observed that there is a direct relationship between the power levels and the BER in the communication system. The graph shows that at a minimum power level of 10 dBm, the BER was found to be 0. This suggests that the system achieved error-free transmission at this power level.

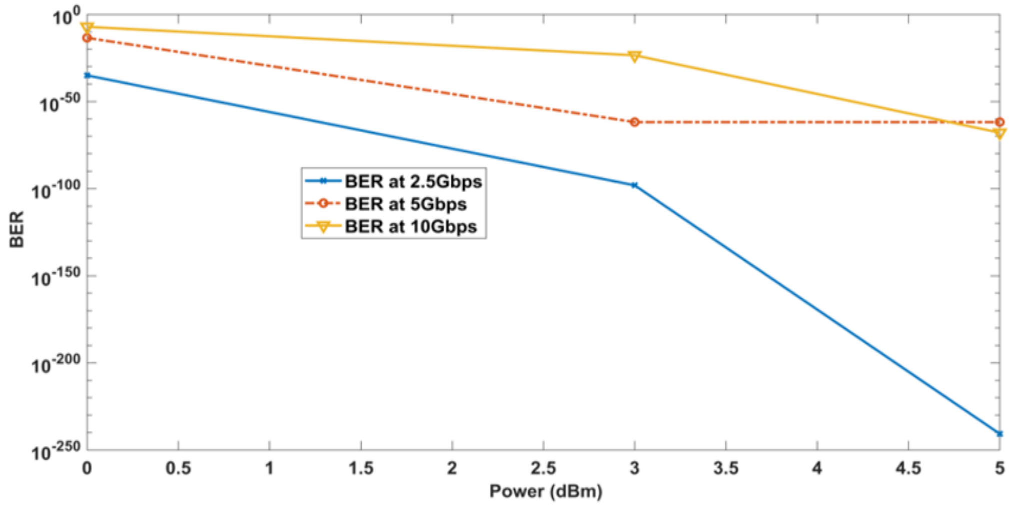

Figure 4. 21 Min BER vs different power

Table 4. 6 Min BER at10km and different power Values

Power(dBm)	BER(2.5Gbps)	BER(5Gbps)	BER (10Gbps)
0	9.83868e-36	3.4434e-14	7.1692e-08
3	8.12526e-99	1.49302e-62	3.25362-24
5	2.0446e-241	1.49302e-62	1.20482e-68
10	0	0	0

4.6.2 BER Comparison with Different Lengths.

Figure 4.22 shows the relationship between the length of fiber and the bit error rate (BER) in a communication system. It can be observed that as the length of the channel increases, the BER also increased.

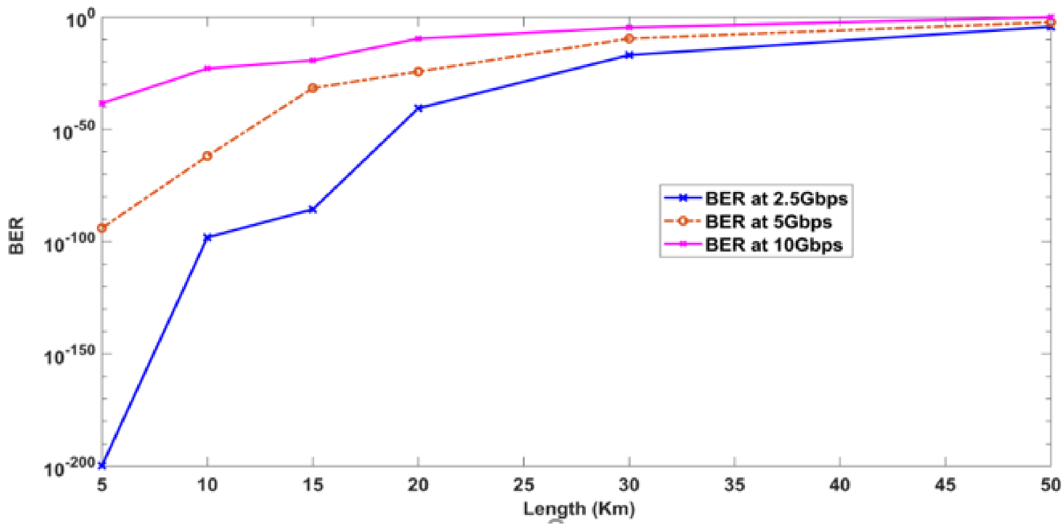

Figure 4. 22 Min BER vs different lengths

We understood from below Table 4.7 that as length increased, the BER also increased, indicating a degradation in the quality of the transmitted signal. It shows as the length of fiber increases, can result in increased signal attenuation, dispersion, and noise, which can contribute to a higher BER.

