Modeling and Performance Analysis of Free Space Optics as a Backup Link for Fiber Connectivity in Urban Area using OptiSystem

Nuguse Birhanu Mengistu

A Thesis Submitted to the Department of Electronics and

Communication Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfilment 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 FOR M.SC THESIS

We, the undersigned, members of the Board of Reviewers of the thesis open defense by Nuguse Birhanu have read and evaluated the thesis entitled "Modeling and Performance Analysis of free space Optics as a Backup Link for Fiber Connectivity in Urban area using Optisystem" and assessed the understanding of the candidate about the research. This is, therefore, to certify that the thesis proposal is accepted and we recommend the implementation of the proposal.

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DECLARATION

I hereby declare that this Master Thesis entitled "**Modeling and Performance Analysis of free space Optics as a Backup Link for Fiber Connectivity in Urban Area Using OptiSystem**" is my original work. That is, it is 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.

Nuguse Birhanu Mengistu	______________	___________
Name of student	Signature	Date

RECOMMENDATION

We, the advisors of this, hereby certify that we have read the revised version of the thesis entitled "**Modeling and Performance Analysis of free space Optics as a Backup Link for Fiber Connectivity in Urban Area Using OptiSystem**" prepared under our guidance by Nuguse Birhanu Mengistu submitted in partial fulfilment of the requirement for the degree of Master's of Science in Communication Engineering. Therefore, we recommend the submission of revised version of the thesis is to the department following the applicable procedures.

Dr. Demissie Jobir Gelmecha	_______________	___________
Major Advisor	Signature	Date
__________________	_______________	____________
Co-advisor	Signature	Date

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LIST OF ABBREVIATIONS

APD	Avalanche Photodiode
BER	Bit error rate
CW	Continuous Wave
DSD	Drop Size Distribution
DEMZM	Dual Electrode Mach-Zehnder Modulator
dBm	decibel milliwatts
ETB	Ethiopian Birr
EGC	Equal Gain Combining
EDFA	Erbium Dopped Fiber Amplifier
FO	Fiber optics
RF	Radio frequency
FTTx	Fiber to home premises
FSOC	Free Space Optical Communication
FSK	Frequency Shift Keying
FWHM	Full Width Half Maximum
IR	Infrared communication
LAN	Local Area Network
LOS	Line of sight
MZM	Mach-Zender Modulator
MRC	Maximum Ratio Combining
OOK	On Off Keying
OSNR	Optical to Signal Noise Ratio
OWHNs	Optical Wireless Home Network
OWTNs	Optical Wireless Terrestrial Network
OWSNs	Optical Wireless Satellite Network
OEM	Optical external modulator
OTSB	Optical Time-Shifted Burst
OSSB	Optical Single Sideband
OFDM	Orthogonal Frequency Division Multiplexing
Pin	Input power

PIN diode	P-N junction Diode
PON	Passive Optical Network
Pout	Output power
PPM	Pulse Position Modulation
PRBS	Pseudo Random Bit Sequence
PSK	Public Switched Telephone Network
PWM	Pulse Width Modulation
Q-factor	Quality factor
QAM	Quadrature Amplitude Modulation
SNR	signal-to-noise ratio
SC	Selection Combining
SDD	Spectral direct decoding
SAN	Storage Area Network
SOA	Semiconductor Optical Amplifier
TCO	Total Cost of ownership
WDM	Wave Division Multiplication
WAN	Wide Area Network
WOC	Wireless Optical Communication

ABSTRACT

The paper presents a study on the potential use of Free Space Optics (FSO) communication for high-speed and reliable data transmission in urban areas of Ethiopia, particularly during heavy rain seasons or in cases where fiber connectivity is not feasible or cost-effective. The study uses Opti System and Mat lab to create an FSO model capable of transmitting data at 2.5 Gb/s at ranges of 5, 10, 15, 20, and 40 kilometers, and examines various transmission parameters, including transmission power, bit error rate (BER), Q-Factors, optical signal-to-noise ratio (OSNR), Pointing error, beam divergences and transmission distances. The study shows that 30 dBm of transmitting power is suitable for improving data transmission during heavy rain and fog seasons in Ambo and Dire Dawa, with a BER below 10^{-9} *for link distances up to 15 km in Ambo and 20 km in Dire Dawa, even in the presence of atmospheric turbulence; and The FSO achieves a maximum Q-factor of 33.0451 and a minimum BER of 7.8383e-240 with a rainfall attenuation of 0.144 dB/km and a link range of 20 km in autumn period and these show that the system is capable of transmitting data at a very high bit rate with an incredibly low error rate in Ambo city. The result shows that the Signal-to-Noise Ratio (SNR) can be improved by increasing the Numerical Aperture (NA) sizes for different values of sigma (0.3, 0.5, 0.8) using diversity techniques like Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC), as demonstrated through simulation results obtained using Mat lab. The result also analyzes Rytov variance impact on BER performance by increasing numerical aperture, improving SNR, and reducing atmospheric turbulence impact and increasing the link range. The study provides valuable insights into the potential use of FSO technology for high-speed and reliable data transmission in urban areas of Ethiopia, where fiber connectivity may not be feasible or cost-effective.*

Keywords: *FSO, BER analyzer, Q factor, NRZ; Rain Attenuation, Atmospheric turbulence*

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

In the modern era, fiber-optic communication has become the most widely used means of communication. It provides high-speed data transmission with low error rates (Muhammad et al., 2020). However, fiber cables can be susceptible to cuts, earthquakes, or other disasters, which can lead to network outages. In order to mitigate these risks and ensure uninterrupted network availability, backup communication links are required. A reliable alternative to fiber-optic communication is free-space optical (FSO) communication (Jahid et al., 2022). FSO has recently generated a lot of interest due to its ability to enable high-speed data transfer at low cost and with minimal infrastructure requirements. In metropolitan areas where many buildings may obstruct radio frequency (RF) transmissions, FSO offers a cost-effective alternative to optical and RF-based backup systems (Jahid et al., 2022). Due to its simplicity of installation and lightweight equipment, FSO technology is used in disaster recovery to provide ad hoc connectivity via temporary lines. FSO is also a low-cost technology that can be used to transport communication over challenging landscapes where installing regular communication networks is a costly task(Kaushal & Kaddoum, 2017).

The expansion and acceptability of FSO communication have dramatically increased with the rise of increasingly advanced optoelectronic devices. There are many difficulties since FSO transmission is sensitive to the weather and atmospheric turbulence(M. Singh et al., 2016). As a result, there are issues with the availability and dependability of FSO links. Knowing the performance characteristics of the FSO links under various weather conditions is one of the requirements for selecting the design parameters of the FSO system prior to its deployment. The most prohibitive weather conditions, fog, rain, and snow, attenuate the optical signal, which can be parameterized or evaluated using the optical signal's observable range in various weather circumstances(Siegel & Ping, 2020). The statistics of atmospheric attenuation are the biggest unknowable. It should be possible to collect these statistical data by measurements or through theoretical computations based on atmospheric optics theory. Researchers have been able to study and analyze the performance of FSO systems with widely used simulation program Opti System.

Free space optics transmission should be viewed as a backup for fiber optics transmission because this type of cable-free optical communications technology transmits data between two fixed places using a highly directed narrow light beam(M. Singh et al., 2016). There are a few issues with optical fiber communications that can be avoided, like the high cost of building roads and the impractical physical connection between transmitters and receivers. Additionally, it might be proposed as a substitute or advancement for short-range wireless communication systems (up to a few kilometers)(Uysal & Nouri, 2014). The absence of radio frequency radiation dangers, ease of installation, and the lack of the need for licensed frequency band allotment are some benefits. Resistance to interference, large data rates.

Despite the many advantages of FSO, the local weather is the main factor that limits the FSO link's availability(M. Singh et al., 2016). Since the transmission medium is free, air attenuation can lower the signal by a few to hundreds of dB per kilometer. In tropical regions without fog, heavy rain is anticipated to improve and reduce the signal in the FSO receiver system(H. Singh & Mittal, 2021). By assessing different characteristics, including channel capacity, signal quality, BER, and link availability under various environmental and meteorological circumstances, one may analyze the FSO's performance as a backup link for fiber connectivity(Ghoname et al., 2020).

Designing and optimizing FSO links by assessing their performance in various environments and conditions is made possible by modeling and performance analysis of FSO as a backup link for fiber connectivity in metropolitan areas using Optisystem software. We will examine the impacts of rain, fog, and other turbulence by altering the transmission distance and transmitting power under a 10dBm optical attenuator while keeping record of the received power, Q-factor, and BER in the simulation.

1.2 Statement of the Problem

Urban areas reliance on fiber optic networks for connectivity is growing along with the demand for high-speed data transfer. However, fiber connections are susceptible to disasters and physical interruptions. As a result, it's important to investigate other backup connectivity options that might deliver effective and reliable performance. Optical communication is one of the best systems for delivering the high-speed data services that users need from the telecom infrastructure. Lack of timely main link maintenance during disasters and installation of redundancy links prevents service providers from affirming their commitment to provide high-quality service, which leaves customers dissatisfied. FSO can be used to safely transfer large amounts of data over long distances when a backup link deployment is necessary without having to spend money on fiber optic cable installation. An urban region is chosen as a case study in order to apply the design. Although putting optical fiber in the ground requires significant costs, time, and effort, it is the most durable method of delivering optical communications. As a result, it is sometimes economically unfeasible. Once installed the fiber cannot be redeployed easily.

In this case, it is clear that FSO is the greatest option for a backup link in terms of price, installation time, bandwidth, and simplicity. FSO technology attracts to communication service providers since it operates in a frequency spectrum without a license. By modeling and analyzing the performance of the FSO link when utilized as a backup for fiber connectivity deployed in urban areas using Opt system software, it also wants to carefully examine this study as a step towards a practical awareness.

1.3 Objective of the study

1.3.1 General Objective

The general objective of this study is to modeling & analyzing the performance of free space Optical link as a backup link for fiber connectivity in urban area.

1.3.2 Specific Objectives

The specific objectives of this study are as follows:

- To model the fiber Space optics communication for urban areas.
- To assess the factors that may affect the Performance of FSO system using rain, Fog, snow and atmospheric turbulence parameters.
- To evaluate the system performance of FSO at various distances between transmitter and receiver

- To measure the system performance of FSO in terms of BER, Q factor and OSNR.
- To improve the performance of FSO system by using diversity combining techniques like MRC, EGC& SC.

1.4 Significance of the Study

The study provides that free space optics technology can provide a cost-effective solution for high-speed communications when fiber optic connections are not feasible. The study recommends using Opti System to predict the performance of free space optical links, considering atmospheric conditions and other factors. The study's findings can be useful for researchers, network designers, and engineers in developing and improving free space optical communication systems. The study has the potential to advance the field of optical communication, given the increasing demand for high-speed data transport.

1.5 Scope of the Study

The scope of the study on "Modeling and Performance Analysis of Free Space Optics as a Backup Link for Fiber Connectivity in Urban Area using Opti System" involves modeling and analyzing the performance of FSO communication system under different atmospheric conditions and link distances, investigating the effect of different parameters such as link distance, atmospheric turbulence, pointing errors, beam divergence, and transmitter power on the performance of FSO link, and identifying the limitations and challenges of FSO communication system and proposing solutions for improved performance

1.6 Limitations of the Study

The study focuses only on two cities in Ethiopia, namely Ambo and Dire Dawa, and may not fully reflect the performance of FSO links in other urban areas with different atmospheric conditions and topographies.

1.7 Contribution of the study

The research could advance our knowledge of FSO technology and its potential for fiber connectivity in metropolitan areas as a back-up. The study may shed light on the viability and constraints of applying FSO technology in real-world applications by examining the FSO link's performance under different atmospheric turbulence using OptiSystem software. The study's contribution is to provide light on the potential use of FSO systems as a backup link for fiber connectivity in metropolitan areas and to identify the variables influencing the performance of FSO systems. Researchers and practitioners interested in FSO systems and their applications in urban settings may find the study's findings useful.

1.8 Thesis Summary

The main points of this thesis are outlined as follows:

Chapter 1 Introduction: The primary topics covered in this chapter are the study's background, problem statement, objectives, contribution, study scope, and study limitations.

Chapter 2 Literature Review: This chapter mainly focuses on Introduction to FSO communication system, use case of FSO technology, FSO Communications in Atmosphere, Characteristics & Architecture of FSO System; Classification of FSO system, Application& Limitation of FSO system; review of related works.

Chapter 3 Materials and Methods: This chapter mainly focuses on materials and methods used to accomplish the research work, Channel model with different Factors, mathematical model for components and simulation parameters.

Chapter 4 Result and Discussion: This chapter mainly focuses on simulation parameters, power spectral density comparison, bit error rate comparison, OSNR, Geometrical & Pointing Error model, Eye diagram of Received signal with different atmosphere like rain and fog in urban areas like Ambo & Dire Dawa city.

Conclusion and Recommendation: This section mainly focuses on conclusion and Recommendation for future study.

CHAPTER TWO

LITERATURE REVIEW& RELATED WORKS

2.1 INTRODUCTION

Line-of-sight communication using modulated optical beams to transfer data over the atmosphere is known as free space optics (FSO) communication, also referred to as optical wireless communication. Its light source is a laser, and a number of modulation techniques are used to modulate the data transmitted on the laser beam(Al-Gailani et al., 2021). FSO technology enables extraordinarily fast data transfer over short distances, often in the order of gigabits per second. Since the transmitter and receiver don't require a physical connection, FSO has advantages over conventional communication techniques like fiber optics and microwave systems. It is perfect for usage in settings where laying cables is challenging or impossible or where connectivity wireless is necessary for security reasons.

Information exchange is the main purpose of a communication system, and it can be done in many different ways. Technology known as free-space optical (FSO) focuses on how different materials interact and change the quality of the optical signal as they transmit the optical beam through them. It is essential to have a thorough understanding of atmospheric phenomena and how they affect light propagation in order to build reliable networks and efficient, intelligent, and cost-effective FSO lines that can offer service without interruption at the required quality.

The random variation in the received optical laser beam's intensity driven on by air turbulence is known as scintillation. As a result, the environment may have an impact on the performance of a dependable high-data-rate wire-free FSO optical communication link. Because of this, it is possible to predict how well FSO communications will function when an atmospheric communication channel is available by studying how the optical wave interacts with the atmosphere.

2.1.1 FSO Communications in Atmosphere

The majority of a light beam's characteristics change in FSO while moving through air. The atmosphere is a fluid mixture of gases, chemicals, and particles that is continually receiving or losing energy (heat). Thermal turbulence is caused by the constant movement of air cells, which have inhomogeneous and constantly changing refractive indices, densities, and air homogeneity. The environment has a significant impact on many of the features of the FSO light beam, including variations in polarization refraction, absorption, scattering, and attenuation. This causes the light beam to fluctuate randomly at a frequency of at least 10 mHz and up to 200 Hz (Alheadary et al., 2018). In an FSO system, atmospheric turbulence causes a laser beam to alter in polarization, coherency, and attenuation due to random fluctuations in the air mass along the path and non-consistent power loss in the air mass along the way. The signal's intensity varies when it reaches the receiver due to random temporal and spatial irradiance changes of the light beam.

A variety of methods, including adaptive optics, error-correcting codes, and diversity approaches, can be employed to minimize the impact of the atmosphere on FSO communication. By altering the optics of the FSO transceiver, adaptive optics can be utilized to correct for distortions brought on by turbulence. Data that is transmitted over the FSO link may contain errors that can be found and fixed. To boost reliability and lessen the impacts of fading and atmospheric interference, diversity techniques can be employed to simultaneously transmit the same data over many FSO lines.

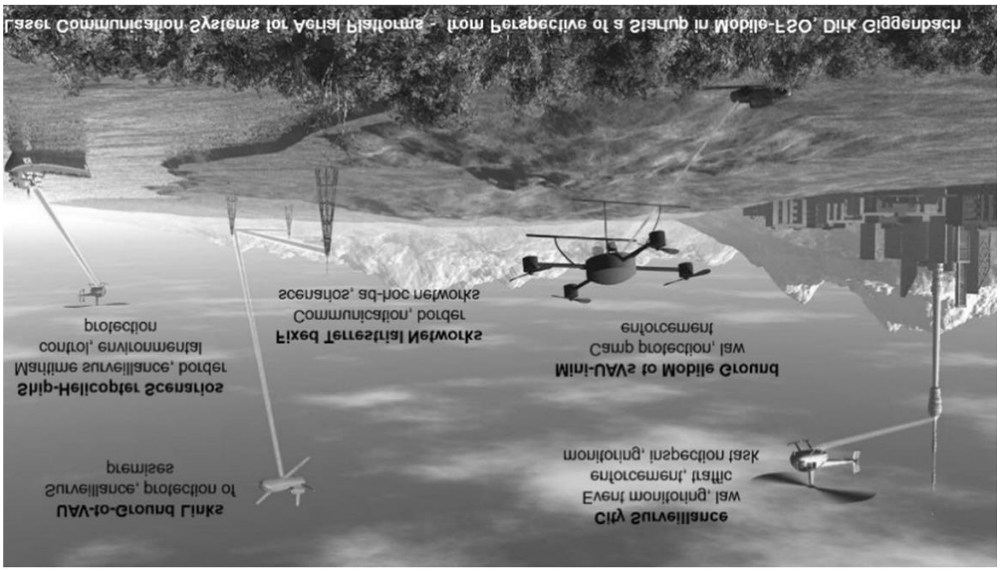

Figure 2. 1 Examples of scenarios of the FSO systems application (Alheadary et al., 2018)

Examples of significant uses for FSO systems include ad hoc mobile communications during emergency situations, so-called "last mile" linkages in metropolitan areas, a special data transfer, as between ships and land, and covert military data lines. It was proved that a command center could send data to soldiers or vehicles within "line-of-sight" at a rate of between 25 Mbps and 1.25 Gbps (Al-Gailani et al., 2021).

The most important advantages of FSO technology include the lack of formal regulation surrounding the use of radiation spectra, high transmission rates up to 10 Gbps(Ghassemlooy et al., 2016), insensitivity to electromagnetic interference (EMI), quick, low-cost, and simple installation, high immunity to interception and jamming, user-adjustable capacity with the option of data link reconfiguration, and commercial viability.

2.2 Wireless Optical Communication (WOC)

Wireless optical communication (WOC) is a technique that sends data over an unguided channel, like the air or open space, using an optical carrier. Because of its extremely high bandwidth, ease of deployment, unlicensed spectrum location, reduced power consumption (half of RF), smaller size (one-tenth of RF antenna diameter), and improved channel security, WOC is viewed as the future of high-speed broadband connectivity ((Kaushal & Kaddoum, 2017).

