Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Comparative Performance Analysis of Free Space Optics as a Backup Link for Fiber Connectivity around the area of Bole Medhanialem using Optisystem15

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Declaration

This thesis is a presentation of my own research work and that any material used from other sources has been clearly identified and properly acknowledged and referenced.

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Abstract

Free space optics (FSO) is a field of curiosity and importance for the scientists because of its numerous applications and advantages like low cost, easy deployment, high data rate, secure links and license free bands. FSO technology utilizes the light propagating in the free space to transmit the data wirelessly for both telecommunications and computer networking domains. In optical communication, we use optical fiber cable as a medium but in the free space optical communication, we use the free space as the medium to propagate the light signal [1].

Even if fiber optics is the most reliable means of providing optical communications, the digging delays and associated costs to lay fiber often makes it economically prohibitive. A telecom service provider in our case Ethiotelecom faced a problem to deliver a quality service because of many technical issues one of them is lack of deploying a redundant link. As we all know unable to deliver a promised service leads to customer dissatisfaction.

This thesis paper proposes a design of point to point FSO as a backup link for fiber connectivity around the area of Bole Medhanialem pointing from Bole exchange to three different enterprise buildings (Sapphire Addis Hotel, Best western Addis Hotel, Skylight Hotel) that is capable of transmitting data at 80Mb/s, 60Mb/s and 200Mb/s for a distances of 0.116km, 0.36km and 1.45km respectively. And it's performance analysis and comparison with fiber optics observed using Optisystem software15 by taking the performance metrics Q factor and BER found from the reading of BER analyzer. From the results it has been understood that FSO link can perform like FO (main link) at a cost of input power. Since FSO link in Ethiotelecom infrastructure has not been studied before we can take this paper as a reference for future deployment of FSO technology in the country.

Keywords– *FSO,FO, BER analyzer, Q factor, PRBS generator*.

Acknowledgement

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Contents

List of Figures

List of Tables

List of Abbreviations

AAiT	Addis Ababa Institute of Technology
APD	Avalanche Photodiode
BER	Bit error rate
Q factor	Quality factor
TCO	Total Cost of ownership
CW	Continuous Wave
EDFA	Erbeium Dopped Fiber Amplifier
FSK	Frequency Shift Keying
FO	Fiber optics
FSO	Free space optics
FTTx	Fiber to home premises
FWHM	Full Width Half Maximum
IR	Infrared communication
LAN	Local Area Network
LOS	Line of sight
MZM	Mach-Zender Modulator
OOK	On Off Keying
OWHNs	Optical Wireless Home Network
OWSNs	Optical Wireless Satellite Network
PIN diode	P-N junction Diode
P_{in}	Input power
PON	Passive Optical Network
P_{out}	Output power
PPM	Pulse Position Modulation
PRBS	Pseudo Random Bit Sequence

PSK	Public Switched Telephone Network
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
RF	Radio frequency
SAN	Storage Area Network
SOA	Semiconductor Optical Amplifier
WAN	Wide Area Network
WOC	Wireless Optical Communication
WTNs	Optical Wireless Terrestrial Network
ETB	Ethiopian Birr

Chapter 1

Introduction

1.1 Background Information

Because of the enormous data speeds that can be achieved, optical communications became an important feature of today's network systems. Optical wireless communication, on the other hand, is gaining popularity due to its greater flexibility than fibers. Free Space Optics (FSO) is a good alternative solution as the demand for larger and unrestricted bandwidth for communication channels grows. Its popularity is rapidly growing because to its protocol transparency, ease of installation, low cost, and fiber optic capabilities. The weather, on the other hand, is the limiting factor for the FSO link. Fog is a key stumbling problem for FSO connection viability in the temperate zone. The availability of FSO links in the tropical region is predicted to be hampered by high rainfall rates. In the tropical region, rain attenuation has the greatest impact on FSO link availability [2]. Free Space Optics (FSO) is an effective solution to the current telecommunication infrastructure connectivity gap.

FSO technology promises high-speed, point-to-point communication connectivity. It's a technique that combines fiber-like speed with wireless flexibility. Despite the fact that fiber optics is now one of the backbones in most cities, the expense of digging and deploying fiber cables is substantial [2].

Moreover, FO deployments are excessively costly in terms of time and money. It is tough to shift fiber cable once it has been installed. Other mature systems, such as microwave, radio frequency, and copper, have some drawbacks in comparison to FSO, such as being susceptible to interference, being expensive, having limited capacity, and not being able to provide full broadband services. FSO is the most realistic solution for fast speed and higher bandwidth due to its benefits over other established technologies. The FSO communication system is related to fiber optics in terms of technology. Both offer similar benefits, such as increased speed, unlimited bandwidth, and protocol independence.

The FSO system is less expensive and takes less time to deploy because it does not require the installation of cable. Despite the fact that FSO offers additional benefits, the key problem that limits the availability of FSO links is the local weather. Because open space serves as the medium of transmission, atmospheric attenuation can cause the link to lose a few dB to hundreds of decibels per kilometer. The availability of FSO links is limited by fog and heavy snow in temperate regions. Heavy rain is likely to attenuate and distort the signal in the FSO receiver system in tropical regions where fog does not exist [2, 3].

Fig 1.1: Conceptual FSO links establish in Bole area of A.A [4].