Table 4. 7 Min BER at 3dBm and different lengths.

Fiber length(km)	BER(2.5Gbps)	BER(5Gbps)	BER (10Gbps)
5	2.03832e-200	1.18596e-94	4.59479e-39
10	8.12526e-99	1.499302e-62	13.25362e-24
15	2.58652e-86	2.79516e-32	5.21900e-20
20	2.64889e-41	5.152e-25	2.62586-10
30	1.1817e-17	2.78198 e-10	2.34622e-05
50	5.24783e-05	0.00506693	1

4.7 BER comparison with Q-Factor

In Figure 4.23, the relationship between the Q factor and BER is shown, which shows that as the Q factor increases, BER decreases, indicating an improvement in the quality of the transmitted signal. Conversely, as the Q factor decreases, the BER increases, indicating a decline in the quality of the signal.

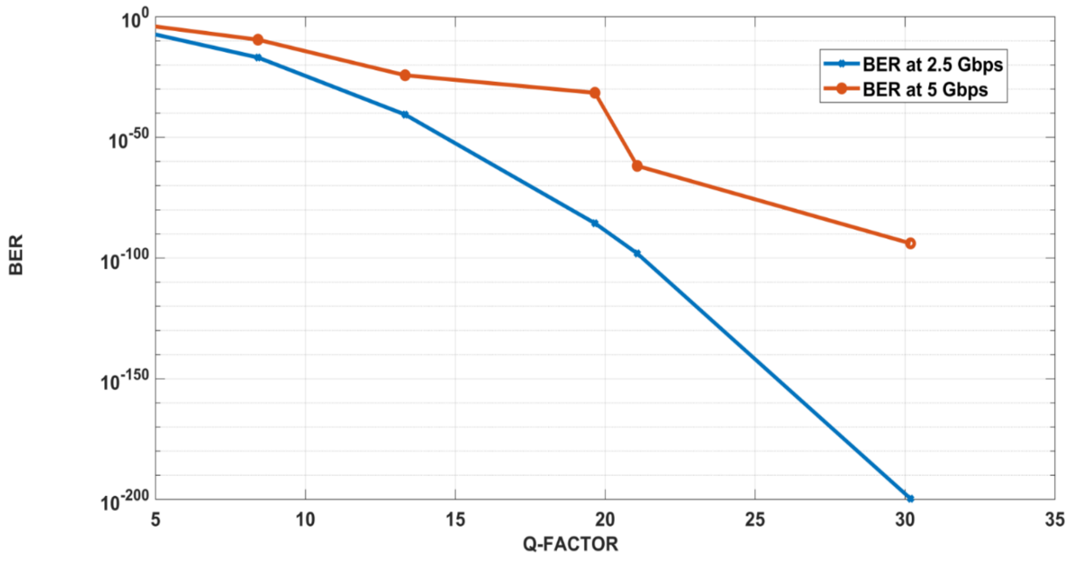

Figure 4. 23 BER comparison with Q-Factor

The relationship between the Q factor and BER at a data rate of 2.5 Gbps and 5 Gbps is typically an inverse relationship.

Table 4. 8 Q-factor vs BER at 3 dBm for 2.5Gbps and 5Gbps

Q-factor(2.5Gbps)	Min. BER(2.5Gbps)	Q-factor(5Gbps)	Min. BER(5Gbps)
30.182	2.03832e-200	20.607	1.18596e-94
21.0661	8.12526e-99	16.6507	1.499302e-62
19.6556	2.58652e-86	11.7695	2.79516e-32
13.3265	2.64889e-41	10.2632	5.152e-25
8.41743	1.1817e-17	6.20218	2.78198 e-10
3.87882	5.24783e-05	2.57035	0.00506693