2.2.1 Classification of Wireless Optical Communication (WOC)

The two main subcategories of wireless optical communications (WOC) are indoor and outdoor WOC. To communicate inside a structure when installing a physical cable connection would be challenging, indoor WOC uses infrared or visible light. The four generic system configurations for indoor WOC are tracked, diffused, non-directed line-of-sight (LOS), and LOS. Outdoor WOC is often referred to as free space optical (FSO) communication. Building-to-building, ground-to-satellite, satellite-to-ground, satellite-to-satellite, and satellite-to-airborne platforms are a few examples of FSO communication systems(Ao et al., 2022)

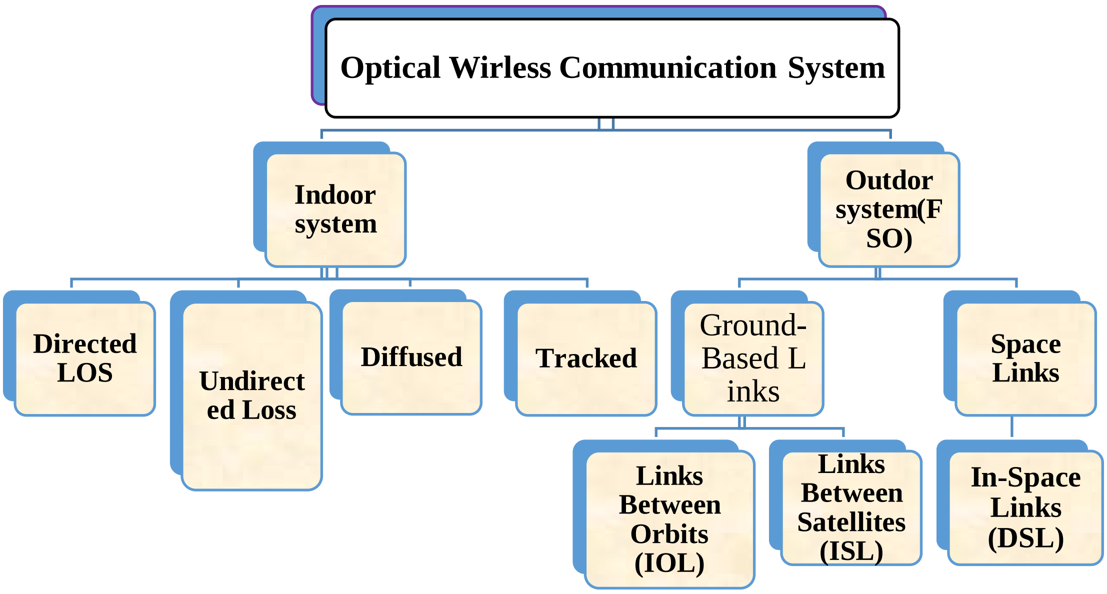

Figure 2. 2 Classification of wireless optical communication system (Kaushal & Kaddoum, 2017)

2.3 Significance of Optical Networks to FSO Communications

Fiber is the most dependable way of optical communications so far, and FSO Networks Concept, Architectures, Protocols, and Topologies to handle the bandwidth shortage and satisfy the bandwidth requirement. However, fiber is substantially more expensive (e.g., for digging, the cost to lay that fiber). Furthermore, in some regions, such as downtown districts or areas with hills or mountains, laying fiber is very impossible or impractical. Even while RF technology is mature, it still necessitates large investments in order to obtain spectrum licenses and cannot be scaled to optical capabilities in order to meet the massive bandwidth requirements (Kaushal & Kaddoum, 2017).

In terms of bandwidth scalability, deployment speed, security flexibility, and cost-effectiveness, FSO technology is the best option. It's worth noting that optical networking provides the lowest cost structure for transporting bandwidth per unit distance, making it incredibly appealing. The FSO for a point-to-point link between two outdoor buildings may deliver data rates of more than 1 Gbps per link, which can be enhanced to 10 Gbps and possibly 50 or 120 Gbps per link utilizing wavelength division multiplexing (WDM)(Kaushal & Kaddoum, 2017).

2.4 Over view of FSO (Free space Optics)

The optical communication technology known as FSO (free space optics) enables optical connectivity by delivering data through the propagation of light in free space. There is no need for the optical fiber cable. While FSO networks function similarly to OFC (optical fiber cable) networks, optical beams are delivered over free air instead of the glass fiber OFC cores. The full duplex (bidirectional) functionality of the FSO system is provided by the employment of an optical transceiver at both ends.

The idea of FSO communication is not new. Although it has changed since the eighth century, it has existed from that time. Line-of-sight (LOS) is a technique used in FSO. It's a fantastic solution to close the current connectivity gap in the telecoms infrastructure. High-speed, point-to-point connectivity is promised by FSO technology. It is a method that combines wireless flexibility and speed similar to fiber. Although one of the city's main routes is now fiber optics, installing fiber cables is expensive. Additionally, the price of deployment time is too expensive. Once fiber cable has been laid, it can be challenging to move it (Suriza et al., 2013).

2.4.1 Characteristics of FSO System

Free Space Optics (FSO) systems use optical wireless communication technology to transmit data between two points through free space (Chauhan et al., 2020). Some of the key characteristics of FSO systems on modeling and performance analysis of FSO as a backup link for fiber connectivity in urban areas using OptiSystem are:

Line-of-sight: FSO systems require a clear line-of-sight between their transmitters and receivers. Any obstacles in the path of the beam can cause signal loss and reduce the performance of the system.

Weather-dependent: FSO systems can be affected by atmospheric conditions such as fog, rain, and snow, which can cause signal attenuation and reduce the range of the system.

Data rate: FSO systems can provide high data rates of up to several gigabits per second, depending on the system configuration and the distance between the endpoints.

Security: FSO systems can provide secure communication as the transmission is confined to the line-of-sight path between the endpoints, making it difficult for unauthorized access.

Reliability: FSO systems can provide reliable connectivity as a backup link for fiber connectivity in urban areas, ensuring uninterrupted connectivity in case of fiber link failures.

2.4.2 Classification of FSO Networks

FSO networks have been explored and used for networks spanning distances ranging from a few meters to thousands of kilo meters due to its significant potential for a wide range of applications. According to the locations of optical transmitters and receivers as well as network range, networks can be divided into three types (Chauhan et al., 2020).

2.4.2.1 Optical Wireless Satellite Networks (OWSNs)

OWSNs are meant to provide end-users with high-bandwidth, optical wireless network connectivity via satellites that cover significant regions of the globe. Because satellites can assist any terrestrial residents regardless of topographical limits as long as a Line-of-Sight (LOS) space path exists, OWSNs create a global space backbone network using optical connectivity. As a result, OWSNs provide high-quality data services to even the most remote locations, such as an island, a remote farm, an ocean ship, and airplane.

2.4.2.2 Optical Wireless Terrestrial Networks (OWTNs)

OWTNs, also called as outdoor FSO networks, use outdoor atmospheric turbulence channels to build a point-to-point and LOS optical wireless connection between two transceivers. The distance of light propagation across empty air space varies from hundreds of meters to tens of kilometers due to the LOS requirement. This telecommunication paradigm offers a lot of potential for wireless communications and is quickly becoming a popular way to get high-speed internet (Chauhan et al., 2020).

2.4.2.3 Optical Wireless Home Networks (OWHNs)

Indoor FSO networks, also known as OWHNs, are ideal for wireless broadband communication inside homes and offices. OWHNs are used to create a LAN made up of cells, with each cell representing one of the building's separated spaces. Each cell usually comprises a base station to which numerous terminals are connected by short-range optical wireless communications like infrared and Light Emitting Diode (LED). Infrared and LED beams, unlike radio frequencies, cannot penetrate walls. Each wireless optical cell should be contained within a single room and must be linked to and integrated with a broadband backbone system. In most cases, nearby cells do not interfere with one other. As a result, the same beam specifications are reused (Chauhan et al., 2020). In this thesis paper we are working on the second classification type of FSO (OWTNs).

2.5 FSO Basic Architectures/Topologies

Three main FSO architectures have been used so far.

2.5.1 Point-to-Point (P2P)

This architecture is used for a connection between two fixed points. In this architecture, two FSO transceivers are placed at the respective end points of the communication, and they are aligned towards each other for optimal transmission. The dedicated connection used in this architecture has a higher bandwidth but is less scalable.

2.5.2 Mesh

This architecture is used to establish a connection between a central location and multiple remote locations. This is achieved by installing a FSO transceiver at the central location and installing FSO receivers at remote locations. This architecture offers redundancy and higher reliability with easy nodes addition, but restrict distances more than other options.

2.5.3 Point-to-Multipoint (P2MP)

This architecture is used to interconnect multiple FSO nodes in a mesh topology. In this architecture, each FSO transceiver communicates with its adjacent nodes to form a network. It Offers cheaper connections and facilitates node addition, but at the expense of lower bandwidth than the point-to-point option.

2.5.4 Hybrid Architecture:

This architecture combines FSO technology with other wireless technologies such as Wi-Fi to provide a more reliable communication system. In this architecture, an FSO transceiver is used as a backup in case of network failures in other technologies.

2.5.5 Mobile Architecture:

This architecture is used for mobile applications and is designed to provide seamless communication between moving vehicles or between a vehicle and a fixed point. This is achieved by using directional FSO transceivers and tracking systems that follow the movement of the vehicles.

Ponto-to-point architecture

Mesh architecture

Point-to-multipoint architecture

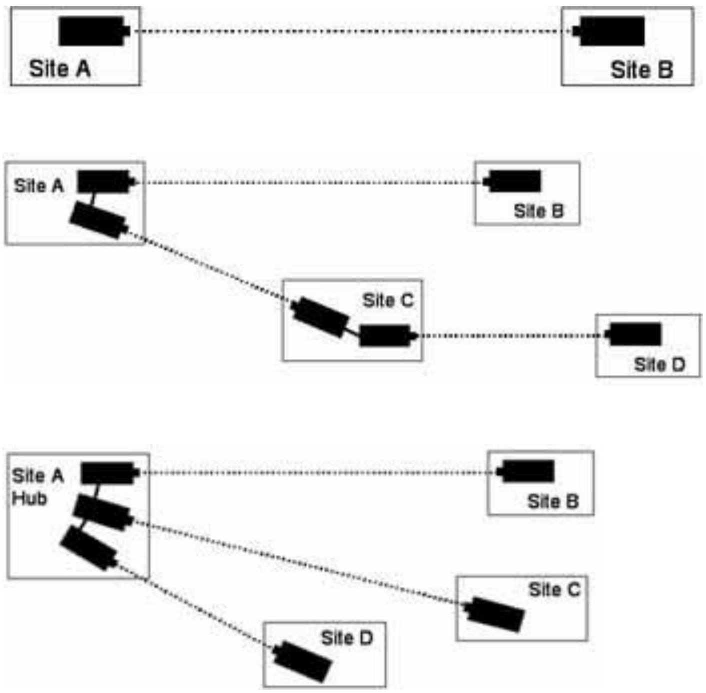

Figure 2. 1 The Main FSO Architecture(Majumdar, 2014)

2.6 FSO Communication Scenarios

2.6.1 Horizontal link

Some FSO nodes may be built on tall poles, from tall building rooftop to rooftop, or from window to window or roof top to roof top. FSO connectivity can be seen in base transceiver stations, backhaul, and cell sites. In a metro area, this horizontal network that links office buildings typically spans a few km. When calculating the fluctuating intensity of the received signal, it is typical to assume that the turbulence strength is uniform for the horizontal link. The laser line of sight may be momentarily or permanently obstructed by birds, insects, trees, branches, and other physical objects. Additionally, over time, earth motion, building movement, and differential heating and cooling may contribute.

2.6.2 Slant Path FSO link

A slant path can happen when the FSO path isn't nearly horizontal and the turbulence strength isn't consistent along the propagation path.

2.6.3 Uplink

Uplink scenarios frequently involve ground-to-space propagation paths, such as those from a ground station to a satellite. The altitude profile of the turbulence strength characteristics must be taken into consideration in order to calculate the variations in the signal intensity received at the receiver.

2.6.4 Downlink

A satellite-to-ground link is an illustration of a downlink FSO communication from space to ground. When calculating the received FSO signal intensity fluctuations, the altitude variation of the turbulence strength must be taken into account (Majumdar, 2014).

2.7 Application of FSO

Line-of-sight Communications: FSO technology can be used to establish high-speed, point-to-point communication links between two stationary or mobile locations that have direct line-of-sight. It is an ideal solution for short haul communication links, such as building-to-building or campus network.

Disaster Recovery: FSO technology can be used in situations where there is a disruption to traditional communication infrastructures such as fiber-optic cables or satellite communication system. FSO can be used as a backup communication system and can provide fast and reliable communication links.

Urban Communications: FSO technology is an ideal solution for cities where traditional communication infrastructures are congested or not available. FSO can help in providing high-speed communication links between buildings or businesses.

Healthcare: FSO technology can be used in medical settings for transmitting data, such as patient records or medical images, between facilities. It is a fast and efficient method of transferring sensitive information between hospitals or healthcare centers

Outdoor Wireless Access: Unlike with microwave bands, it is possible for wireless service providers to use the FSO for communication without a licence (Alheadary et al., 2018).

Fiber Backup: If a transmission across a fibre link fails, FSO can also be used to provide a backup link (Garg et al., 2021).

Metro-Network Extensions: It can be used to extend the fibre rings of an existing metropolitan region. The FSO system is easier to set up and can easily be connected to new networks and core equipment. Additionally, it helps in completing SONET rings (Garg et al., 2021).

Backhaul: It can be useful for transferring cellular phone traffic with high speed and high data rate from antenna towers back to the PSTN. There would be an increase in gearbox speed (Garg et al., 2021).

Service Acceleration: Additionally, it can be utilized to offer customer's immediate service while their fiber infrastructure is being installed (Garg et al., 2021).

Military Access: Due to its secure and undetectable nature, FSO can be used for military applications to safely connect large areas with minimal planning and deployment time(Alheadary et al., 2018).

2.7.1 Limitation of FSO

The benefits of using Free Space Optics are apparent, but since FSO relies on air as the transmission medium and the light passes through it, some environmental challenges cannot be avoided. The troposphere regions are where most atmospheric phenomena occur(Fadhil et al., 2013).

Some of these limitations are briefly described below:

Physical obstructions: When a single beam appears in the line of sight (LOS) of an FSO system transmission, flying birds, trees, and tall buildings have the potential to temporarily obstruct it (Alheadary et al., 2018).

Scintillation: Variations in temperature caused by heat from the Earth and man-made sources such as heating ducts can result in different air packets having different temperatures. These temperature variations can cause fluctuations in the amplitude of the signal, resulting in "image dancing" at the receiving end of the FSO system. Light Pointe's multi-beam technology is designed to address the effects of scintillation (Gupta & Goel, 2023).

Geometric losses: Optical beam attenuation, also known as geometric losses, occurs when the beam spreads, resulting in reduced signal power as it travels from the transmitter to the receiver (Vigneshwaran et al., 2013).

Absorption: The molecules of water that are suspended in the earth's atmosphere are what cause absorption. Particles in the air can absorb the energy of photons, which can directly affect the transmission availability and optical beam power density in an FSO system. Carbon dioxide can also contribute to signal absorption (Vigneshwaran et al., 2013).

Atmospheric turbulence: The weather and environment's physical makeup cause the atmospheric disturbance. The air parcels at various temperatures were combined by wind and convection, which is what generated it. This results in variations in air density and changes in the refractive index of the atmosphere.

Scattering: When an optical beam strikes airborne particles like dust, smoke, or water droplets, scattering takes place. This may cause the light to disperse in many directions, reducing the strength of the beam at longer distances.

There are three types of atmospheric attenuations **(**Zabidi et al., 2011):

The three types of atmospheric attenuation are molecule scattering, also known as Rayleigh scattering, aerosol scattering, also known as Mie scattering, and geometric scattering, also known as non-selective scattering.

The physical size of the scattered object determines the type of scattering (Alheadary et al., 2018):

Rayleigh scattering occurs when the size of the scattered object is smaller than the wave-length, while Mie scattering occurs when the size of the scattered object is comparable to the wavelength. Non-selective scattering occurs when the size of the scattered object is much larger than the wavelength.

2.8 Characterization of Attenuation Caused by Weather Phenomenon

2.8.1 Fog

Given that their size is comparable to the wavelength of concern in FSO communication (0.5-2 m), fog particles are regarded as important photon scatters. The signal is significantly attenuated for a long period of time, which makes it difficult to achieve high availability in FSO transmissions. Applying the Mie scattering theory will allow for an accurate prediction of the optical attenuation in the case of fog droplets(H. Singh & Chechi, 2019a).

Based on information about the visibility range, one method predicts the attenuation of the fog using widely used empirical models. The visibility range is the distance a parallel light beam must travel through the atmosphere before losing 2% of its initial intensity. Typically, 550 nm serves as the reference wavelength for the visibility range. Equation (1) defines the attenuation coefficient for Mie scattering that is typically provided by empirical models(H. Singh & Chechi, 2019a).

$$\beta_{fog} = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-p} \tag{2.1}$$

where V (km) stands for visibility range, λ (nm) is the operating wavelength, and p is the size distribution coefficient of scattering.

According to Kim model (H. Singh & Chechi, 2019a) p is given as

$$p = \begin{cases} 1.6, V > 50 \\ 1.3, 6 < \mathrm{V} < 50 \\ 0.16\,\mathrm{V} + 0.34, 1 < \mathrm{V} < 6 \\ \mathrm{V} - 0.5, 0.5 < \mathrm{V} < 1 \\ 0, V < 0.5 \end{cases} \tag{2.2}$$

According to Kruse model (H. Singh & Chechi, 2019a) p is given as

$$p = \begin{cases} 1.6, V > 50 \\ 1.3, 6 < V < 50 \\ 0.58V, V < 6 \end{cases} \tag{2.3}$$

2.8.2 Effect of Snow

Depending on the amount and velocity of precipitation, snow attenuation might change. Snowflakes produce deeper fades in the signal compared to raindrops since they are larger than raindrops in size. Depending on the optical signals beam width, snowflakes as large as 20 mm can totally obstruct the signal's path. Dry and wet snow attenuation are two categories of FSO attenuation for snow. Wet snow has a higher snow rate of impact than dry snow, which has a lower snow rate of impact. A key element that is utilized to calculate attenuation at a specific distance is specific attenuation, which is expressed in dB/km. Given by is the precise attenuation for snow rate S in mm/h (H. Singh & Chechi, 2019a)

$$\beta_{Snow} = aS^{b} \tag{2.4}$$

For an Operating wavelength λ, values of parameters a and b in dry and wet snow are

$a = 5.42*10^{-5} + 5.4958776, b = 1.38 and a = 1.023*10^{-5} + 3.785566$, b=0.72 respectively.

The snow attenuation based on visibility range can be approximated by the empirical model (Los, n.d.) Given as $\alpha_{"snow} = \frac{58}{V}$ (2.5)

2.8.3 Effect of Rain

Rain and fog droplets randomly degrade the optical signal. Even though fog is the primary cause of attenuation, large raindrops can still scatter light at different wavelengths. Rainfall attenuation rises linearly as a function of rainfall rate. In (Hameed et al., 2017) specific attenuation against rain rate of R (mm/h) for a FSO link is given as

$$\beta_{rain} = 1.067R^{0.67} \tag{2.6}$$

The rain attenuation for FSO link can be reasonably well approximated by empirical formula (H. Singh & Chechi, 2019a)given as

$$\alpha_{rain} = \frac{2.8}{V} \tag{2.7}$$

where V is the visibility range in km and its values based on rainfall rates (Shahiduzzaman et al., 2019).

2.8.4 Visibility Calculation for Cloud

We can assess the cloud attenuation using the visibility condition, which is provided

$$V = a\left(LWC\right)^{b} \tag{2.8}$$

and $0.63 \leq b \leq 0.96$. Table 2.1 shows LWC which is taken from modified gamma distribution (H. Singh & Chechi, 2019a). Once the visibility range is estimated, the cloud attenuation can be predicted using the visibility range-dependent Kruse (H. Singh & Chechi, 2019a) empirical model given by Eq. (2.8). Even though there are more varieties of clouds in the atmosphere, just three (Stratus, Cumulus, and Stratocumulus) have been taken into account since they are found at a lower altitude, below 1 km, whereas the height of the buildings is only measured in meters.