1.2 Statement of the Problem

Today, a combination of technological advancements, ease-of-use characteristics, and budgetary considerations are all helping to advance the cause of FSO. FSO provides point-to-point transmission of communication information through the atmosphere using the Optical signals as the carrier frequencies. It has drawn attention in telecommunication industry, due to its cost effectiveness, easy installation, quick establishment of communication link especially in the disaster management scenario, high bandwidth provisioning and wide range of applications. The range of frequencies where it operates makes FSO communication free from licensing [5].

Ethiotelecom infrastructure in our capital city of Addis Ababa use different technology to satisfy the high speed data service demand of users, Optical communication is one of the preferable system. Lack of on time maintenance on the main link and deploying redundant link caused the service provider unable to keep the promise on delivering quality of service which leads to customer dissatisfaction. FSO is helpful to send large amount of data securely over moderate distances without the expense of laying fiber optic cable when there is a need of back up link deployment. To apply the design one of the sub cities in Addis Ababa is selected as a case study. Without a doubt fiber is the most reliable means of providing optical communications, but the digging delays and associated costs to lay fiber often make it economically prohibitive laying optical fiber in the ground requires huge expenses and a considerable time and efforts once laid the fiber can't be redeployed easily. Speaking of deployment time and cost the data from Ethiotelecom showed as the company spend a total cost of 392,662.00 ETB(Ethiopian Birr) including radio link devices like an antenna, planning/designing, deployment, transportation and labor costs for the deployment of a radio link specifically Radwin (A technology more similar to FSO) in the selected areas. Here we took the estimation cost of Radwin because FSO technology is not applied in the company yet. And the time required to deploy the link is only 3 days. In the other hand the estimated total cost for FO link in the same area is about 412,045.00ETB(Ethiopian Birr) including designing/planning, installation /transfer/recovery ,digging, jointing/splicing, transportation and labor costs, with a time requirement of 18 days. From the comparison we noticed that FSO is definitely a better choice in terms of cost and time efficiency [33].

These points have motivated this study to demonstrate the performance of FSO technology. It also strives to analysis and compare the performance of the FSO link as a backup for fiber connectivity deployed to selected enterprise buildings (Sapphire Hotel, Best Western Addis Hotel and Sky light Hotel) around the area of Bole Medhanialem using Opti system software 15, So this work can be considered as a step towards a practical realization.

1.3 Objective

1.3.1 General Objective

The aim of this thesis is to analyze and compare the performance of free space Optical link as a backup link for fiber connectivity around the area of Bole Medhanialem in Addis Ababa.

1.3.2 Specific Objectives

- Performance analysis of both fiber optics and free space optics in terms of
  - ✓ Q factor and BER reading for both FO and FSO link
  - ✓ 2D graph for Q factor vs BER
  - ✓ 3D graph for Q factor vs Range vs Data rate
- Evaluate and compare the performance of FSO technology as a backup link for fiber optics connectivity using the reading of an eye diagram.

1.4 Contribution of the thesis

The main contribution of this thesis work is to analyze and compare the performances of fiber optics and free space optics based on BER and Q factor by applying constant value of input power for different ranges and this can be proposed for implementation of free space optics as a backup link for fiber optics deployed from Bole Exchange to the selected enterprise buildings around the area of Bole Medhanialem.

Since the thesis work is initiated considering the advantage of using free space optics in telecom industry it will help Ethiotelecom through their way of achieving their goal of providing high Speed, flexibility, easy to install and license free fast and reliable wireless communication link.

1.5 Methodology

The methods employed to achieve the objective of this thesis work are:

- **Literature Review**

This includes the survey and reading of books, articles, journals, white papers, simulation tools and all forms of other resources which are related to free space optics.

- **System Modeling**

Involves modeling of the overall end to end communication link including transmitter, receiver and transmission medium components finally detecting the performance matrix using BER analyzer.

- **Simulation**

It is the approximation of the modeled communication system in Optisystem software.

- **Performance comparison of FSO and FO**

It compares the value of BER and Q factor taking the constant value of input power for different distances and data rate requirements of both fiber and free space optics links.

- **Analysis and Discussion of the Results**

Performance analysis and interpretation of the results and findings obtained from the simulated system.

1.6 Scope and Limitations of the Thesis

1.6.1 Scope of the thesis

The scope of this thesis work is limited to performance analysis and comparison of free space optics and fiber optics link from bole exchange to Sapphire Hotel, Best Western Addis Hotel and Sky light Hotel by comparing Q factor ,BER ,eye diagram from the detection of BER analyzer in Optisystem software and examine the relation of Q factor and BER in 2D graph , 3D graph showing the relation of Qfactor, data rate and range.

1.6.2 Limitation of the thesis

However, the implementation will be only in Optisystem software and it will not include hardware implementation. This thesis will not include laboratory tests and hardware implementations.

1.7 Literature Review

After the work of Alexander Grham Bell,many scholars and researchers at different times have studied too many scenarios that can help the implementation of wireless optical communication including free space optics. from those many literatures and books published on the issue of free space optics , the following four papers are selected to be discussed in this section [6].