4.8 Comparison of proposed technique with Previous technique

Comparison between the proposed Mode division multiplexing technique and the previous MDM-RoF technique done in other papers. In our previous study, it was concluded that the performance of the fiber optic receiver for various fiber lengths was evaluated with and without an amplifier. Three parameters BER, Q-factor, and eye diagram - were analyzed through simulations, and it was found that using an amplifier resulted in a significant improvement in Q-factor, eye diagram, and BER, indicating better overall system performance. The proposed system utilized modulation techniques and Bessel filters (both with and without) and resulted in improved performance compared to the previous system. In the previous system, the Q-factor was measured to be 6.42003 and 5.6144 with and without the amplifier, respectively, for a fiber length of 20km. In contrast, the proposed system achieved a Q-factor of 13.3265 and 5.757 with and without the Bessel filter, respectively, demonstrating significantly better performance. Therefore, the proposed system is superior to the existing technique.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Mode Division Multiplexing-Based Passive Optical Networks for High Capacity Data Rate via Radio over Fiber Technology are presented. The Simulation was performed on Optisystem Version 20 software. A good power budget is obtained from the minimum BER and maximum Q-factor at the output. From the above analysis, the BER and Q-Factor were analyzed depending on data rate, power input, and different distances of fiber kilometers. The system was simulated and analyzed using different power source values, lengths of the fiber, and operating wavelengths for both downstream and upstream directions. As the distance between transmitters and receivers increases, the Q factor decreases; at 50 km, it reads a Q factor of 3.87882. This indicates that the eye diagram becomes narrower. In contrast, at a fiber length of 5 km, the value of the Q factor is increased to 30.182, which indicates a wide-opening eye diagram. While BER has a value of 2.03832e-200 at 5 km, which also indicates good performance. The relationship between input power and Q factor is directly proportional, which means as input power increases, we get a good Q factor. We understand from the result analysis that we have the best Q-factor of 50.212 at 10 dBm and a 2.5 Gbps data rate.

When we analyze the result of BER in terms of power and length, at 10 Gbps, we get a zero value, which shows good performance, and BER increases as length increases, and we see a high value of 5.2478 e-05 at 50 km, which indicates poor signal quality. Therefore, when we see the performance of the eye diagram on the Q factor and min BER at a data rate of 5 Gbps and 5 Gbps, the eye diagram at 5 Gbps becomes narrower than at 2.5 Gbps because of the increase in data rate from 2.5 Gbps to 5 Gbps. The performance analysis of Mode division multiplexing during the Bessel filter and without the Bessel filter is understood. At a data rate of 2.5 Gbps and 20 km, the Q factor for MDM with a Bessel filter is 13.3265, and without a Bessel filter is 5.718. This indicates that using a Bessel filter can improve signal quality and result in a higher Q factor. The difference in the Q factor between MDM with and without the Bessel filter indicates that using the filter can lead to a more reliable and efficient communication system. Similarly, at a higher data rate of 5 Gbps and the same distance of 20 km, the Q factor for MDM with a Bessel filter is 10.263, and without a Bessel filter is 4.04623. Again, the Q factor for MDM with the Bessel filter is significantly higher, indicating that using the filter can improve the signal quality and result in a more reliable and efficient communication system.

Finally, we compare 8-DPSK and 16QAM modulation schemes, we can analyze their RF performance and electric constellation. RF analysis involves measuring and evaluating the radio frequency (RF) characteristics of the signal, like the signal-to-noise ratio (SNR), bit error rate (BER), and spectral efficiency. While Electric constellation analysis involves plotting the signal points on a constellation diagram to determine the signal quality and the level of distortion. In, 16QAM has a higher spectral efficiency compared to 8-DPSK, which can transmit more data per symbol. But, 8-DPSK has a lower BER. Therefore, the choice between 8-DPSK and 16QAM depends on the specific requirements of the communication system. Modulation of 16QAM is preferred due to it has high spectral efficiency.

5.2 Recommendations and Future Work

Mode division multiplexing (MDM) is a promising technology for increasing the capacity and performance of passive optical networks (PONs). MDM-based PON uses multiple modes within a single optical fiber to transmit data, allowing for higher data rates and greater capacity than traditional single-mode PONs.

Some points that will be recommended for future work are:

- ✓ Applying Advanced modulation formats, such as orthogonal frequency-division multiplexing (OFDM) and Nyquist pulse shaping.
- ✓ Use signal processing techniques such as digital signal processing (DSP) and error correction coding.
- ✓ Increasing the number of ONUs to 32, 64, and 128 users.

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