Table 2. 1 Visibility range values for different Cloud types

Cloud type	$LWC\left(g/m^{-3}\right)$	**Visibility Range(m)**
Cumulus	1.0	67-178
stratus	0.29	29.8-54.2
stratocumulus	0.15	19.7-28.8

The LWC in Table2.1 is derived from a modified gamma distribution (Rammprasath & Prince, 2013).

2.9 Related Works

An article(M. H. Ali et al., 2022);discusses the analysis of the fog attenuation penalty in terrestrial optical wireless communication using a modified duo-binary return-to-zero system with various receiver pointing errors. The Authors conclude from the results that the main problem is the pointing error caused on by beams travel, which significantly reduces SNR, link margin, and raises BER as turbulence severity and track length increase.

According to a study by (H. Singh & Chechi, 2019a), a Free Space Optical communication system's performance in various air conditions is affected by the number of transmitters and receivers.To enhance the performance of the FSO communication system, the study examines the Q-factor, bit error rate (BER), and eye diagram for a single transmitter/receiver FSO model under clear, hazy, and fog weather conditions.
The article by(Alatawi et al., 2022), Employing daily meteorological data, it investigated how air turbulence affected FSO communication for a smart city in Saudi Arabia. It was simulated how the FSO link will perform in terms of SNR, BER, and link availability. The findings indicate that the air turbulence is mild during the winter and substantial throughout the summer. Furthermore, the high summer temperatures and the comparably high winter wind speeds are the two primary meteorological elements affecting the FSO performance.
The analysis and presentation of(Al-Gailani et al., 2021);research on FSO technologies for the next-generation network looked closely at the most recent developments in single beam and multiple beam FSO systems. The challenges the optical beam had while traveling through the atmospheric link were then described, along with how heavy rain and haze affected the FSO link's degeneration. To further enhance the scalability of any communication networks, multi beam and DWDM technologies were combined
In the study "Performance Analysis of FSO Link under Different Atmosphere Conditions" by(H. Singh et al., 2021);the authors used the OptiSystem program to simulate the effects of various weather conditions, such as fog, rain, and snow, on the performance of the FSO system. The study demonstrated that bad weather had a negative impact on the FSO link's functioning.
Rainfall amounts have a significant effect on the performance of the FSOC link, with the attenuation coefficient varying depending on the location, claims a study by(H. Singh & Mittal, 2021), the city's inland location has the lowest attenuation coefficient due to rain and can maintain links up to 5.43 km distance with bit error rates of the order of 10^{-9} in typical wet conditions. On the other side, Mumbai's coastal region has the highest attenuation coefficient due to average rainfall, which limits the maximum link range to 3.48 km and produces bit errors of the order of 10-9. Overall, the study underscores how important it is to consider how rainy weather affects the functionality of FSOC.
According to a study by (Chauhan et al., 2020); different modulation forms and spatial diversity strategies might improve the performance of FSO links even under difficult conditions.

2.9.1 Literature Reviews summary

Table 2. 2 Contribution and gap of different related works.

Performance Evaluation of FSOC Link: Effects of Rain, Snow and Fog (Singh & Chechi, 2019)	The study examines the turbulent nature of free space optical links using the G-G Turbulence Model for weak, moderate, and strong atmospheric turbulence.	Pointing errors, both trans-ceiver side effects, and real data of environmental con-dition is not considered. Only global parameters theoretically used in the study.
Effects of Atmospheric Turbulence on Optical Wireless Communication in NEOM Smart City((Alatawi et al., 2022)	The study explores the im-pact of atmospheric turbu-lence on FSO communica-tion in NEOM city using meteorological data and identifies the key environ-mental factors affecting FSO performance.	The study does not provide specific recommendations for mitigating turbulence effects on FSO in NEOM or consider cost-effective-ness and comparison with other communication tech-nologies.
Comparative Performance Analysis of Free Space Op-tics as a Backup Link for Fiber Connectivity around the area of Bole Medhani-alem using Optisys-tem15((Engineering & Ambaye, 2021)	The study aims to compare FSO and FO links by ana-lyzing BER parameters and reading the optical meter.	The study does not con-sider the feasibility of de-veloping FSO technology in Ethiopia from an atmos-pheric perspective, and does not model atmos-pheric turbulent effects and channel coefficients. Additionally, the study does not consider the aper-ture diameters of the trans-ceivers.

Investigations of FSOC Under Real - World Atmospheric Conditions(Siegel & Ping, 2020)	It investigates the performance FSOC under various conditions, such as atmospheric channel, distance-dependent beam divergence, weather conditions, turbulence, and scattering.	Does not consider the impact of pointing errors or real environmental data on the performance of FSOC.

CHAPTER THREE

MATERIAL AND METHODS

3.1 INTRODUCTION

This chapter mainly focuses on materials and methods used to accomplish the research work, FSO modulation techniques, FSO Channel Model with different factors, Mathematical model of the parameters used and simulation parameters.

3.2 Materials

OptiSystem 20 and Mat lab R2018 software were used in this research. Utilizing a uniform random number generator engine, Mat lab R2018 software is used to generate random binary bits, simulate, offer numerical computing, and do the necessary analysis. Opti system is a software platform that enables users to simulate, test, plan, and analyze the performance of FSO systems.

3.3 Methodology

The study involved reviewing the literature, identifying research gaps, collecting rainfall data from Ethiopian Meteorology Agencies, analyzing the data, understanding the concept of rain attenuation in different seasons in two urban areas of Ethiopia, designing a system model, simulating the system model using OptiSystem 20 and MATLAB R2018, and analyzing the results to suggest the best solution for a specific and specified case.

3.4 SYSTEM DESIGN

Here is a high-level system design for modeling and performance analysis of free space optics (FSO) as a backup link for fiber connectivity in an urban area using OptiSystem.

3.4.1 Free Space Optical Link System Model

The block diagram of a FSOC system contains three primary subsystems: transmitter, Channel, and receiver. Transmitter its primary function is to modulate the incoming message signal onto the optical carrier which is then propagated through the atmosphere to the receiver. Essential components are the modulator, the optical source which is most likely a laser diode, and a transmitting telescope or optical antenna. The telescope is not only responsible for beam shaping but also the movable part for beam tracking Channel.

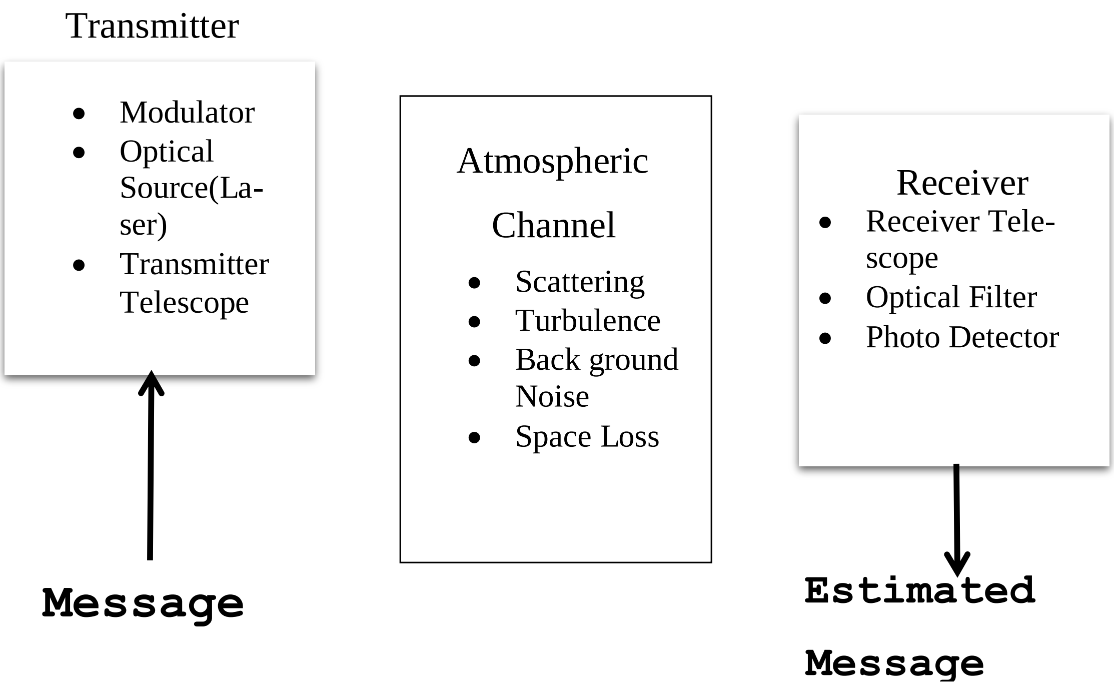

Figure 3. 1 Block diagram of free space optical communication systems

Since erratic weather like snow, fog, rain, or clouds can affect the strength of the received signal, the channel is a significant FSOC limiting factor. It is crucial to note that these variables change greatly over time and do not have fixed properties. The transmitted data is recovered using a receiver. The system comprises of a demodulator, an extremely sharp optical band pass filter to cut down on background noise, and a receiver telescope that is equivalent to the transmitter telescope.

3.5 Channel Model with Different Factors

3.5.1 Atmospheric Channel

The choice of optical wavelengths is influenced by a number of variables. Costs, eye safety, and transmission windows are crucial for terrestrial FSOC systems. Since wavelengths between 400 nm and 1400 nm are dangerous because they are concentrated directly within the human eye on the retina, 1.5 m and above wavelengths are always the preferable choice in terms of eye safety laws (Degnan, 2017).

3.5.2 Beam Divergence Loss

The most significant loss in FSOC is usually the beam divergence loss which describes the attenuation between two antennas. The divergence loss is dependent on propagating beam width and the diameter of the receiving telescope which can be noted as an equivalent to the antenna gain in radio transmission(Siegel & Ping, 2020). It also depends on the propagating wavelength because of the inclusion of the free space loss. The formula for the calculation of the received power is(Siegel & Ping, 2020):

$$P_R = P_T . G_T . G_R . \mathrm{L}_P \tag{3.1}$$

where L_P is the free space path loss, G_T and G_R the effective gain of receiver and transmitter, P_T the transmitted power and P_R the received power. The gain of both optical antennas and telescopes is approximated by:

$$G = \left(\frac{4\pi . \mathrm{A}}{\lambda^2} \right) \tag{3.2}$$

where λ is the wavelength of the transmitted signal and ***A*** the effective optical antenna area.

Depending on the efficiency and optical antenna characteristics, the total gain can vary (Siegel & Ping, 2020). With this equation in mind, it can be said that a narrow beam divergence is preferable with the condition that the antennas are perfectly aligned. Otherwise, active beam tracking and pointing systems are required to reduce the pointing loss that occurs when the center of the beam does not directly face the receiver. The free space loss factor is given by:

$$L_p = \left(\frac{\lambda}{4\pi R} \right)^2 \tag{3.3}$$

where R is the distance between both optical antennas

3.5.3 Influence of Weather Conditions

An FSOC link's quality can be significantly impacted by the effects of the line of sight on the weather. Snow, rain, and fog typically weaken the signal that is received. If the concentration of particles in the atmosphere rises above a certain point, a complete loss of connectivity may occur. Regarding the size of the particles, this effect is separated into three different ranges for a theoretical approach. Raindrops and snowflakes are significantly larger and cause deeper signal fades than fog, which is made up of microscopic particles that cause Mie-scattering(Degnan, 2017). The effect of fog can be calculated with the Mie-scattering theory which is very sophisticated and requires detailed fog parameters. Alternatively, an approach based on visibility range information can be used (Shah et al., 2016). It defines the attenuation coefficient of fog given by an empirical model for Mie-scattering. The specific attenuation in dB/km is derived by: $A(dB/km) = 10\log[\gamma(\lambda)]$

$$\gamma(\lambda) = \frac{3.91}{V}\left(\frac{\lambda}{550nm}\right)^{-p} \tag{3.4}$$

where V stands for the visibility range and λ is the operating wavelength, ρ is the size distribution coefficient that describes the "thickness" of the fog. 550 nm is the reference wavelength used in this approach. The Kruse model (Grabner & Kvicera, 2011) defines ρ for different visibility factors:

$$p = \begin{cases} 1.6, V > 50 \\ 1.3, 6 < V < 50 \\ 0.58V, V < 6 \end{cases} \tag{3.5}$$

Unaffected by the visibility range, the attenuation factor for fog is always dependent on propagating wavelength. A larger wavelength leads to lower attenuation (Grabner & Kvicera, 2011). Rain and snow attenuation are not affected by the propagating wavelength. The specific attenuation increases with the rainfall or snowfall rate.

3.5.4 Turbulence

The transmitted laser beam is directly impacted by the different refractive index values in the environment that come from inequalities in temperature and pressure.These elements cause cells to be turbulent.These cells, often referred to as eddies, are availiable in a range of diameters and refractive indexes.

According to (R. N. Ali et al., 2017) claim that an optical signal dispersed through a turbulent atmosphere causes a wave front to exhibit phase and amplitude distortion.A complete breakdown of connectivity may result from this.When the cells are bigger than the beam size, a phenomena called beam wandering occurs.

3.5.5 Rain attenuation model

Rain attenuation prediction is normally referred as "specific attenuation" which means attenuation per unit length. In Terahertz wave system like FSO, rain attenuation is particularly severe and greatly dependent on various models of raindrop-size distribution(Shah et al., 2016). Marshal and Palmer have been proposed as the two most widely used raindrop size distributions (Ajayi, 1985). By fitting both their own data and the data of Laws and Parsons, Marshal and Palmer distribution proposed a well-known empirical expression. For a rain rate of R mm/hr., the wireless optical link's specific attenuation is given by:

$$\gamma\left(\frac{dB}{km}\right) = a.R^{b} \tag{3.6}$$

where a & b are power law parameters equal to 0.365, 0.63 respectively.

The power law parameters depend on frequency, rain drop size distribution and rain temperature. For the purpose of calculating the attenuation, it is adequate to assume that raindrops have spherical shape. This assumption makes a & b independent of polarization (Rashid & Semakuwa, 2014).

3.6 The Proposed Block Diagram of FSO-NRZ System Model

In our proposed design; FSO has subsystem Transmitter, Propagation channel and Receiver. The subsystems of the transmitter are the data source, NRZ driver, CW laser, and Mach-Zehnder modulator.

The first subsystem, which represents the information of the data that needs to be transmitted, is the pseudo-random binary sequence (PRBS) generator. A PRBS's output is a bit string made up of the numbers 1 (ON) and 0 (OFF), which stand for the binary pulses that make up a repeatable pattern.

A subsystem Mach-Zehnder modulator that has two input ports, one for electrical input and

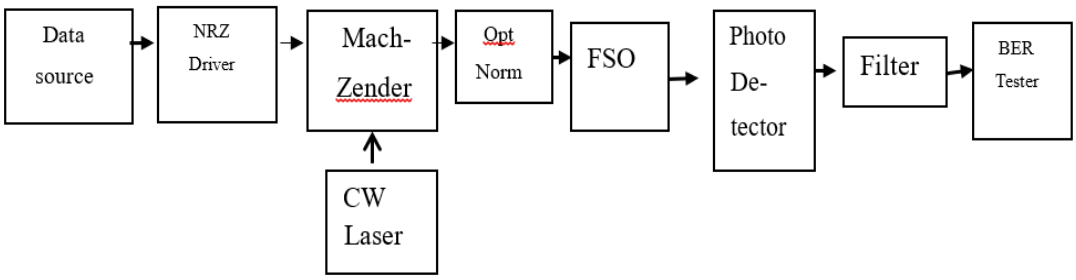

Figure 3. 2 System model of FSO using Mach Zehnder modulator

the other for optical input, receives the output of an NRZ driver. The optical input port of the Mach-Zehnder modulator is coupled to a CW laser. The CW laser's operational wavelength is 1550 nm. The 1550nm band is desirable because to its compatibility with the third window and eye safety. The PIN photo diode (PIN) and low pass filter (LPF) make part of the optical receiver. With a cutoff frequency of 0.75*bit rate of signal, a Bessel LPF is employed. To cancel out the undesirable high frequency signal, an LPF is utilized. As indicated in the block diagram, a receiver is used for regenerating an electrical signal that contains the original bit sequence, and a BER analyzer is used to evaluate the bit error pattern. The usage of measurement equipment like the BER Analyzer and Electrical Power Meter is also common. Pseudorandom bit generator that produces logical signals, such as 1010, etc., and sends them to the NRZ pulse generator.

The logical signal is converted into an electrical signal by the NRZ pulse generator, which then sends this signal to the Mach-Zender modulator. This modulator's main job is to change electrical signals into optical signals because the system uses free space optics. Now, using a medium known as the FSO channel, this modulator transmits the optical signal along with the carrier signal to the photodetector. The optical signal is received, further converted by the photo-detector into electrical form, and then it is sent to the LPF.

To separate the desired electrical signal from the unwanted noise signals, the signal has now been filtered. By employing a BER analyzer and an electrical power meter, we measure the errors and power in the output signal, respectively. To ensure the best performance under various circumstances, optical norms are used to establish the optical power levels in FSO systems. They specify the minimum necessary optical power levels needed for reliability communication as well as the maximum optical power levels that can be utilized safely without hurting the eyes or other equipment.

The optical norms can be used to set the input and output power levels of the transmitter and receiver, as well as to optimally perform the link under various conditions such as weather, distance, and atmospheric attenuation, in the modeling and performance analysis of FSO systems using OptiSystem. To achieve high data rates, reliability, and efficiency in FSO systems, the optical power levels must be optimized.

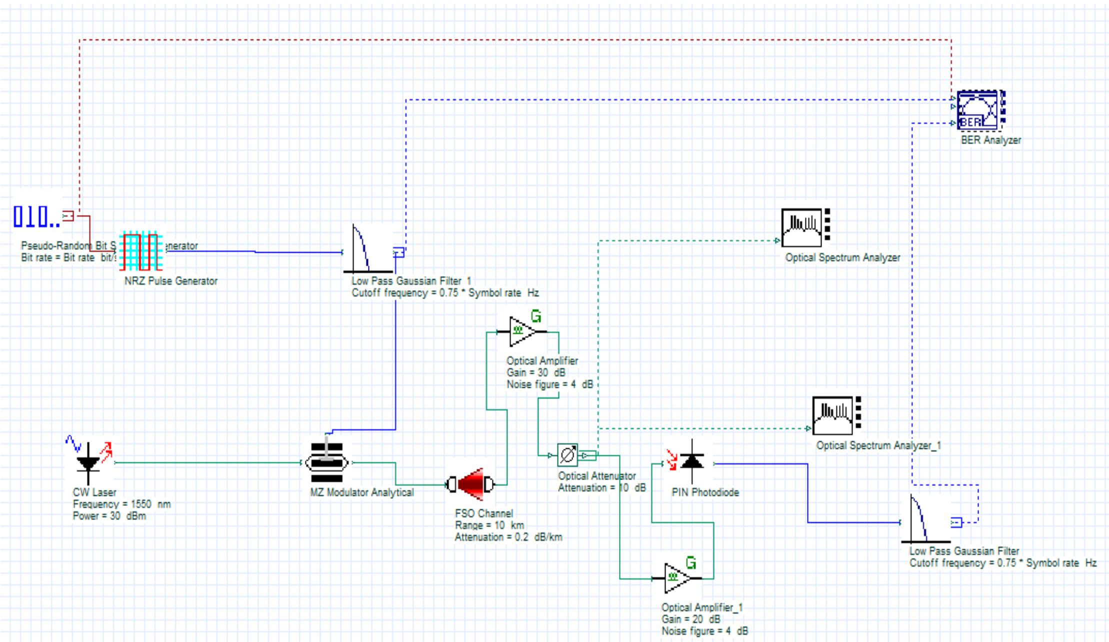

Figure 3. 3 Proposed Circuit diagram of FSO System under Turbulent channel

PRBS generator: Generates a pseudo-random bit sequence that is used as the data signal.