Jai P. Agrawal, Omer Farook and C.R. Sekhar proposed the design of a gigabit-rate data free space optics link between two university buildings. About 500 meters separates the two structures. In typical operation, the free-space optical link employs a 1550 nm wavelength, but it also features a 2.4 GHz wireless link as a backup. Only the FSO technology is used in this design. In a lab setting, the feasibility was demonstrated [7].

Dr.Shehab A. Kadhim used Opti system 7.0 simulation program to characterize the performance of the free space optical system design. This study examines FSO designs and simulations utilizing a mathematical and computational program based on mathematical correlations between weather conditions and their impact on beam movement to evaluate the computer course [8].

Mehtab Singh demonstrated the modeling and simulation of a Free Space Optical (FSO) communication link employing various system characteristics. Using OPTISYSTEM modeling software, the Q Factor and SNR of the received signal were measured under various data transmission rates, connection lengths, divergence angles, and transmitted power levels of the information signal. According to the findings, as the FSO link distance increases, the Q Factor of the received signal falls, and the BER value rises. In addition, when the system's data transmission rate increases, the Q Factor of the received signal falls. The Q Factor of the received signal diminishes as the divergence angle increases, degrading the system's performance [9].

In the University of Oklahoma, Hakki H. Refai, James J. Sluss Jr, and Hazem H. Refai of the Tulsa School of Electrical & Computer Engineering presented the successful transmission of modulated RF analog signals over an FSO link and compare main performance parameters to a fiber optic link configured in the same way. The results of optical power, transmission response, reflection response, group delay, carrier-to-noise ratio, and dynamic range experiments are reported. FSO for RF applications is used as a substitute for fiber optic transmission connections across short distances, according to the findings of this comparative study [10].

In the first three reviewed papers study was limited to the design of FSO system. But in our thesis paper besides designing the FSO link in the simulation software we include the performance comparison of FSO link against FO link. Using Q factor and BER as a performance metrics makes our study differ from the last reviewed paper.

1.8 Thesis Organization

This thesis consists of six main chapters. The first one is an introductory part which mainly includes the background, goal and motivational aspects of the thesis. The second chapter will present wireless optical communication specifically free space optics including the application area of FSO whereas, the third chapter discuss advantage and limitations of both FSO and FO. The fourth chapter deals with the end to end system model of free space optics system. The fifth chapter includes simulation of the modeled communication system as well as analysis and interpretation of the outcomes. The last chapter is the conclusion and recommendation part of the thesis which discuss the important conclusions drawn based on the results obtained from the whole thesis work.

Chapter 2

Free space Optics

2.1 History of Optical Communication

Alexander Graham Bell created the first wireless optical communication system in 1880, four years following inventing the telephone, using the sun's beams instead of electric wire. After the initial demonstration of the working of this contraption, which would be dubbed the "photo phone," he wrote to his father, "I heard the sun rays to laugh, cough, and sing." It was a transmission in free space across a distance of around 200 meters using sunlight as the carrier, demonstrating for the first time the basic principle of modern optical communications, in which the optical fiber substitutes ai as the medium for light transmission [6].

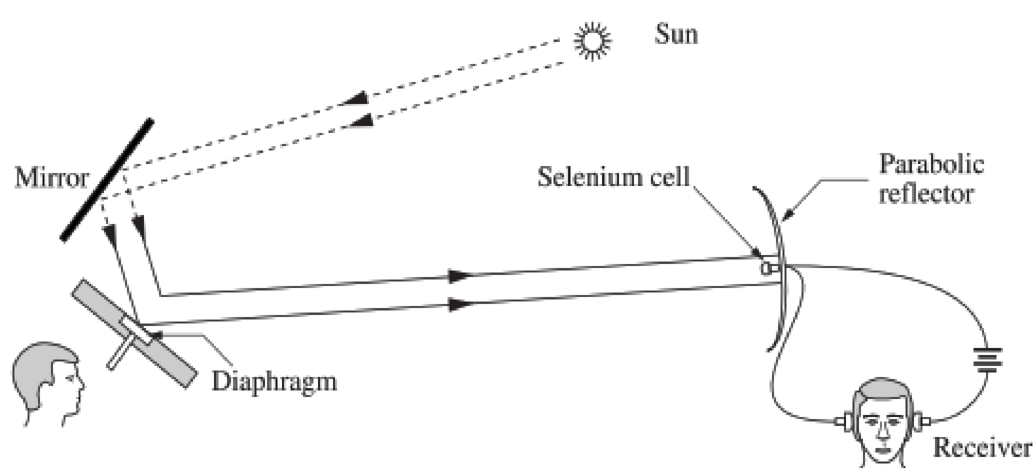

Figure 2.1: Schematized representation of the photo phone [6].

A flexible reflective membrane is used to focus the sun's rays. This membrane is used by the user to speak into. By modifying the reflected sun rays, the spoken word is communicated in the air. After being displaced in the air, the modulated reflected light is gathered by a photoconductive selenium cell coupled to a pile and the earphones.

This invention, which received a patent on June 3, 1880, was considered by Graham Bell to be his greatest, far more important than the telephone, Despite the fact that we are all aware of what occurred. The transmission durations were too short, and the sun did not transmit in the same way every day of the year. Engineers picked up the idea of the photo phone 120 years later and utilized free-space optical lines for high-speed wireless transmissions, as shown in Figure 2.1. Thanks to optical transmission through optical fibers, precisely regulated pencils of light were utilized instead of the sun, which was far too variable. These photon beams are generated by lasers with precisely specified properties (wavelength, number of emitted photons, duration or sequences of emission), and they are collected by very sensitive and repeatable detectors. The transmission medium remains air, which can be changeable (due to variations in climate, vegetation, or the industrial environment), although optics and contemporary electronics can mitigate uniformity to some extent. The issue of non-reproducibility of the medium of transmission is similar to that encountered in radio-electric communications, such as broadcasting. It can be fixed by incorporating appropriate electronics into the receivers [6].

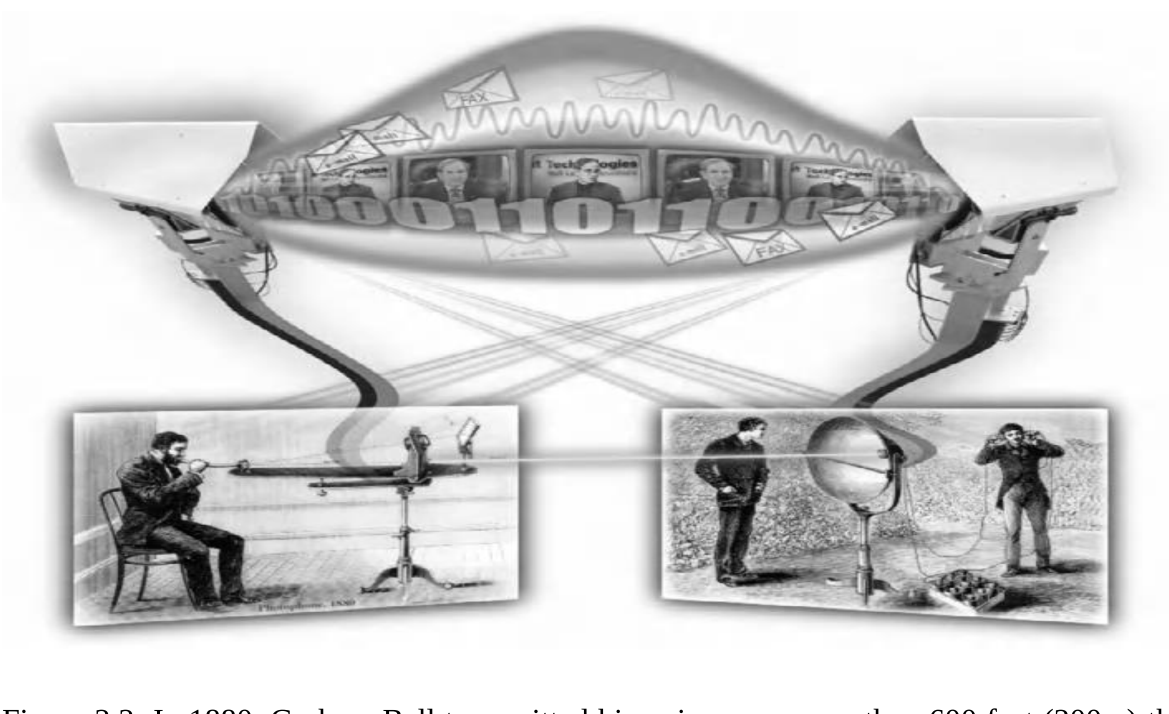

Figure 2.2: In 1880, Graham Bell transmitted his voice over more than 600 feet (200m) through the air and using the reflected rays of the sun. In 1999, Engineers took up the idea of the photo phone [6].

Information and communication technology have experienced enormous growth and advancement in recent years. With the increased use of high-speed internet, video conferencing, and live streaming, bandwidth and capacity requirements are rapidly increasing [11].

2.2 Wireless Optical Communication (WOC)

"Wireless optical communication" (WOC) is a method that uses an optical carrier to send data from one location to another over an unguided channel, such as the atmosphere or open space. WOC is seen as the future stage for high-speed broadband connectivity because it provides extremely high bandwidth, ease of deployment, unlicensed spectrum allocation, reduced power consumption (half of RF), reduced size (one-tenth of RF antenna diameter), and better channel security [11].

2.2.1 Classification of Wireless Optical Communication (WOC)

Indoor and outdoor wireless optical communications (WOC) are the two primary categories of WOC. Indoor WOC employs infrared or visible light to communicate inside a building when putting up a physical cable connection would be difficult. Directed line-of-sight (LOS), non-directed LOS, diffused, and tracked are the four generic system configurations for indoor WOC. Free space optical (FSO) communication is another name for outdoor WOC. Building-to-building, ground-to-satellite, satellite-to-ground, satellite-to-satellite, satellite-to-satellite, and satellite-to-airborne platforms are all examples of FSO communication systems [11,12].