CW laser: Provides the optical carrier signal that is modulated with the data signal.

NRZ pulse generator: Converts the digital data signal from the PRBS generator into a series of electrical pulses that are used to drive the Mach-Zehnder modulator.

Mach-Zehnder modulator: Modulates the optical carrier signal with the electrical data signal to produce the modulated optical signal that is transmitted through the FSO channel.

FSO channel: Represents the transmission medium between the transmitter and receiver, consisting of a link range, attenuation factor, Tx and Rx aperture diameter, and beam divergence.

Photodetector: Converts the optical signal received from the FSO channel into an electrical signal.

Low-pass filter: Filters out high-frequency noise and other unwanted signals from the electrical signal from the photodetector.

Optical amplifier: Amplifies the optical signal to compensate for any signal attenuation that occurred during transmission through the FSO channel.

BER analyzer: Analyzes the received data signal to determine the bit error rate (BER), which is used to measure the quality of the data transmission.

3.6.1 System Model Considerations

The following system model considerations should be taken into account while simulating and analyzing the performance of free space optics (FSO) as a backup link for fiber connectivity in metropolitan settings using OptiSystem:

Link budget analysis: This is to determine out the FSO system's power budget while considering the transmitter power, receiver sensitivity, atmospheric attenuation, and other system losses.

Atmospheric effects: Scintillation, turbulence, and absorption caused by atmospheric gases are only a few of the atmospheric elements that have an impact on FSO systems. These variables need to be carefully examined and modeled using the proper models in Opti system since they have the potential to change the system's performance.

Alignment and tracking: The transmitter and receiver devices must be precisely tracked and aligned for FSO connectivity. The accuracy and stability of the alignment and tracking determine the system's performance, so this needs to be modeled and evaluated in Opti System.

3.6.2 Modulation Techniques

FSO systems can use various modulation techniques to improve the capacity and efficiency of data transmission.

1. On-off keying (OOK): In OOK modulation, the presence or absence of light is used to represent the modulated data. OOK is easy to implement but has low energy efficiency.
2. Pulse position modulation (PPM): PPM transfers the input bit onto a symbol with a set duration, making it a synchronous modulation. PPM has good bandwidth efficiency but not good energy efficiency.
3. Pulse width modulation (PWM): PWM is similar to PPM but uses the pulse width to represent the modulated data. PWM is also a synchronous modulation.
4. Differential phase shift keying (DPSK): DPSK modulates the phase difference between consecutive symbols instead of the absolute phase of each symbol. DPSK can increase spectral efficiency and reduce the impact of scintillation.
5. Quadrature amplitude modulation (QAM): QAM is a more advanced modulation technique that modulates the amplitude and phase of the carrier signal to transmit multiple bits per symbol. QAM is excellent for high data rates and is also fading-resistant.

For greater capacity, several modulations of phase, frequency, and amplitude, such as Phase Shift Keying (PSK), Frequency Shift Keying (FSK), Amplitude Shift Keying (ASK), Quadrature Shift Keying (QPSK), and DPSK, can be utilized. According to (Sree Madhuri et al., 2019);DPSK increases spectral efficiency and reduces the scintillation impact. The most recent FSO proposal is QAM. It is excellent at producing high data rates and is also fading-resistant.

3.6.3 Photo detectors

In free-space optics (FSO) devices, photo detectors are crucial. These devices are used to capture optical signals that are sent across free space and transform them into electrical signals that may be amplified and processed for transmission or analysis. Photo detectors are used to measure light intensity and transform optical energy into electrical energy.

Both P-i-N (PIN) and Avalanche Photo Diode (APD) diodes are utilized as photo detectors. PIN and APD are used for low- and high-range communications, respectively. PIN is less expensive, but its receiver performance is limited. In contrast, APD has a significant current gain because of the impact ionization phenomena. The APD has the drawback of producing too much noise in the output. PIN photo detectors are used in the study in accordance with the specifications of our design (Attri et al., 2016).

3.6.4 Transmission Windows

The wavelengths utilized in optical transmissions are in the near-infrared portion of the spectrum, just above the visible, and are therefore not visible to the unaided eye. The common wavelengths for optical transmission are 850 nm, 1310 nm, and 1550 nm. Both lasers and LEDs can be utilized to transport light via free space optics. Standard wavelengths for lasers are either 1310 nm or 1550 nm, whilst 850 nm or 1310 nm are used for LEDs (Kasprzak et al., 2010).

The two often used windows are 1550 nm and 850 nm. The operation in this window can use inexpensive transmitter and reception components since the PIN photo detector at 850 nm is so dependable. The 1550 nm window is good because of its low attenuation. Through the employment of high-speed laser technology and amplifiers, transmission power is boosted in this window. The FSO functions best in certain wavelength bands. Every range is referred to as an operational window

3.6.5 Aperture Size

Aperture size is an important factor in modeling and performance analysis of free space optics (FSO) as a backup link for fiber connectivity in metropolitan areas using Opti System. The diameter of the transmitter and receiving lenses used in FSO systems is referred to as the aperture size. The aperture size determines how much light is captured by the receiver; a bigger aperture size implies more light will be captured, improving signal-to-noise ratio, increasing data transmission rates, and extending transmission range. Larger aperture sizes are, however, also more susceptible to atmospheric turbulence, which could widen the beam and degrade the quality of the signal.

The simulation can be used to examine how different aperture sizes affect various aspects of system performance, including the bit-error-rate (BER) and the probability of a link outage. The optical power grows together with the aperture size, which reduces fading. Calculating the geometric losses brought on by the divergence of the beam is made easier by the receiver lens's aperture size. (Attri et al., 2016).

3.6.6 Laser

There are several advantages of semiconductor lasers for free space optics (FSO) compared to LEDs (Light emitting diodes), better optical spectrum, high optical output, advantages for beam shaping, and so on. There are several atmospheric transmission windows and high-quality semiconductor lasers with a suitable wavelength for these windows are available.

In many FSO systems Laser is preferable due to its high coherence, directivity of the transmitter section in FSO, the electrical signal will be converted in to optical signal, and it will be transmitted over free space and finally reaches to the receiver with lots of atmospheric obstacles. At the receiver side, the optical signal is converted into electrical signal which is done by the photo detector. The received signal is very weak signal.so that it will be amplified for the next procedure At the transmitter and receiver side modulation and demodulation is found in the form of electrical signal (Hameed et al., 2017).

3.6.7 Eye Safety

Laser sources are harmful to the human body after a certain power threshold, especially to the eyes. A laser-emission power restriction must be put in place in optical wireless networks as a result. IEC 60825-1 states that the classification of lasers and laser products based on their level of hazard is intended to safeguard the human body from excessive laser radiation with wavelengths ranging from 180 nm to 1 mm. There are laser safety regulations like ANSI Z136.1 and IEC 60825-1. Class 1 and Class 2 optical beams (400-700 nm) are believed to be completely safe, with the exception of circumstances requiring direct and extended exposure. Despite having a good power budget, class 3 beams shouldn't come in contact with people's bodies(Attri et al., 2016).

Table 3. 1 Simulation Parameters values

Parameters	**Values**
Modulator Type	Mach-Zehnder Modulator
Extinction ratio	20 dB
Transmitter aperture diameter	5 cm
Receiver aperture diameter	20 cm
Ionization ratio	10^-9
Dark current	$\leq$ 2 nA
Transmitted Power	30dBm
Divergence	2 mrad
Noise Figure	4 dB

Bit Rate	2.5 Gbps
Attenuation	5dB/km
Pulse Generator	NRZ
Link Range	$1 \leq 5km, 5km \leq 10km,$ 5km to 20km and above 20km

3.6.8 SNR in FSO System under Turbulent condition

The signal-to-noise ratio (SNR) in a free-space optical (FSO) communication system under turbulent atmosphere can be calculated using the following formula(Hufnagel, 1978):

$$SNR = \left(P_t * A\eta_c / P_{rn} + P_{atm.}\right) \tag{3.7}$$

where P_t is the peak power of the transmitted signal,

- A is the effective area of the receiving aperture

η_c is the coupling efficiency of the receiver

- P_{rn} is the receiver noise power
- $P_{atm.}$ is the atmospheric noise power

*The atmospheric noise power $P_{atm.}$ is caused by the scintillation effect of the atmospheric turbulence and can be modeled as(Hufnagel, 1978):

$$P_{atm.} = cn^2 . k^{7/6} . L^{11/6} \sigma i^2 \tag{3.8}$$

where cn^2 is the refractive index structure constant that characterizes the strength of the atmospheric turbulence

- K is the wave number of the optical carrier frequency
- L is the propagation distance
- σi^2 is the scintillation index, which is a measure of the variation of the received signal due to atmospheric turbulence.

3.7 FSO System simulation process.

3.7.1 Generating random binary bits

The random binary bits, also known as the pseudo-random binary sequence (PRBS), are used to represent any random input data for the FSO system. These bits are generated by a uniform random number generator engine.

3.7.2 Bit to electrical signal conversion

Each bit in the resulting PRBS is represented by a NoS (Number of sample) after being resampled.

Rect-pulse is a MATLAB function.

The number of samples (NoS) produced during a stationary time window in a Free Space Optics (FSO) system depends on the available memory and the duration of the stationary period. A larger number of samples can be produced for higher data rates or slower-moving trains.

3.7.3 Electrical to optical signal conversion

When implementing OOK modulation, the high and low powers corresponding to bits 1 and 0 are determined using the following formulae; given the average output optical power P_{avg} and extinction ratio ε;

$$P_1 = \frac{2P_{avg}}{1+\frac{1}{\varepsilon}} \tag{3.9}$$

$$P_0 = \frac{2P_{avg}}{1+\varepsilon} \tag{3.10}$$

$$\Delta P = P_1 - P_0 \tag{3.11}$$

Where the P_{avg}, Average signal Power, P_1 and P_0 cross ponding to high & low Power; ε is extension ratio(Yang et al., 2014)&(Abadi, 2018).

The optical signal at the transmitter side is formed by multiplying the electrical signal $Selec$ from step 2 by ΔP and adding the necessary optical power offset to account for the optical power average value. $\Delta P \times S_{elec} + P_{avg}$ (Abadi, 2018).

The extinction ratio is the ratio of the optical power level for the high state to the optical power level for the low state in OOK modulation. It is a measure of the signal contrast and is typically expressed in decibels (dB).

3.7.4 Applying the channel effects

After determining the channel coefficients h , the optical power produced in step 3 is multiplied by the coefficients. The result is what is known as the optical received power at the receiver side. The coefficient h may be applied to the average optical power $Pavg$ portion or the variable optical signal $Psig$ depending on the simulation's goal.

If calculating BER is the target of the simulation, the received signal is $h \times \Delta P \times S_{elec}$. However, if simulating a real system is desired the received signal would be $h \times \left(\Delta P \times S_{elec} + P_{avg} \right)$

3.7.5 Optical to electrical signal conversion

In FSO system, the received optical power at the receiver side is converted back into an electrical signal using an optical-to-electrical converter. The converter typically consists of a photodiode and a Trans-Impedance Amplifier (TIA). The photodiode converts the received optical power into a current, which is proportional to the optical power. The TIA then converts the current into a voltage signal, which can be further amplified and processed to retrieve the original data.

3.7.6 Adding white Gaussian noise

If the *SNR* is known, the needed noise power Pn is determined by measuring the transmit signal's power in step 3. Random numbers are generated based on the random normal distribution $N\left(0, \sqrt{P_n}\right)$ to produce the additive noise. MATLAB function: randn.

3.7.7 Bit extraction

Based on the average value of the electrical signal received, a threshold level is established. Each received bit's midway is compared to the threshold to determine whether it is a 0 or 1. The duration of the averaging is reduced from the entire received signal to smaller segments in order to perform adaptive thresholding.

3.7.8 Analysis

The analysis is done by comparing the original transmit and received bits, which yields the BER value. MATLAB function: bit error.

The Q-factor is another metric that has been taken from the signal that has been received. With bits 0 and 1's electrical signal levels, we can determine the Q-factor as:

$$Q-factor=\frac{|V_1-V_0|}{\sigma_0+\sigma_1} \tag{3.12}$$

where V_1 and V_0 are the mean values of received electrical signal corresponding to bits 1 and 0, respectively. While σ_0 and σ_1 are the standard deviation values of received electrical signal corresponding to bits 1 and 0, respectively.

Based on the signal power ΔP and pre-existing noise power, the electrical SNR value is also determined. The power ΔP of the optical signal is from Section 3, and at the receiver it produces a voltage Vsig that is specified as

$$V_{sig}=G\times\eta\times\Delta P \tag{3.13}$$

where G, and η are trans impedance (TIA) gain, and responsivity, respectively(Abadi, 2018). Knowing the load impedance RLoad the electrical signal power will be

$$P_{sig}=\frac{(G\times\eta\times\Delta P)^2}{R_{Load}} \tag{3.14}$$

If noise equivalent power (NEP) of the receiver is given and the signal bandwidth BW is known, the detector noise power is obtained as

$$P_{\det}=NEP\sqrt{BW} \tag{3.15}$$

To take into account the background light and shot noise we have

$$i^2{}_n=2\times q\times I\times BW \tag{3.16}$$

where q is the electron charge and I is the induced current due to the noise. For background noise $I_{bg}=\eta P_{bg}$, where P_{bg} is the background illumination power. In case of shot noise, if the received average optical power is P_r then $I_{sn}=\eta P_r$. Finally, the noise power at the output of TIA will be

$$P_n=\frac{2q\eta G^2 BW}{R_{load}}\left(P_{bg}+P_r\right) \tag{3.17}$$

And the total noise power will be:

$$P_{noise}=NEP\sqrt{BW}+\frac{2q\eta G^2 BW}{R_{Load}}\left(P_{bg}+P_r\right) \tag{3.18}$$

3.7.9 Generating random number for channel fading

Various random number types are created depending on the fading kind. Turbulence and pointing errors are occurs randomly in our simulation. The random numbers can be generated using statistical distributions, such as the gamma-gamma distribution for scintillation and the Gaussian distribution for pointing error.

A) Turbulence, Log-Normal model:

$$X = \mathrm{N}\left(\mu_{x,turb}, \sigma_{x,turb}\right) \tag{3.19}$$

$$h_t - LN = \exp\left(2X\right) \tag{3.20}$$

where *X* is generated random numbers and h_t is turbulence channel coefficients(Abadi, 2018)

Mat lab Function: randn.

B) Turbulence, Gamma-Gamma model:

$$\begin{aligned} X &= \Gamma\left(\alpha,1\right) \\ Y &= \Gamma\left(\beta,1\right) \\ h_{t-GG} &= \frac{1}{\alpha\beta} XY \end{aligned} \tag{3.21}$$

where h_{t-GG} is channel coefficient for Gamma-Gamma model(Abadi, 2018).

MATLAB function: gamma

Pointing error, Log-Normal-Rician model:

$$\begin{aligned} X &= N\left(\mu_x, \mathrm{PE}, \sigma_j, \mathrm{PE}\right) \\ Y &= N\left(\mu_y, PE, \sigma_j, PE\right) \end{aligned} \tag{3.22}$$

$$r = \sqrt{\left(X^2 + +y^2\right)} \tag{3.23}$$

$$h_{PE} = A_0 \exp\left(-\frac{2r^2}{{w_{eq}}^2}\right) \tag{3.24}$$

Where h_{PE} is channel coefficient for Log Normal Rician model (Chatzidiamantis et al., n.d.) & ${w_{eq}}^2$ equivalent noise variance.

3.7.10 Generating channel coefficient for turbulence and pointing errors

The values are resampled once they have been generated in order to replicate the correct channel effect. After resampling the bits in step two, if the bit rate is *DR*, the sampling frequency is $F_S = DR \times NoS$. For turbulence and aiming error, the typical channel temporal coherence is 1–1 msec.

We pick F_{fading} = 500 Hz for our work. To fit the entire signal, fading effects are resampled using these values. There are two resampling methods that can be used: polyphaser anti-aliasing filter or staircase resampling.

MATLAB functions: *rectpulse*, and *resample*.

The simulation results are compared with the existing theory in order to validate each model.

BER in clear channel:

$$BER = Q\left(\frac{\eta I_0}{\sqrt{2N_0}}\right) \tag{3.25}$$

$Q(x) = \dfrac{1}{2\pi}\int_x^{\infty} \exp\left(-\dfrac{u^2}{2}\right)du$ is Q _ function(Chatzidiamantis et al., 2009).

BER in pointing errors channel:

$$BER = \exp\left(-\frac{s^2}{s\sigma_s^2}\right) \times k \sum_{i=1}^{k} w_i Q\left[\frac{\eta I_0 A_0}{\sqrt{2N_0}} \exp\left(-\frac{4\sigma_s^2}{w^2{}_{eq}} x_i\right)\right] I_0\left(s\sqrt{\frac{2x_i}{\sigma_s^2}}\right) \tag{3.26}$$

It is based on Gauss-Laguerre quadrature formula (refer to Appendix A from Doc-F02-D2). *I*0(·) is zero-the order modified Bessel function of first kind. (Yang et al., 2014) is used for PDF.

BER in turbulence channel – Log-Normal model:

$$BER = \frac{1}{\pi} \sum_{i=1}^{k} w_i Q\left[\frac{\eta I_0}{\sqrt{2N_0}} \exp\left(-2\sigma_s^2 + x_i \sqrt{9x_x^2}\right)\right] \tag{3.27}$$

It is based on Gauss-Hermite quadrature formula (Chatzidiamantis et al., 2009).

BER in turbulence channel – Gamma-Gamma model:

$$BER = \frac{2^{\alpha+\beta-3}}{\sqrt{\pi^3}\Gamma(\alpha)\Gamma(\beta)} G_{5,2}^{2,4}\left[\left(\frac{2}{\alpha\beta}\right)^2 \times 2\frac{\eta I_0}{\sqrt{2N_0}}\left|\frac{1-\alpha}{2},\frac{2-\alpha}{2},\frac{1-\beta}{2},\frac{2-\beta}{2},1\right.\right] \tag{3.28}$$

where $G_{5,2}^{2,4}$ [·] is Meijer's G function (Chatzidiamantis et al., n.d.).

BER in pointing errors and turbulence channel -Log-Normal model:

$$BER = \frac{2^{\gamma^2-1\Gamma\left(\frac{\gamma^2}{2}+\frac{1}{2}\right)}\exp\left(\frac{s^2}{\sigma_s^2}+2\sigma_s^2\gamma^2+2\sigma_x^2\gamma^4\right)}{\sqrt{\pi(A_0)\gamma^2}} \times \left(\frac{\eta I_0}{\sqrt{2N_0}}\right)^{\frac{\gamma^2}{2}} \tag{3.29}$$

This BER formula is an asymptotic .approximation for large SNR values (Yang et al., 2014).