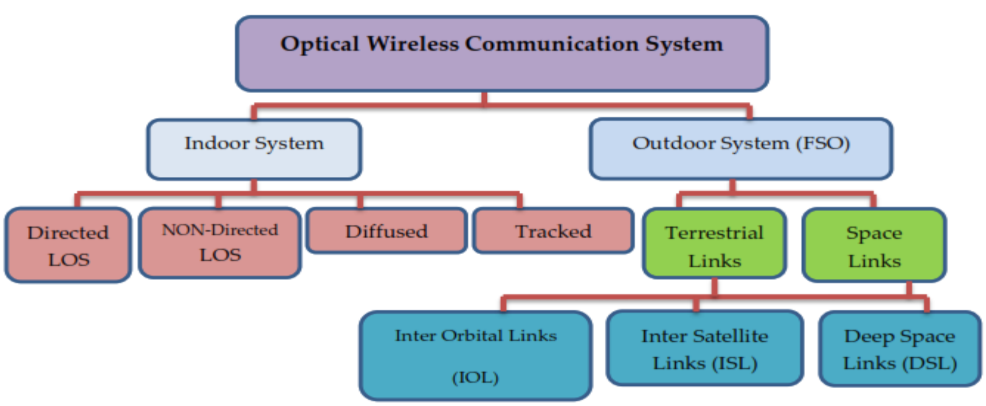

Fig 2.3: Classification of wireless optical communication system[11].

2.3 Relevant 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 [13].

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) [13].

2.4 Over view of FSO (Free space Optics)

FSO (free space optics) is an optical communication technology that allows for optical connectivity by transmitting data through the propagation of light in free space. The optical fiber cable is not required. FSO networks work similarly to OFC (optical fiber cable) networks, with the exception that optical beams are sent over free air rather than OFC cores, which are glass fiber. An optical transceiver is used at both ends of the FSO system to give full duplex (bidirectional) functionality. FSO communication isn't a novel concept. It has been around since the eighth century, although it has evolved since then. FSO [5] is a line-of-sight (LOS) technique.

It's a great way to bridge the telecommunications infrastructure's current connectivity gap. FSO technology promises high-speed, point-to-point communication connectivity. It's a technique that combines fiber-like speed with wireless flexibility. Although fiber optics is now one of the city's backbones, the expense of digging and deploying fiber cables is significant. Furthermore, the cost of deployment time is too high. It's difficult to relocate fiber cable once it's been installed [2].

2.4.1 Characteristics of FSO System

FSO systems should be able to run at higher power levels for longer periods of time. High speed modulation is critical for high-speed FSO systems. Because of its upkeep, an overall system design should have a small footprint and low power consumption. FSO systems should be able to operate in a wide range of temperatures, with less performance deterioration for outdoor systems. The system's mean time between failures (MTBF) should be more than 10 years [5].

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 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 [14].

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, an airplane, and so on [14].

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 [14].

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 [14].In this thesis paper we are working on the second classification type of FSO (OWTNs).

2.4.3 FSO Basic Architectures/Topologies

There are three basic main FSO architectures that have been used.

2.4.3.1 Point-to-Point (P2P)

This architecture is a dedicated connection that offers higher bandwidth, but is less scalable.

2.4.3.2 Mesh

This architecture offers redundancy and higher reliability with easy nodes addition, but restrict distances more than other options.

2.4.3.3 Point-to-Multipoint (P2MP)

Offers cheaper connections and facilitates node addition, but at the expense of lower bandwidth than the point-to-point option.

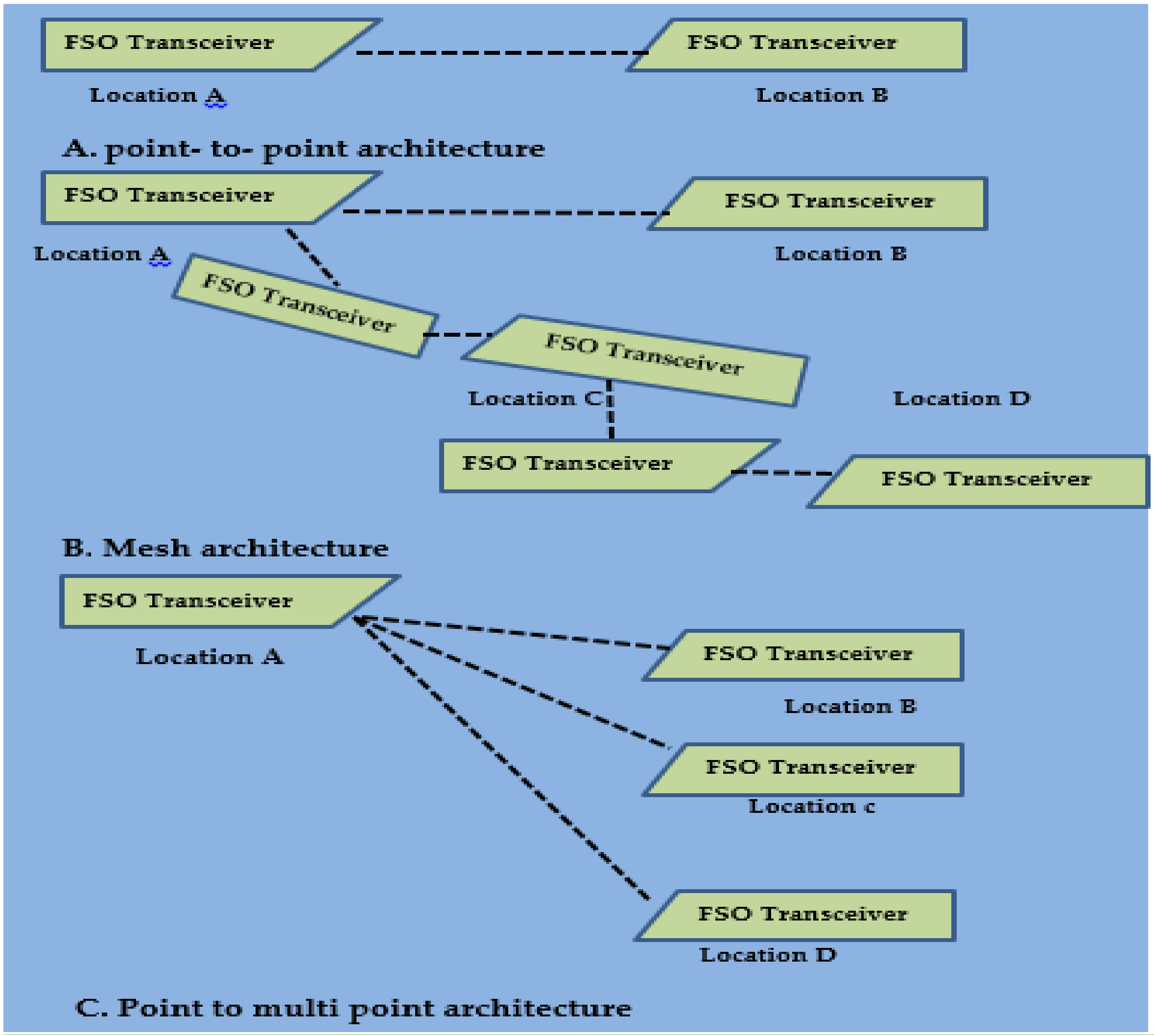

Fig 2.4: Three basic main FSO architecture [13].

Any two transceivers must have line of sight (LOS) to establish a full duplex communication link in these FSO systems, and there must be no obstructions. The FSO transceivers in a given place are connected to the electronic routers through cables, which are housed in cabinets within the building and connected to the public or private network. We chose to use P2P architecture because of its simple connectivity, low latency, high bandwidth, and ease of maintenance [13].

2.4.4 FSO Communication Scenarios

The FSO is an outdoor wireless communications technology with a potential high data rate and bandwidth per link exceeding 10 Gb/s or even 50 or 120 Gb/s per link [13]. Here we discussed different scenarios of FSO link.

2.4.4.1 Horizontal link

Some FSO nodes may be erected on tall poles, from rooftop-to-rooftop of tall buildings, or from window-to-rooftop or window-to-window. A base transceiver station, backhaul, and cell sites are examples of FSO connectivity. This horizontal network, which connects office buildings in a metro region, usually has a range of a few kilometers.

The strength of the turbulence is commonly assumed uniform for the horizontal link when determining the varying intensity of the received signal. Birds, insects, trees, branches, and other physical objects can momentarily or permanently impede the laser line-of-sight. In addition, over time, differential heating and cooling, building sway, or ground motion can cause substantial misalignment of a fixed-position FSO communication system [13].

2.4.4.2 Slant Path FSO link

When the FSO path isn't nearly horizontal and the turbulence strength isn't uniform along the propagation path, a slant path can occur.

2.4.4.3 Uplink

Ground-to-space propagation paths, such as from a ground station to a satellite, are a common example of uplink scenarios. In order to compute the fluctuations in the signal intensity received at the receiver, the altitude profile of the turbulence strength parameters must be taken into account.

2.4.4.4 Downlink

From space-to-ground is an example for a downlink FSO communication, such as a satellite-to-ground link. The altitude variation of the turbulence strength must be considered to compute the received FSO signal intensity fluctuations [13].

2.5 Application of FSO

FSO communication link is currently in use for many services at many places. Some of them are:

Outdoor Wireless Access: It can be used for communication by wireless service providers, and it does not require a license to utilize the FSO, as is the case with microwave bands [5].

Storage Area Network (SAN): FSO links can be used to form a SAN. It is a network which is known to provide access to consolidated, block level data storage [5].

Last-Mile Access: It is very expensive for service providers to lay user cables in the final mile because the cost of digging to lay fiber is so high, and it would make sense to lay as much fiber as possible. FSO can be used to remedy such a problem by integrating it with other networks in the last mile. It's a high-speed connection. It's also utilized to get around other sorts of networks' local-loop systems [6].

Enterprise Connectivity: FSO systems are easily installable. This feature makes it applicable for interconnecting LAN segments to connect two buildings or other property [15].

Fiber Backup: FSO can also be applicable in providing a backup link in case of failure of transmission through fiber link [16].

Metro-Network Extensions: It can be used to extend an existing metropolitan area's fiber rings. The FSO system takes less time to set up, and connecting additional networks and core equipment is simple. It's also useful for completing SONET rings [17].

Backhaul: It can be helpful in carrying the traffic of cellular telephone from antenna towers back to the PSTN with high speed and high data rate. The speed of transmission would increase [15].

Service Acceleration: It can also be used to provide instant service to customers when their fiber infrastructure is being deployed in the meantime [18].

Bridging WAN Access: In the WAN, FSO is useful because it supports high-speed data services for mobile users and small satellite terminals, as well as serving as a backbone for high-speed freight networks [9]. It can be used for short and long-range communication between point-to-point links, such as two buildings or two ships, and point-to-multipoint linkages, such as airplane to ground or satellite to ground [19].