BER in pointing errors and turbulence channel Gamma-Gamma model:

$$BER = \frac{2^{\beta-1}\Gamma\left(\frac{\beta}{2}+\frac{1}{2}\right)\exp\left(-\frac{s^2}{2\sigma_s^2}+\frac{-s^{2\frac{\gamma^2}{\sigma_s^2}}}{2\beta-2\gamma^2}\left(\frac{\alpha\beta}{A_0}\right)^2\right)}{\Gamma(\alpha)\Gamma(\beta)\sin\left[(\alpha-\beta)\pi\right]\Gamma(\alpha-\beta)+1)\left|\gamma^2-\beta\right|\beta} \times \Gamma\left(\frac{\beta+1}{2}\right)\sqrt{\pi\gamma^2}\left(\frac{\eta I_0}{\sqrt{2N_0}}\right)^{-\frac{\beta}{2}} \tag{3.30}$$

This BER formula is an asymptotic .approximation for large SNR values (Yang et al., 2014). In case, the receiver has an aperture with diameter of ds then for Gamma-Gamma model the parameters will be:

$$K = \frac{2\pi}{\lambda}$$
$$d = \left(kd_s^2/4L\right)^{0.5} \tag{3.31}$$

$$\sigma_{\ln X}^2 = \frac{0.49\sigma_R^2}{\left(1+0.65d^2+1.11\sigma_R^{12/5}\right)^{7/5}} \tag{3.32}$$

$$\sigma_{\ln Y}^2 = \frac{0.51\sigma_R^2\left(1+0.69\sigma_R^{\frac{12}{5}}\right)^{-5/6}}{1+0.90d^2+0.62d^2\sigma_R^{12/5}} \tag{3.33}$$

For Log-Normal model, it is given as:

$$\frac{\sigma_I^2(d_s)}{\sigma_I^2(0)} \approx \left[1+1.062d^2\right]^{-7/6} \tag{3.34}$$

3.7.11a Fog/smoke loss

Based on the visibility ***Vis*** and by using Kim model***, q*** parameter is defined (Ijaz & Pesek, 2013):

$$q = \begin{cases} 1.6, \mathrm{Vis} > 50 \\ 1.3, 6 < \mathrm{Vis} < 50 \\ 1.6 \times Vis + 0.34, 1 < Vis < 6 \\ Vis - 0.5, 0.5 < Vis < 0.1 \\ 0, Vis < 0.1 \end{cases} \tag{3.35}$$

Having the laser wavelength $\lambda(nm)$, the parameter β_λ in $1/km$ is defined as:

$$\beta_\lambda = -\frac{\ln 0.02}{Vis}\left(\frac{\lambda}{550}\right)^{-q} \tag{3.36}$$

And finally by using Beer's lambert law, the fog/smoke loss will be:

$$h_{FS} = \exp(-\beta_\lambda L) \tag{3.37}$$

where L is the link distance in km.

3.7.11b Geometrical loss

Geometrical or propagation loss refers to the reduction in signal power that occurs as a result of the spreading of the optical beam over distance. In an optical communication system, the received signal power is affected by various factors such as attenuation, dispersion, and noise, as well as the geometrical loss. The geometrical loss can be estimated based on the distance between the source and receiver, as well as the size of the beam at the receiver aperture. For an elliptical beam, the geometrical loss can be estimated using the following formula:

$$L_{geo} = (\pi * a * b)/(\lambda * L) \tag{3.38}$$

where L_{geo} is the geometrical loss, **a** and **b** are the minor and major axes of the elliptical beam at the receiver aperture, λ is the wavelength of the signal, and L is the distance between the source and receiver(Abadi & Light, 2018).

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 SIMULATION RESULTS

This section discussed the results obtained from our proposed simulative setup consisting of random generated- NRZ data signals transmitted via FSO link under turbulent condition like rain; fog/smoke losses, Pointing errors, and Geometric losses. The results are investigated over Ambo & Dire Dawa city in Ethiopia during its heavy rain seasons, which are Winter & Autumn (fall) for Ambo city and in spring seasons for Dire Dawa city, 2018 to 2022, using Marshal and Palmer rain attenuation prediction model as shown in Table 4.1 It is observed that in Ambo, during heavy rain month of June, July and August, data can be transmitted with less BER over a maximum of 10km under the transmission power of 30dBm as shown in Fig.4.1.

4.2 Detection of BER analyzer for FSO link in Ambo City

Eye diagram of FSO channel in Rainy season (during winter- June, July and August) in Ambo city with Link length 10km (2020). Here during heavy rain around ambo city the Maximum Q factor is 11.3841 is achievable with Min BER of 1.9734e-30. And we have widest an open eye by using Op.amplifier, we can increase Q factor values. Op-amp amplifier increase the Q factor values and widen the open eye, the signal can be transmitted with a higher degree of accuracy and reliability, even in challenging conditions.

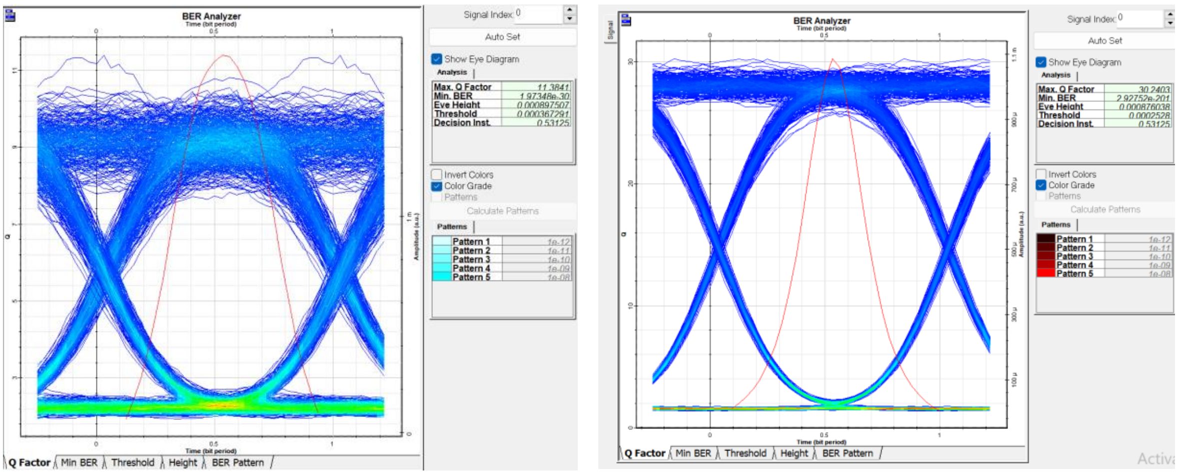

Figure 4.1 Eye diagram for 1.5 GB/s data rate with attenuation of 5dB/km during heavy rain seasons and link range with 10km

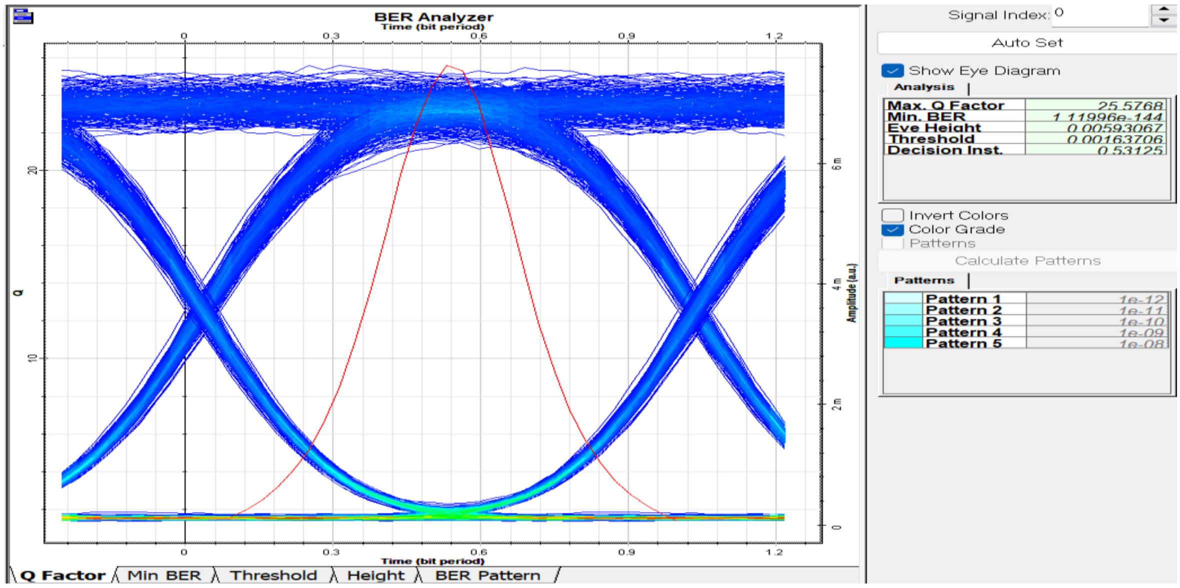

Figure 4. 2 Eye diagram for 2.5 GB/s data rate with attenuation of 0.289 dB/km or medium rain season and link range with 15km.

Fig.4.2: shows during medium rain of 15km link range with transmission Power of 30dBm the Max Q-factor increase from 11.3841 to 25.5768 which suggests that the system is able to maintain a high signal-to-noise ratio, which is critical for reliable communication over long distances and Min BER is reduced from 1.934e-30 to 1.11996e-144 indicates that the system is able to transmit data with a very high degree of accuracy under medium rain conditions as shown in figure 4.2.

In Fig.4.3, the eye diagram of Q-factor which depict that in Ambo, autumn the data can be transmitted with a transmission power of 30 dBm and with a Max- Q-factor (33.0451) over transmission distance of 20km. The Q-factor and BER are inversely proportional, meaning that a higher Q-factor corresponds to a lower BER. In this case, the maximum Q-factor of 33.0451 corresponds to a very low BER of 7.8383e-240, which indicates that the FSO link is performing well and can be utilized as a backup link during natural disasters or periods of signal congestion in Ambo city.

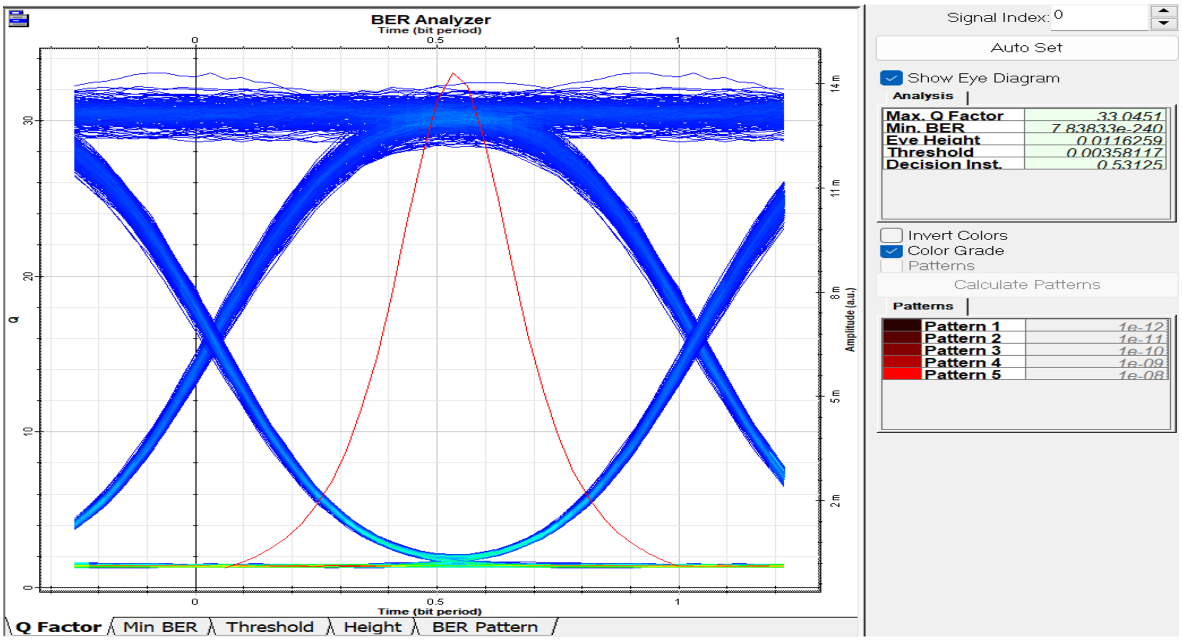

Figure 4.3 Eye diagram for 2.5 GB/s data rate at attenuation of 0.144 dB/km light rain season and link range of 20 km.

Figure 4.4: A Q factor of 32.2778 is a very high value, which indicates that the system is able to maintain a high signal-to-noise ratio, resulting in a high level of signal quality. The minimum BER of 6.10601e-229 is an extremely low value, which indicates that the system is able to transmit data with a very high degree of accuracy. Eye diagram of FSO channel in winter season (during June, July and August in Ambo city (2021) with Link length 20km with Attenuation 0.285dB/km from the collected data.

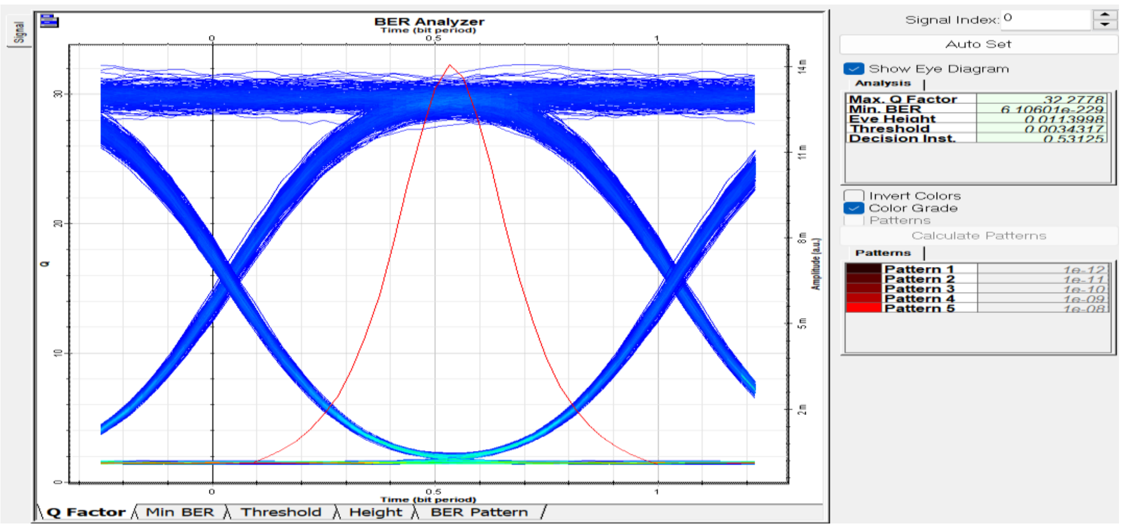

Figure 4. 4 Eye diagram of FSO channel in winter Season with link range of 20km at Attenuation 0.285dB/km

Table 4. 1 Rain Attenuation data from EMA for Ambo city.

Year	Winter(June to August)			Fall(Autumn) from March to May		
	Rainfall (mm)	Rain Rate (mm/hr.)	Rain Attenuation(dB)	Rainfall (mm)	Rain Rate (mm/hr.)	Rain Attenuation(dB)
2018	1678.5	0.777083	0.3113775	450.2	0.2085648	0.1359611
2019	1889.4	0.874722	0.3354833	373.2	0.1727778	0.1207564
2020	1865.9	0.8638425	0.33285	291.9	0.08264	0.07586763
2021	1494.5	0.691898	0.289413	299.6	0.12014	0.0960497
2022	1264.8	0.5855556	0.2596913	290.4	0.39097	0.20199621

From Table 4.1 Rain Attenuation is calculated from the collected data by Using Marshal and Palmer rain attenuation prediction model.

Table 4. 2 Eye diagram Result Summary in Tabular form

Link Range	Attenuation dB/km	Max. Q- factor	Min.BER	Eye height
5km	0.236	49.6379	0.00098e-280	0.053839
10km	0.285	32.2778	6.1060e-229	0.0113988
20km	0.198	33.0451	7.73283e-20	0.1016259

The table 4.2 shows that the maximum Q-factor achieved by the system is 49.6379, which indicates that the system is capable of transmitting data with high quality and low error rates. The corresponding minimum BER achieved by the system is 0.00098e-289, which is an extremely low value and indicates that the system is highly reliable.

4.2 Detection of the BER analyzer for the FSO link in Dire Dawa city

In Fig.4.5, The FSO system in Dire Dawa City is performing exceptionally well, achieving a maximum Q factor of 61.5049 and a minimum BER of 0. These results suggest that the system is able to maintain a very high level of signal quality and accuracy. A Q factor of 61.5049 is an extremely high value, indicating that the system is able to maintain a very high signal-to-noise ratio, resulting in a very high level of signal quality. The minimum BER of 0 indicates that the system is able to transmit data with perfect accuracy, without any errors or loss of data during transmission.

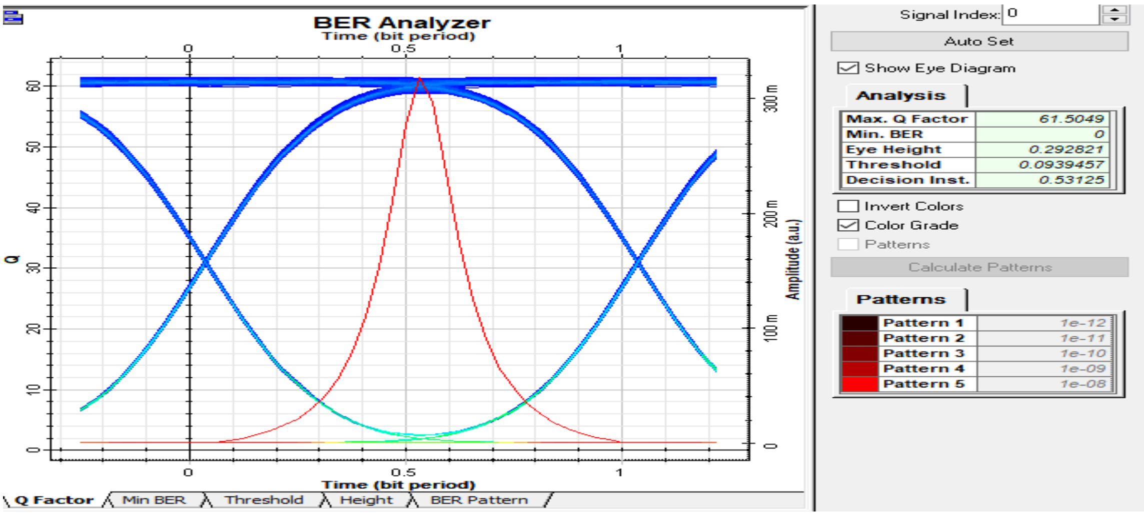

Figure 4. 5 Eye diagram of FSO system in moderate rain period in Dire Dawa city with Link Length 5km, at attenuation =0.285dB/km.

Fig. 4.6, shows the FSO system in Dire Dawa city is able to maintain a good level of signal quality during the autumn period, as indicated by the eye diagram in Fig. 4.6. The system is analyzed for a link length of 10 km, attenuation coefficient of 0.235 dB/km, and a visibility range of 20-40 km with a power law exponent of 1.3.

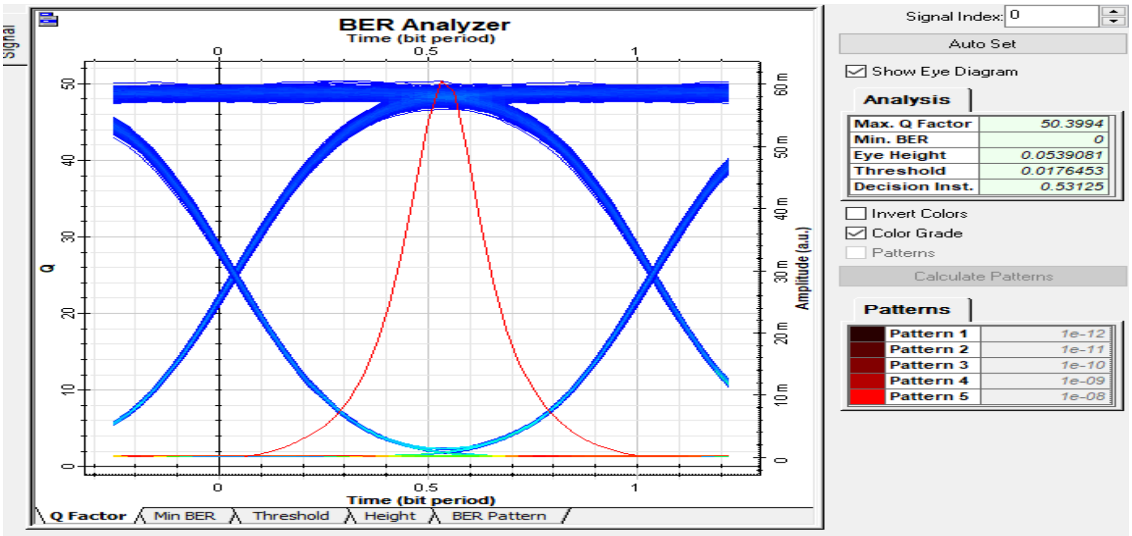

Figure 4. 6 Eye diagram of FSO system in autumn period in Dire Dawa city with Link Length 10km, at attenuation (0.235dB/km)

The maximum Q-factor has decreased from 61.5049 in Fig. 4.5 to 50.3994 in Fig. 4.6 as the link length increases. This decrease in the maximum Q-factor is expected, as the signal experiences more attenuation and degradation over longer distances. In figure 4.7 the maximum Q factor drop from 50.3994 to 28.1838 due to several variables, including attenuation, dispersion, noise, or distortion as transmission distance increases, and Min BER is some little increase from 0 to 3.80363e-175 indicate that the FSO system is experiencing a decrease in signal quality and an increase in errors as the transmission distance increases.

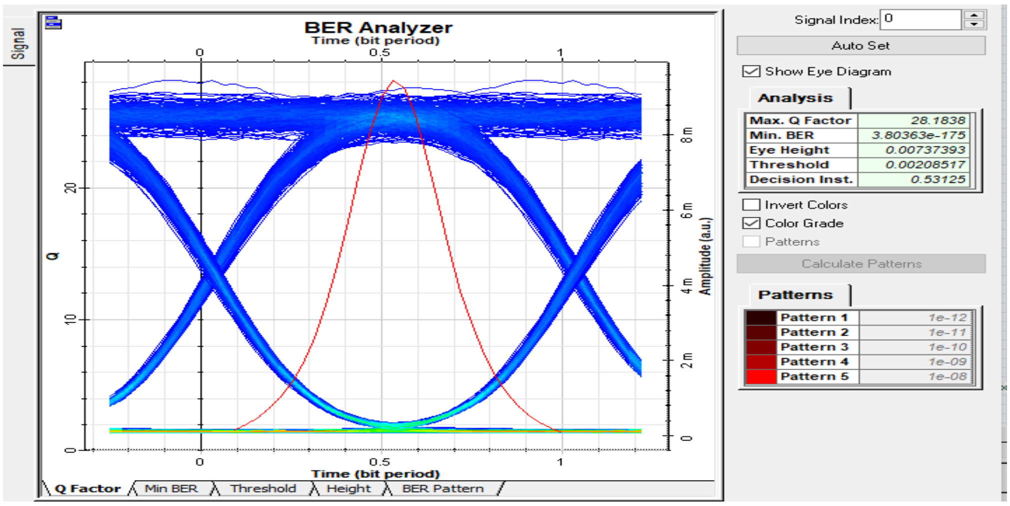

Figure 4. 7 Eye diagram of FSO system during winter period in Dire Dawa city with Link Length 20km, at attenuation (0.25dB/km)

Figure 4.8 a Q-factor of 0 indicates that the signal quality has degraded to the point where it cannot be recovered, while a bit error rate (BER) of 1 signifies that every bit of the sent signal is incorrect.

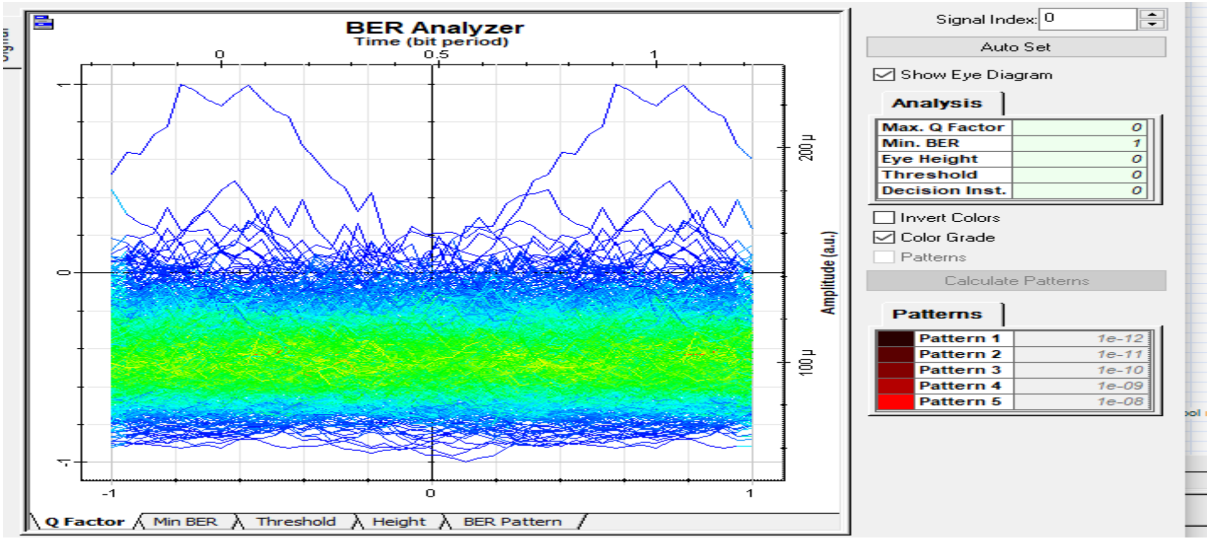

Figure 4. 8 Eye diagram of FSO system during winter period in Dire Dawa city with Link Length 40km, at attenuation (0.25dB/km).

Table 4. 3 Detection of BER analyzer for FSO link for autumn season in Ambo City at different.

Link Range	Attenuation dB/km	Max Q- factor	Min BER	Eye height
5km	0.194	38.5768	1.11996e-144	0.00593067
10km	0.24482	35.95768	6.1060e-229	0.0113988
20km	0.298	25.0459	7.8383e-240	0.0116259

Table 4.3 shows the relationship between transmission distance, attenuation, and BER for a specific FSO communication system. The table also show that as the transmission distance increases, the attenuation of the signal also increases.

Table 4. 4 Detection of BER analyzer for FSO link in autumn and winter season Dire Dawa City

Link Range	Attenuation dB/km	Max Q- factor	Min BER	Eye height
5km	0.275/km	61.5049	0	0.29282
10km	0.187	50.3994	0	0.05399081
20km	0.235	28.1838	3.8036e-175	0.00737393
40km	5dB	0	1	0

The table 4.4 shows that the FSO system has a maximum Q-factor of 61.5049 and a BER of 0 at link ranges of 5 km to 20 km, indicating that the system is performing very well at this range. As the transmission distance increases, the signal power decreases due to spreading and atmospheric attenuation.

Figure 4.9 shows the FSO system is performing very well in the 5 km transmission distance, achieving a maximum Q-factor of 61.1649 and a minimum BER of 0. The attenuation coefficient of 0.3293 dB/km also indicates that the signal is able to maintain its quality over the transmission distance. A Q-factor of 61.1649 is an extremely high value, indicating that the system is able to maintain a high signal-to-noise ratio and a very high level of signal quality.

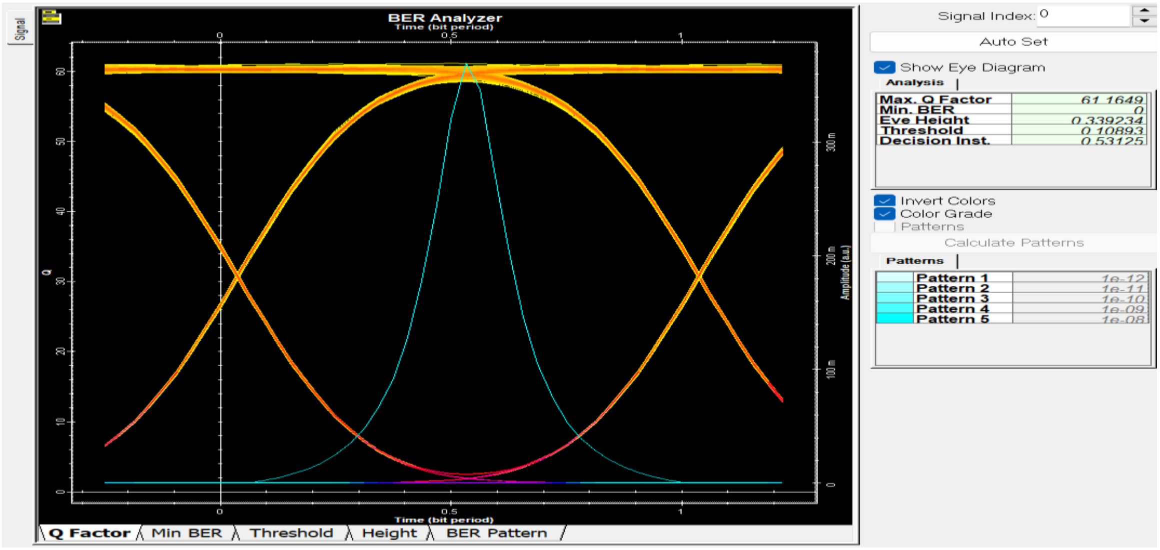

Figure 4. 9 Eye diagram for 2.5 GB/s data rate with attenuation of 0.3293dB/km at link distance of 5km (Pin = 30 dBm) in case of Light fog.

In Figure 4.10, the FSO system is operating at a data rate of 2.5 with an attenuation coefficient of 0.8844 dB/km and a transmission distance of 10 km in medium fog conditions in Dire Dawa city. The results show that the maximum Q-factor drops from 61.1649 to 34.4659 as the transmission distance increases from 5 km to 10 km. The decrease in the maximum Q-factor can be attributed to turbulence in the atmosphere, which can cause variations in the refractive index of the air and result in signal distortion.

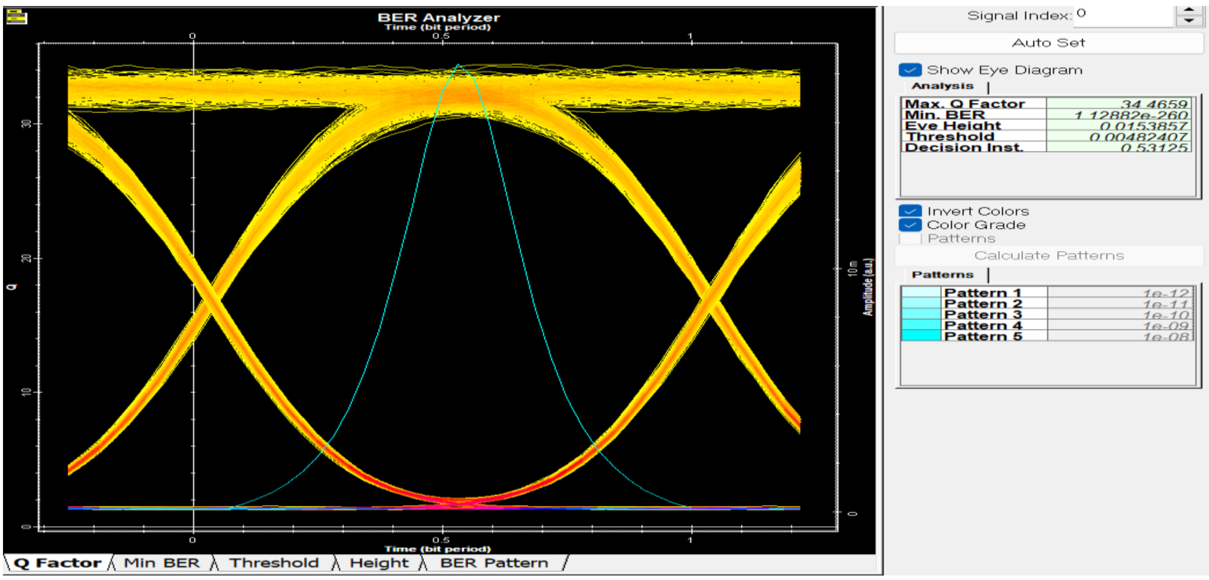

Figure 4. 10 Eye diagram for 2.5 GB/s data rate with attenuation of 0.8844dB/km at link distance of 5km (Pin = 30 dBm) in case of moderate fog.

In Figure 4.11, the FSO system is operating at a data rate of 2.5 with an attenuation coefficient of 2.177 dB/km and a transmission distance of 20 km in heavy fog conditions in Dire Dawa city. The results show that the maximum Q-factor drops to 28.267 and the minimum BER increases from 1.1288e–260 to 3.5961e–3.5996. This indicates a decrease in the signal-to-noise ratio and a degradation of the signal quality.

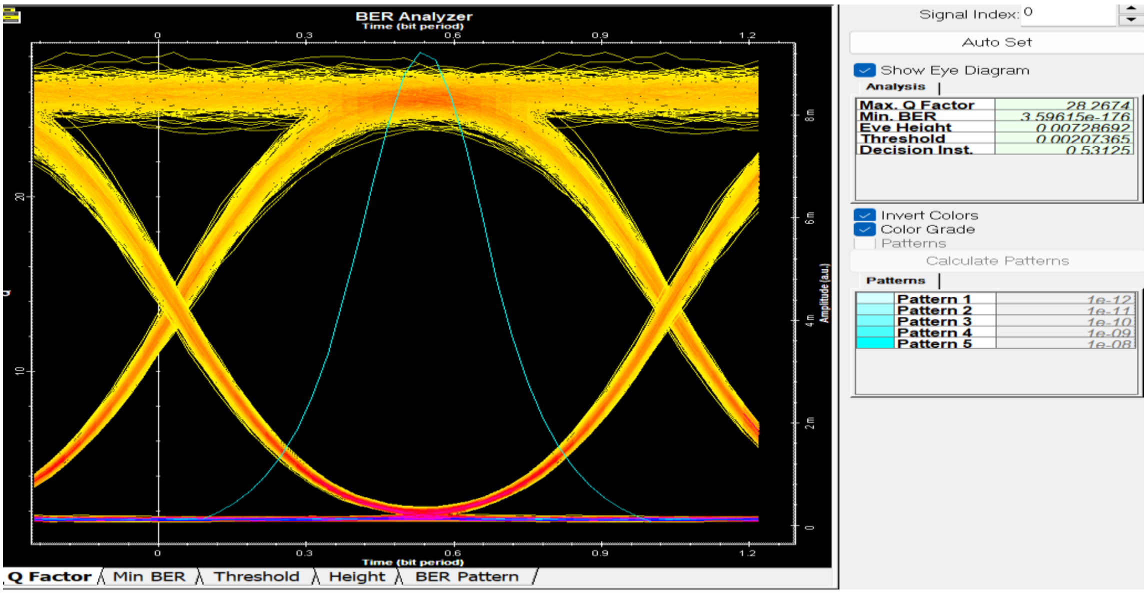

Figure 4. 11 Eye diagram for 2.5 GB/s data rate with attenuation of 2.177dB/km at link distance of 20km (Pin = 30 dBm) in case of heavy fog. And p=-1.3

Table 4. 5 Simulation Result of Fog with Link ranges

Weather Conditions	Link Ranges	Attenuation(dB/km)	Visibility Range (km)	BER
Heavy fog	5km	0.3293	0.2	0
Moderate Fog	10km	0.8844	0.5	1.12882e-260
Light fog	20km	2.177	0.77-1	3.5961e-176

Table 4.5 likely shows the relationship between transmission distance, fog attenuation, and BER for a specific FSO communication system.

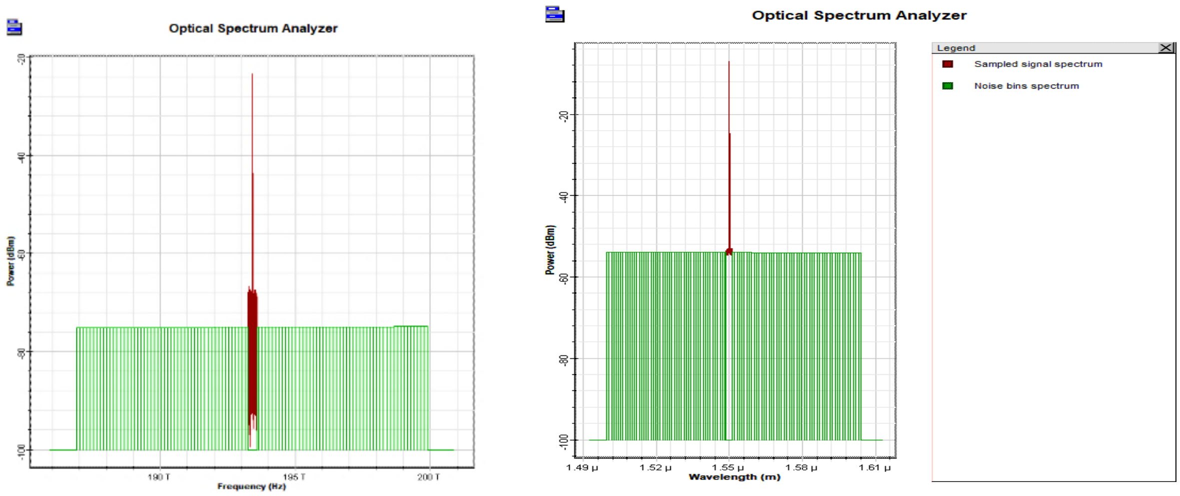

Figure 4. 12 Optical spectrum analyzer at Power vs Frequency and power vs wavelength

The frequency is represented by the x-axis, the power is represented by the y-axis, which can be used to examine the signal's frequency components and spot any spectral abnormalities or distortions that might impair system performance. From the left side figure the maximum power needed is -20dBm and the frequency is 193.2THZ in the right figure ;the power is the same (-20dBm) and the wavelength used is 1553nm/1.553.

Figure 4.12 shows the power distribution of a sampled signal in the frequency domain is shown on a sampled signal spectrum graph, also known as a power spectral density (PSD) plot. The frequency of the signal, which is given in hertz (Hz) units, is plotted on the x-axis of the graph along with the signal's amplitude.