Military Access: As it is a secure and undetectable system it can connect large areas safely with minimal planning and deployment time and is hence suitable for military applications [20].

Chapter 3

Comparison of FSO and FO technologies

3.1 Fiber Optic (FO)

Fiber optics, often known as Optical Fiber, is the science of carrying data, speech, and images through thin, transparent fibers. Fiber optic technology has virtually replaced copper wire in long telephone lines and is used to connect computers within local area networks in telecommunications [16]. According to analysts, this market will continue to grow at a rapid pace well into the next decade and beyond. Anyone with a vested interest in telecommunication would be well advised to learn more about fiber optic communication's numerous advantages. Fiber optics is a light-based channel for transporting data from one location to another. Fiber optics, unlike copper transmission, is not electrical in nature. A simple fiber optic system consists of a transmitter that turns an electrical signal into light, an optical fiber cable that carries the light, and a receiver that absorbs the light signal and converts it back to an electrical signal [16].

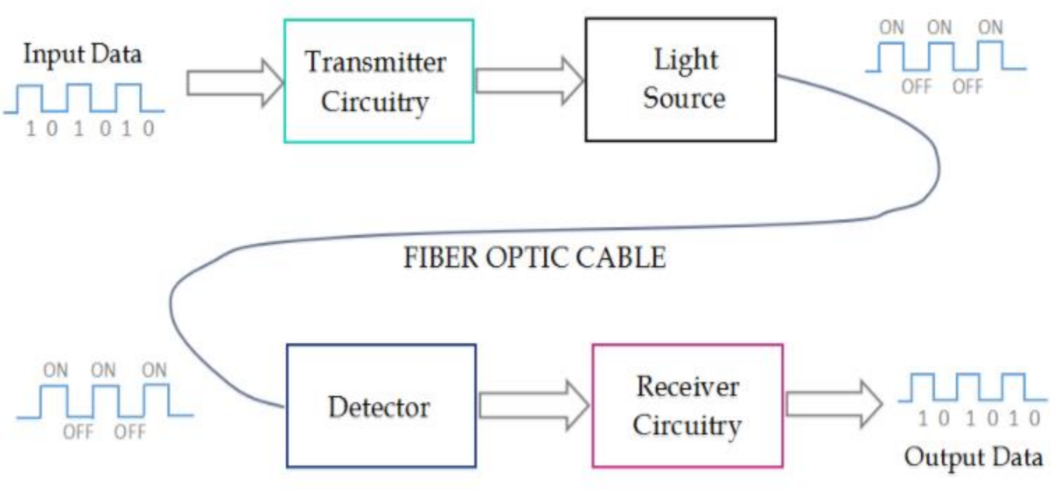

Fig 3.1: Basic Fiber Optics Transmission System [16].

Optics is a means for transmitting information in the form of light from one location to another. Fiber optics, unlike copper transmission, is not electrical in nature. A basic fiber optic system consists of a transmitter that converts an electrical signal into light, an optical fiber cable that transmits the light, and a receiver that absorbs the light signal and converts it back to an electrical signal. A fiber optic system's complexity can range from very basic (i.e., a local area network) to exceedingly complicated and costly [16].

3.1.1 Merits and Limitations of Fiber Optics

3.1.1.1 Merits

Optical fiber systems have many advantages over metallic-based communication systems. These advantages include:

Greater Bandwidth: Fiber optic cables have a higher bandwidth than copper cables of the same diameter, allowing them to transmit more data [21].

Faster Speed: Fiber optic cables have a light-carrying core that allows data to be transmitted. Fiber optic lines can now deliver signals at speeds that are only roughly 31% slower than the speed of light, compared to Cat5 or Cat6 copper cables. Fiber cables also provide reduced signal degradation [22].

Longer Distances: Fiber optic connections can transport signals far further than copper wires, which are limited to 328 feet. Some 10 Gbps single mode fiber lines, for example, can transmit signals nearly 25 kilometres. The exact distance is determined by the cable type, wavelength, and network [23].

Better Reliability: Temperature variations, extreme weather, and moisture do not affect the connectivity of fiber, which can be a problem with copper cable. Furthermore, because fiber does not transport electric current, it is immune to electromagnetic interference (EMI), which can disrupt data transmission. It also doesn't catch fire as easily as old or worn copper cables do [10].

Thinner and Sturdier: Compared to copper cables, fiber optic cables are thinner and lighter in weight. Fiber can withstand more pull pressure than copper and is less prone to damage and breakage [23].

More Flexibility for the Future: Fiber can be integrated onto existing networks using media converters. UTP Ethernet connections are extended over fiber optic cable using the converters. Modular patch panel solutions combine equipment with speeds of 10 Gb, 40 Gb, and 100/120 Gb to suit present needs while also allowing for future growth. These solutions have panels that can hold a number of cassettes for different types of fiber patch cables [12].

Lower Total Cost of Ownership: Although certain fiber optic cables are more expensive than copper at first, the longevity and reliability of fiber can reduce the total cost of ownership (TCO).

Fiber optic cables and related components are also becoming less expensive as technology progresses [24].