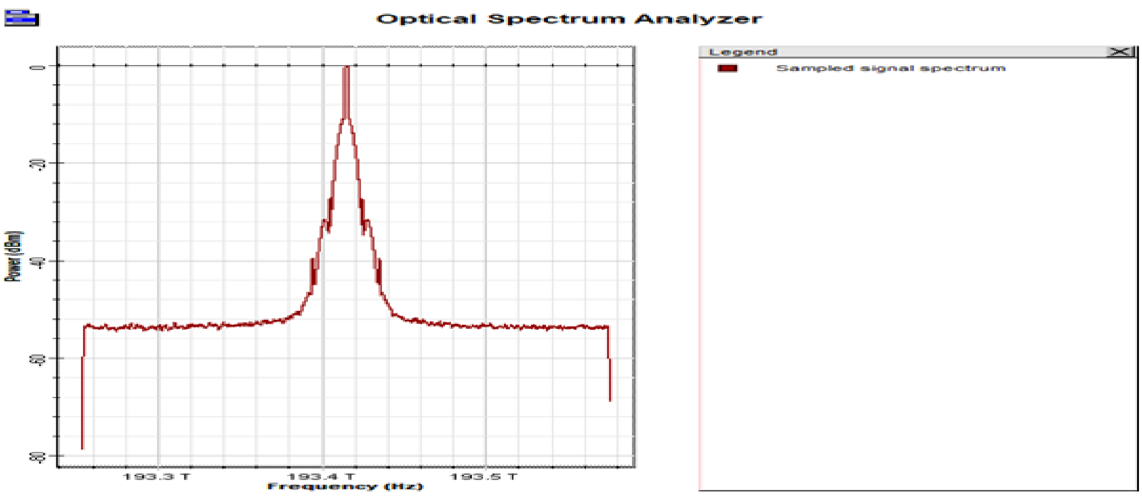

Figure 4. 13 Sampled Signal Spectrum

In Figure 4.13, the optical signal's power is shown against frequency in the figure.

From the figure 4.14 below the optical spectrum analysis, graphs of power against wavelength and frequency is shown. From Power vs Wavelength: The y-axis represents power and x-axis represents wavelength, which is typically shown on logarithmic scale.
Using this kind of graphic, we can examine the optical spectrum and identify any spectral patterns or distortions that might impair system performance and used to show how an optical signal's power varies with wavelength or frequency. The graphs include important details regarding the bandwidth, center frequency, and power level of the optical signal's spectral properties. The Graph can be used to determine the bandwidth of the signal, which is the range of wavelengths over which the signal has significant power.

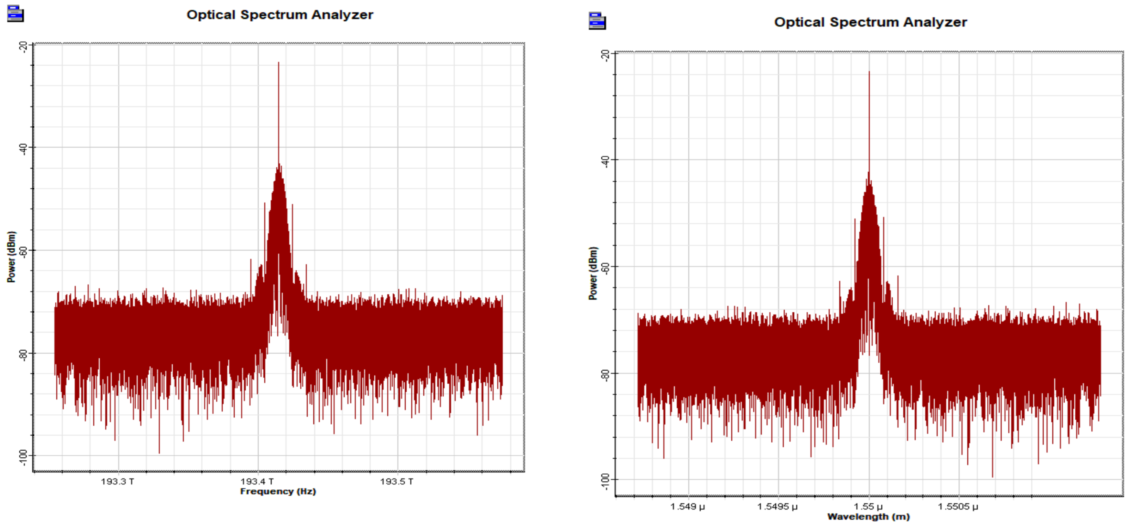

Figure 4. 14 Optical Spectrum Analyzer at Power vs Frequency and Power vs Wavelength

In figure 4.15 Power vs. Frequency: The frequency is represented by the x-axis, the power is represented by the y-axis, which can be used to examine the signal's frequency components and spot any spectral abnormalities or distortions that might impair system performance. From left side figure; the maximum power needed is -20dBm and the frequency is 193.2THZ in   right side figure the power is the same (-20dBm) and the wavelength used is 1553nm/1.553.

From the right figure we note that Power vs Wavelength: The y-axis represents power, and the x-axis represents wave-length, which is typically shown on a linear or logarithmic scale. Using this graph we can examine the optical spectrum and identify any spectral patterns or distortions that might impair system performance.

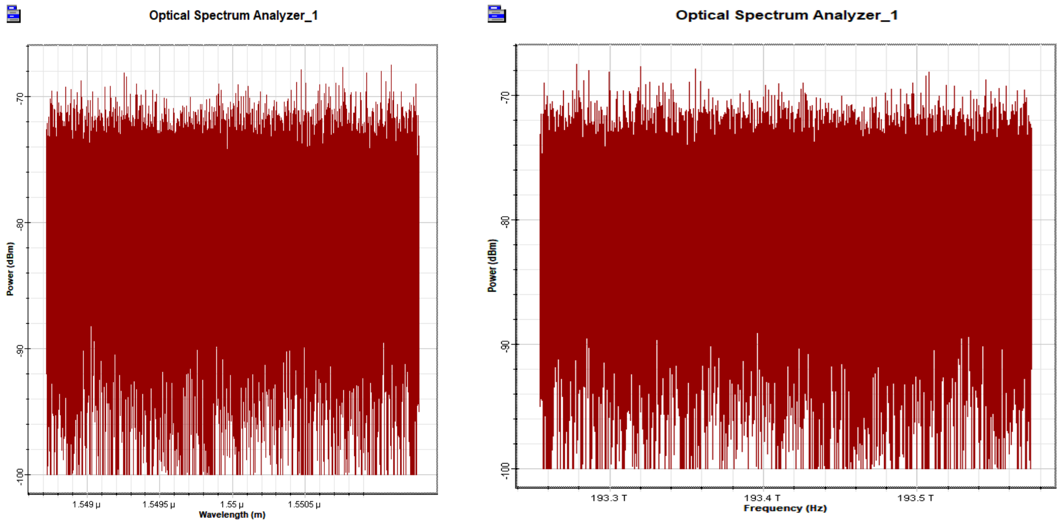

Figure 4. 15 Optical spectrum analyzer for Power vs wavelength and power vs frequency

In Figure 4.16 Q-Factor vs. Time: The graphic can identify fluctuations in signal quality caused by external factors and displays how variations in channel circumstances, such as noise, interference, or fading, affect the signal quality over time. It can spot patterns in the signal quality as well as any unexpected changes or abnormalities that could impair the communication system's operation

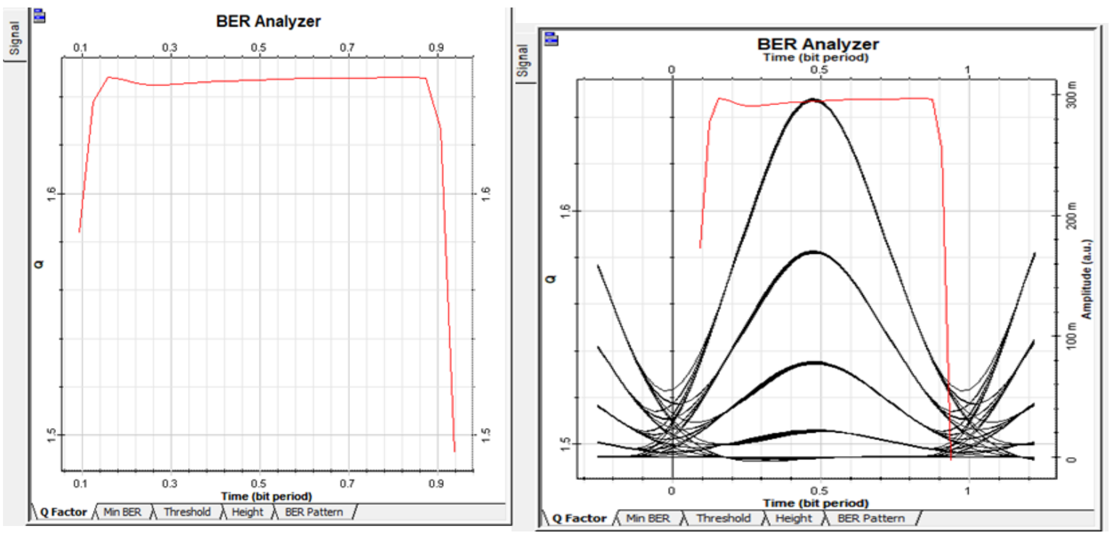

Figure 4. 16 BER analyzer at Q-Factor vs Time and Q-Factor with Eye diagram

In figure 4.17 Min BER vs Time plot: the minimum BER that can be achieved at each bit period is plotted against time. This shows about the durability and performance of the optical communication system. It can be used to detect any changes in signal quality that might be caused on by changes in the external environment or other elements.

Min BER with Eye Diagram: With a horizontal axis for time and a vertical axis for amplitude, the resulting pattern has the appearance of "eye" shape. The eye diagram's shape indicates details about the timing and amplitude jitter of the signal, as well as whether or not noise and other channel imperfections are present

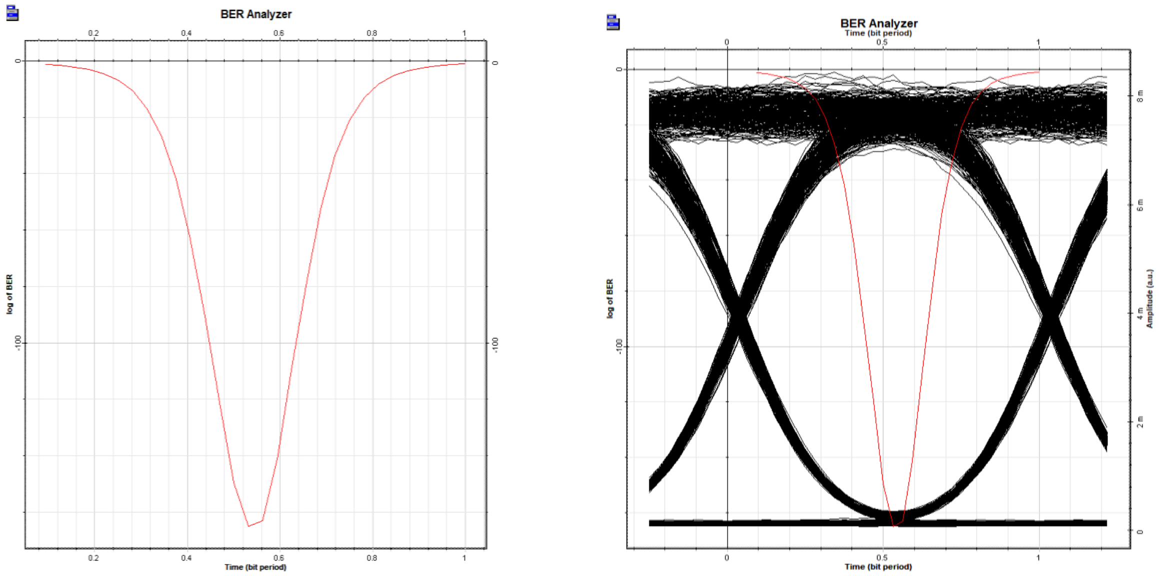

Figure 4. 17 BER analyzer for Min BER vs Time (bit period) and Min BER with eye diagram

In figure 4.18: The threshold is a measured tab that expresses the amplitude (y-axis) and time (x-axis) of the signal. The highest threshold height in figure (a) is approximately 3.99 meters, while the lowest is 1.25 meters. To create the eye diagram in figure (b), the optical signal's height is first calculated using this threshold height. The eye diagram illustrates the relationship between signal amplitude and time and offers perceptions into the FSO system's effectiveness. Amplitude vs Time: shows due to different factors like attenuation, dispersion, and noise, the received signal's amplitude in an optical communication system may change over time.

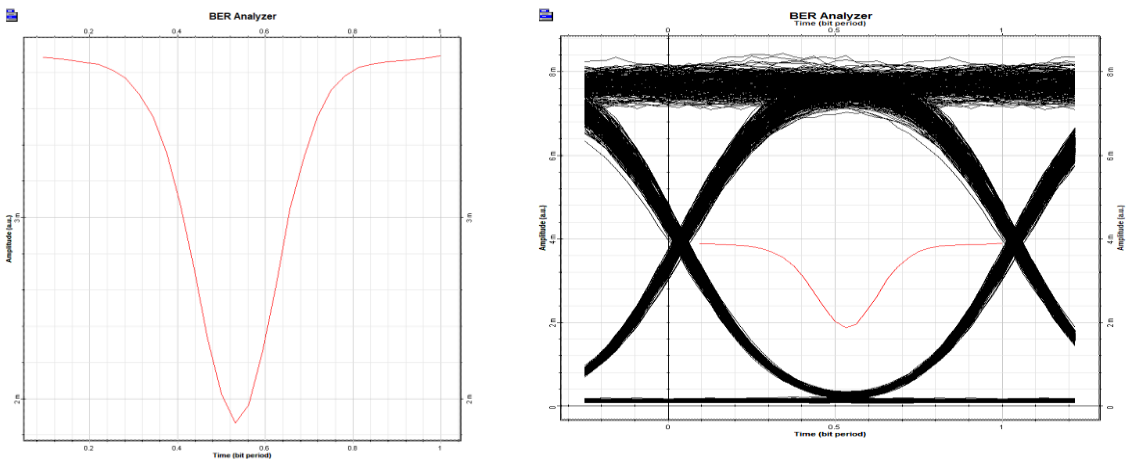

Figure 4. 18 BER analyzer for Min BER vs Time (bit period) and Min BER with eye diagram

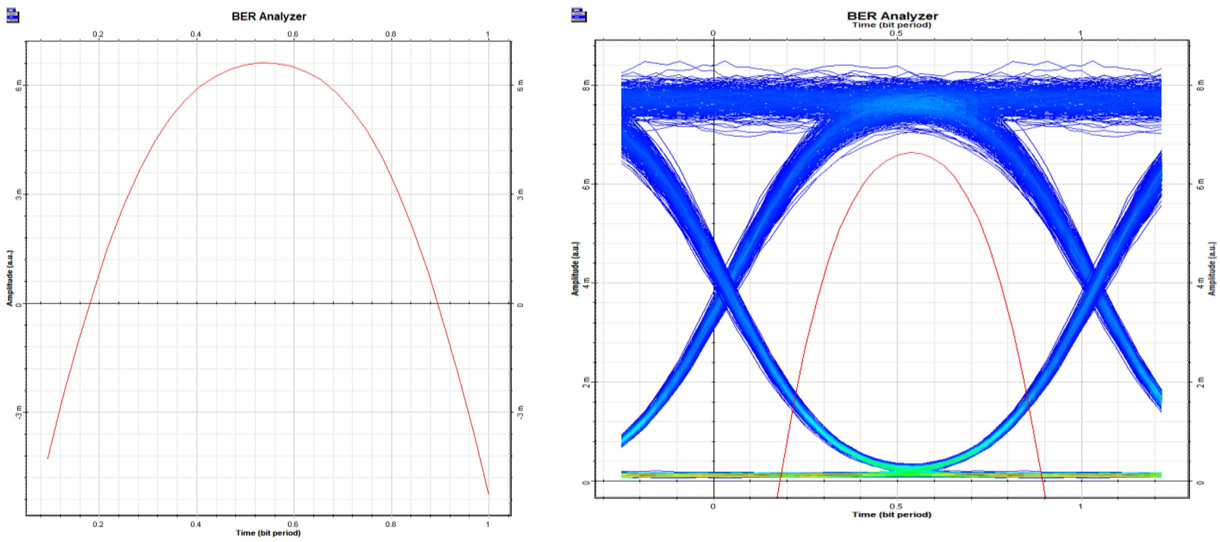

Figure 4. 19 BER analyzer for Height vs amplitude and height with the eye diagram

The maximum height of the optical signal using the BER analyzer is around 6.6 μ a.u.

With time 1-bit period. Here, the signal height is high, and as a result, the quality, SNR, and optical SNR (OSNR) are all high. Eye diagram height and eye opening can be combined to assess optical communication system performance. In Figure 4.19: A flat power spectrum in left figure across a broad range of wavelengths shows that the optical signal is being performed with minimal attenuation or distortion. The graph used to determine the bandwidth of the signal, which is the range of wavelengths over which the signal has significant power. The right-side Figure shows the power level considerably varies across different frequencies, this is an indication of optical interference or other signal degradation.

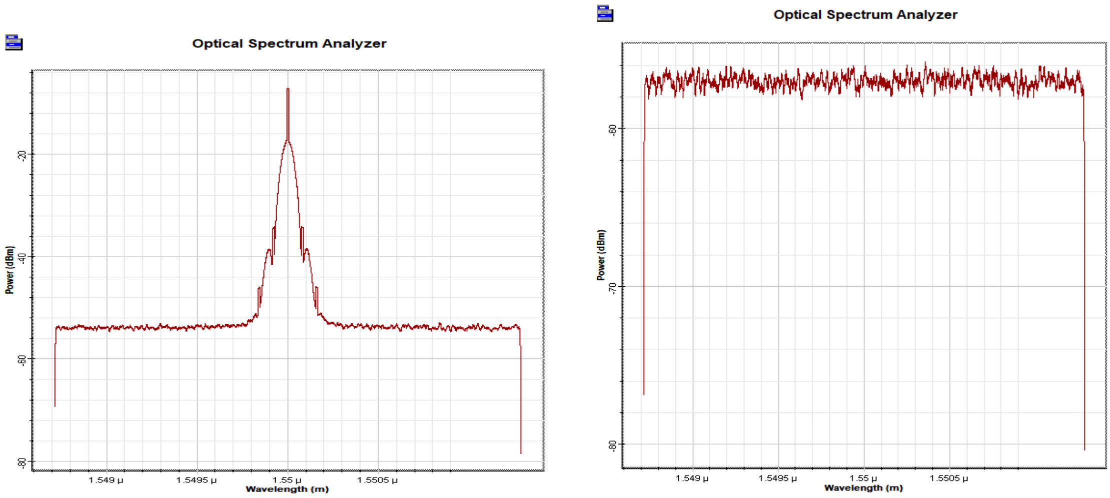

Figure 4. 20 Optical spectrum analyzer for Power vs wavelength and power vs frequency

From Table 4.7 a maximum SNR of 68.16 and an OSNR of 49.87 dB at a frequency of 193.4 THz, with a signal power of -2.452679 dBm, indicate that the signal has a high quality and is relatively strong compared to the noise power at that frequency.

The SNR of 68.16 indicates that the signal power is about 68 times higher than the noise power, which means that the signal can be detected and received with high accuracy, and that the bit error rate is likely to be very low. The OSNR of 49.87 dB indicates that the signal power is about 10^(49.87/10) or about 14,000 times higher than the optical noise power in a 0.1 nm bandwidth, which is a good indicator of the quality of the optical signal. In general, a higher OSNR value would indicate a better received signal quality, and a lower OSNR value would indicate a degraded signal quality.

4.3 Detection of Optical Spectrum analyzer for OSNR & SNR of FSO system

Table 4. 6 Result of Signal Power, Noise Power, and SNR & OSNR of FSO system at receiver side

Frequency (THz)	Signal power(dBm)	Noise power(dBm)	SNR (dB)	Noise Power: 0.1nm (W)	OSNR (dB)
193.4	-3.620345	-72.646037	69.025692	-75.243681	71.623336
193.3	-3.531145	-51.520334	47.98919	-54.681149	51.15004
193.2	-2.452679	-54.681149	52.228549	-54.681149	52.2247
193.1	-2.449979	-51.520334	49.07043	-54.563656	52.11097

According to the Table above, it appears that the system operates at its peak efficiency with an OSNR of 71.6233 and a maximum SNR of 69.025692dB at frequency of 193.4THz. This shows that even in the face of atmospheric circumstances which could generate noise and interference, the system is able to send the signal with acceptable quality. A higher SNR indicates a better-quality signal, with less interference from noise.

4.3 SNR Analysis by Log Normal and Gamma - Gamma Model

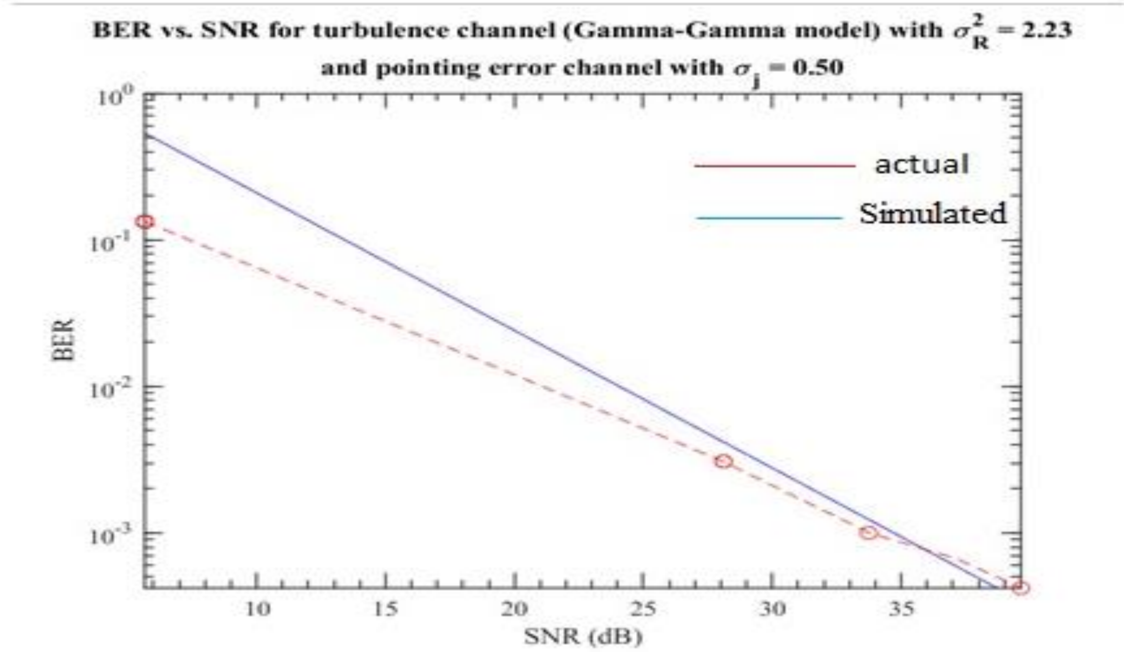

Figure 4. 21 BER Vs SNR for Turbulence channel for Gamma-Gamma Model & Pointing Error channel

In figure 4.21, the turbulence channel modeled by the gamma-gamma distribution with a scintillation index (σ^2) of 2.23, and a pointing error channel with a standard deviation (σj) of 0.5 shows the BER vs. SNR characteristics. The value of σj, representing the pointing error channel's standard deviation, increases, it will result in a higher BER for a given SNR and the scintillation index (σ^2) representing the turbulence channel, increases, it will result in a higher BER for a given SNR. This is because higher turbulence values cause fluctuations in the refractive index of the atmosphere, leading to phase distortions in the transmitted signal and errors in signal reception.

4.3 Diversity combining techniques like MRC, EGC& SC and Numerical Aperture

As shown in blow figure 4.22 effectiveness of different diversity combining techniques in improving the BER performance of a single-input single-output (SISO) system. The graphs show MRC is the most efficient diversity combining method, offering the lowest BER across the entire SNR range. As the system's numerical aperture (N) increases, the system's BER also improves, leading to a stronger received signal and less attenuation from atmospheric effects.

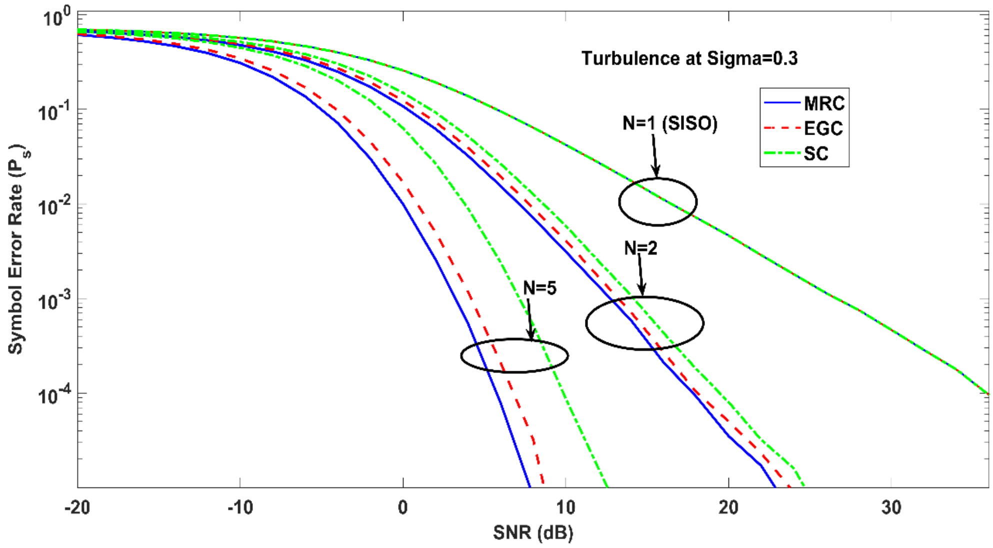

Figure 4. 22 BER Vs SNR for MRC, EGC & SC for different Numbers of aperture and Turbulence strengths

Figure 4.22 shows the (BER) performance of Maximum Ratio Combining (MRC), Equal Gain Combining (EGC), and Selection Combining (SC) for the case of a point receiver with a Rytov variance of 0.3 and over the Signal-to-Noise Ratio (SNR) range of -20dB to 30dB and numerical aperture (N) of 1, 2 and 5; over Single-Input Single-Output (SISO), The BER vs. SNR performance for all diversity approaches improve as the numerical aperture (N) increases because more light can be coupled into and out of the optics.

Figure 4.23 shows that Rytov variance (sigma) is increased from 0.3 to 0.5, indicate that the level of atmospheric turbulence is higher which lead to stronger fluctuations in the refractive index of the atmosphere, resulting in more severe fading and signal level is degradation.

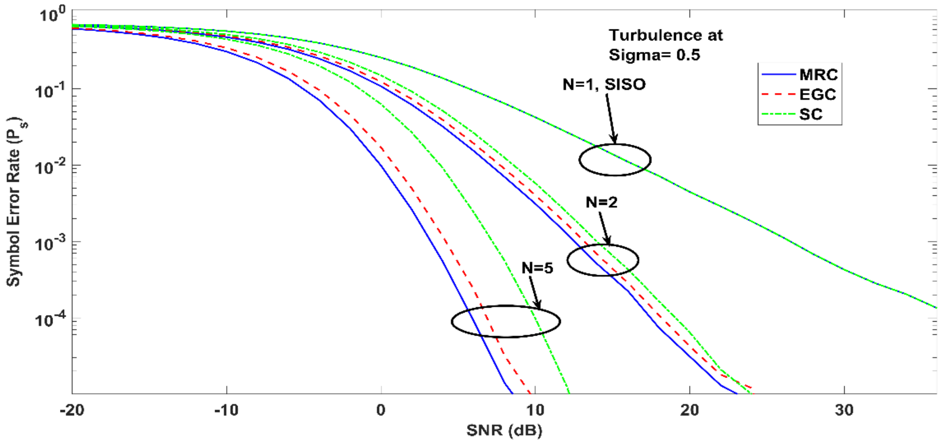

Figure 4. 23 BER Vs SNR for MRC, EGC & SC for Turbulence strengths at 0.5.

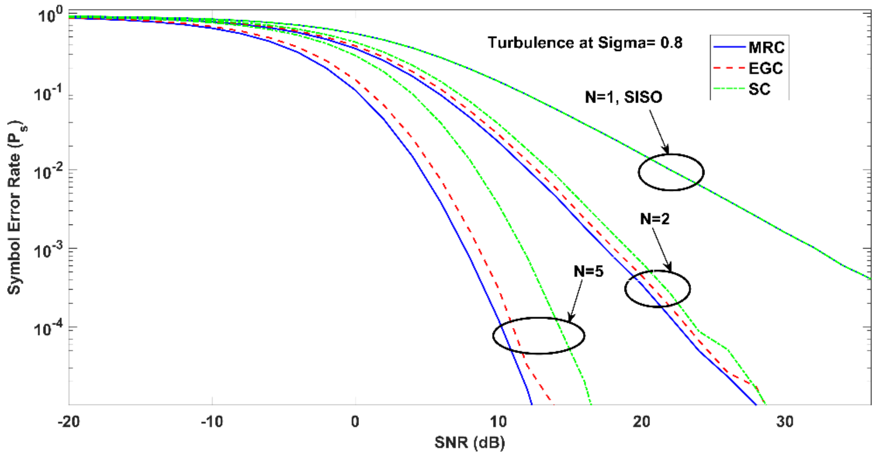

Figure 4. 24 BER Vs SNR for MRC, EGC & SC for Turbulence strengths at 0.8

Figure 4.24 shows the Rytov variance is increased from 0.3 to 0.8, it indicates higher levels of atmospheric turbulence, resulting in e severe fading and signal degradation

Figure 4.25 shows BER Vs SNR of FSO communication system under different atmospheric turbulence model. From the graph we note that using Gamma-Gamma model for strong atmospheric turbulence is accurate than Log normal and lowest BER.

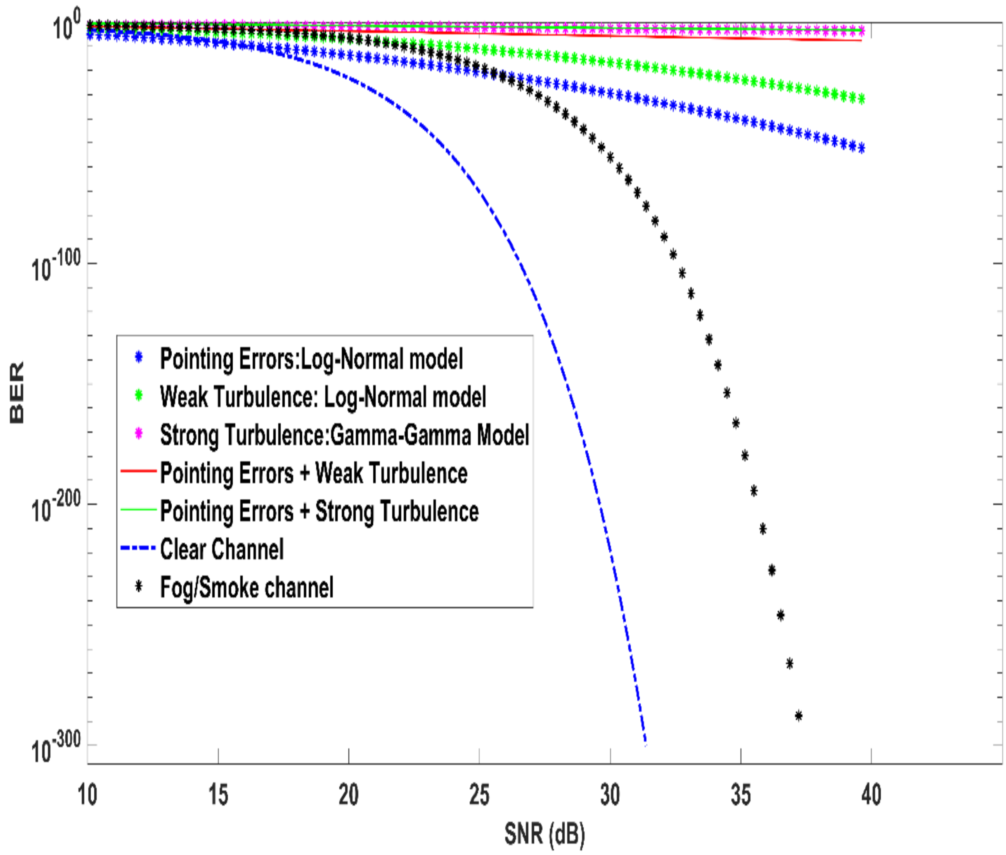

Figure 4. 25BER Vs SNR of FSO System under Log-Normal and Gamma-Gamma Model with Pointing Errors

In the case of a clear channel, where there is no atmospheric turbulence or other sources of signal degradation, the BER versus SNR graph show that the system can achieve very low BER values even at low SNR levels.

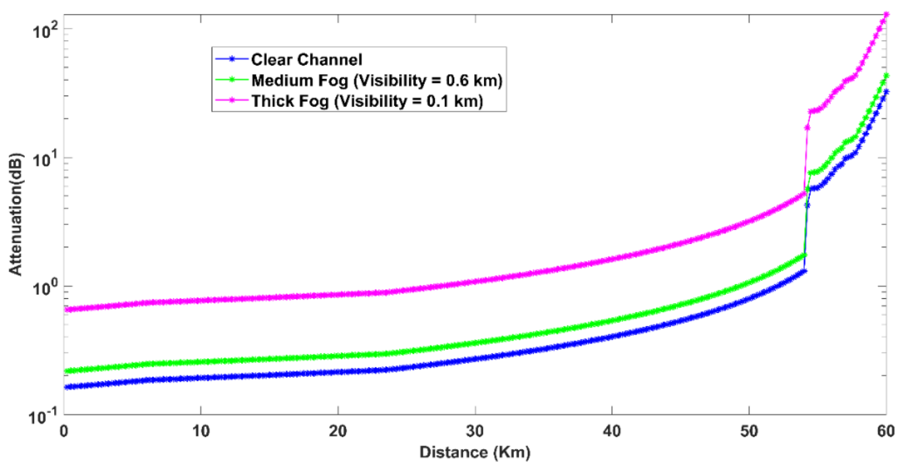

Figure 4. 26 Attenuation (dB) Vs Distance (link range (km)

The Attenuation vs. Distance graph illustrates the relationship between the FSO link's distance and the attenuation caused by air losses, expressed in decibels (dB). As the distance of the link increases, the attenuation due to atmospheric losses also increases, resulting in a higher signal loss and a lower received signal strength. In the case of medium fog (visibility = 0.6 km), the graph shows a higher level of attenuation, with values ranging from 0.5 dB/km to 1.0 dB/km. This is because the fog particles scatter and absorbing the optical signal, resulting in a weaker and more degraded signal over shorter distances. In a clear atmosphere, there are no sources of signal degradation such as atmospheric turbulence, scattering, or absorption that can cause signal fading or attenuation. As a result, the signal is transmitted with high fidelity and can be accurately received by receiver.

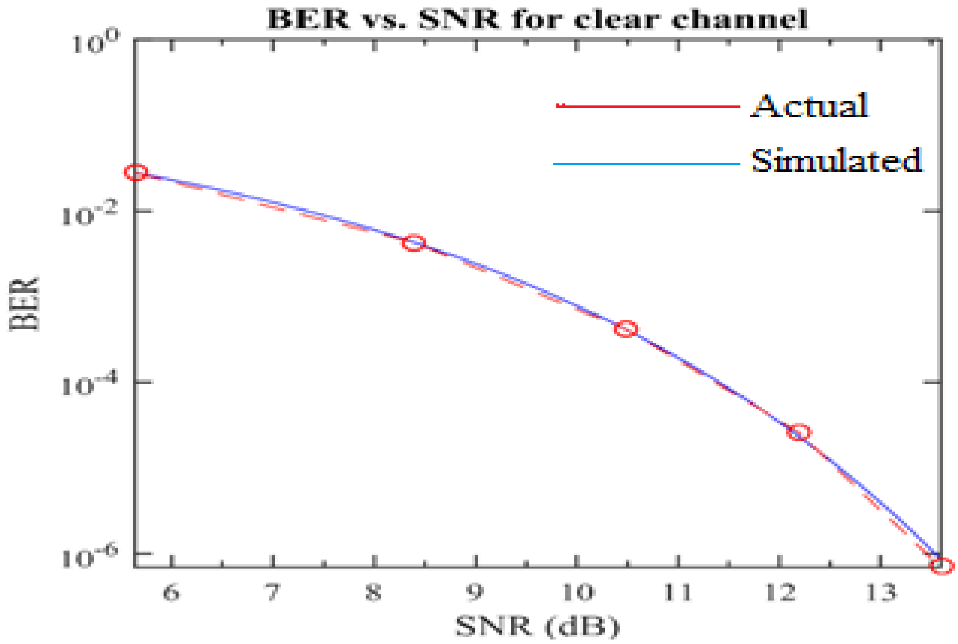

Figure 4. 27 BER Vs SNR in clear Atmosphere

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The thesis has successfully modeled and analyzed the performance of Free Space Optics (FSO) as a backup link for fiber connectivity in urban areas using OptiSystem. The study has considered the impact of atmospheric effects on the FSO link's performance by observing the detection of BER analyzer such as Q-factor, BER, OSNR, and optical meter readings. The FSO system achieves a minimum BER of 1.9734 e-30 and a maximum Q-factor of 11.3341 with a link range of 10 km and an attenuation of 5 dB/km. This shows that despite the presence of heavy rain and severe signal attenuation, the system is still able to transfer data at a high bit rate with low error rates. The FSO system achieves a higher maximum Q-factor of 25.5768 and a lower minimum BER of 1.1993e-144 under moderate rain circumstances with a link range of 15 km and an attenuation of 0.289 dB/km. This shows that the system can transfer data under less adverse air conditions at an even greater bit rate with even lower error rates.

The FSO system in Ambo city achieves a maximum Q-factor of 33.0451 and a minimum BER of 7.8383e-240 with a rainfall attenuation of 0.144 dB/km and a link range of 20 km in autumn period and these show that the system is capable of transmitting data at a very high bit rate with an incredibly low error rate. The study has shown that a 1550 nm CW laser diode with a 30 dBm output can provide a reliable FSO link, but as the link range increases, the strength of the FSO link reduces due to different impairments in the atmosphere. In Dire Dawa City, the study used ranges of 5 km to 20 km in all seasons to evaluate the performance of the FSO system. This suggests that the system was tested under a wider range of link distances and seasonal conditions to assess its performance in various scenarios, and performance metrics such as BER and Q-factor were likely measured to determine the system's overall performance. To achieve the minimum intended data rate of 2.5 GB/s and above, the study has used the ranges of 5, 10, and 20 km in winter and fall in Ambo City and the ranges of 5 km to 20 km in Dire Dawa City in all seasons

The Study explores Rytov variance impact on BER performance by increasing numerical aperture, improving SNR, and reducing atmospheric turbulence impact and increasing the link range.

5.2 Recommendation

It is crucial to remember that simulation findings may not always correspond to the system's performance in the actual world because they are based on assumptions and idealized settings. Depending on particular environmental conditions, the impact of atmospheric turbulence and other impairments can differ, prompting the need for extra mitigation measures.

Additional experimental research are required to verify the simulation results and show that FSO may function as a backup link for fiber connectivity in practical settings.

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