3.1.1.2 Limitations

Though fiber optic transmission brings lots of convenience, its disadvantages also cannot be ignored.

Fragility: Optical fiber cables are typically composed of glass, making them more brittle than electrical wires. Furthermore, glass can be harmed by a variety of substances, including hydrogen gas (a issue with underwater cables), necessitating extra caution when used beneath [21].

Difficult to Install: Splicing fiber optic cable is a difficult task. They will break if you bend them too much. Moreover, fiber cable is extremely vulnerable to being cut or damaged during installation or construction. All of this makes installation tough. Dispersion and attenuation Light will attenuate and spread as transmission distances increase, necessitating the addition of additional optical components such as an EDFA (Erbium Dopped Fiber Amplifier) [16].

The Cost of fiber is higher than Free Space Optics: Despite the fact that fiber optic installation costs are reducing by as much as 60% each year, fiber optic cabling installation expenses are still higher than FSO installation costs. Because unlike fiber lines, FSO installation does not necessitate digging. Optical fiber is still making its way into the local loop, providing subscriber and end-user broadband access through technologies like FTTx (fiber to the home, premises, etc.) and PONs (passive optical networks) [16].

3.2 Free Space Optics (FSO)

For data communication, it uses a line of sight optical beam. It's essentially a hybrid of wireless and optical technology. The invisible beam of light at the heart of technology provides optical bandwidth for transmission of data such as voice, information, and video. Optical communication is an old technique that was employed for signal communication in the past, but at very low data speeds. Laser technology has improved the utilization of free space optics to the point where it is now completely reliant on it. NASA created FSO in its original version, which was employed for military purposes in many areas as a quick communication link. Although the technology has many similarities to fiber optics, it acts differently in the field due to the transmission mechanism used by both technologies [25].

3.2.1 Merits and limitations of FSO

3.2.1.1 Merits

- Free space optics is a flexible network that delivers better speed than broadband.
- Installation is very easy and it takes less than 30 minutes to install at normal locations
- It has very low initial investment.
- It is a straight forward deployment system. There is no need for spectrum license or frequency coordination between users as it is required in radio and microwave systems.
- It is a secure system because of line of sight operation and so no security system upgradation is needed.
- High data rate can be obtained which is comparable to the optical fiber cable's data rate and the extremely narrow laser beam enables having unlimited number of FSO links which can be installed in a specific area.
- Electromagnetic and radio-magnetic interference cannot affect the transmission in FSO link.
- FSO offers dense spatial reuse.
- Low power usage per transmitted bit is merit of FSO system.
- There is relatively high bandwidth.
- Transmission of optical beam is done in air. Hence, transmission is having speed of light [5].

3.2.1.2 Limitations

The benefits of free space optics are numerous. However, because FSO uses air as its transmission medium and the light passes through it, some environmental issues are inherent. The troposphere is where the majority of the atmospheric phenomena happened [26].

Physical obstructions: Flying birds, trees, and tall buildings can temporarily block a single beam, when it appears in line of sight (LOS) of transmission of FSO system [1].

Scintillation: There would be temperature variations among different air packets due to the heat rising from the earth and the man-made drives like heating ducts. These temperature variations can cause fluctuations in amplitude of the signal which causes "image dancing" at the FSO receiving end. The effect of scintillation is addressed by Light Pointe's unique multi beam system [11].

Geometric losses: Geometric losses, also known as optical beam attenuation, are caused by the spreading of the beam, which reduces the signal's power level as it travels from the transmitter to the receiver [23].

Absorption: The water molecules floating in the terrestrial atmosphere are responsible for absorption. These particles would absorb the photon's energy. Absorption reduces the optical beam's power density, and therefore has a direct impact on the availability of transmission in an FSO system. Signal absorption can also be caused by carbon dioxide [26].

Atmospheric turbulence: Weather and the structure of the surroundings cause atmospheric disturbance. It's caused by wind and convection, which mix air particles of various temperatures together. This generates changes in air density, which results in a change in the refractive index of the air [26].

Atmospheric attenuation: Fog and haze are the usual causes of atmospheric attenuation. Dust and rain play a role as well. Atmospheric attenuation is thought to be wavelength dependent, although this is not the case. In hazy weather, attenuation at 1550 nm is lower than at other wavelengths. In a fog weather state, attenuation is wavelength independent [17].

Scattering: When an optical beam and scattered light collide, a scattering effect occurs. It's a wavelength-dependent phenomena in which the energy of an optical beam remains constant. However, only directional redistribution of optical energy occurs, resulting in a decline in beam intensity across longer distances [5].

3.3 Free Space Optics Vs Fiber Optics

End customers' most basic necessity in today's society is reliable and cost-effective communication. A fiber optics-based transmission medium is used as a backbone in the communication system that has previously been deployed [25]. In contrast to the FO connection, free-space optical technology (FSO) uses light travelling in free space to transmit data between two sites. Free Space Optics employs an energy beam that travels through free space, while Fiber Optics uses an energy beam that travels through an optical cable. Pulse-code modulation is used in fiber-optic telecommunication systems, whereas intensity modulation is used in FSO systems, and the power consumption of FO links is lower than that of FSO links [25].

Chapter 4

End to end System Model

4.1 End to end system block diagram

FSO design has been developed for performance characterization using computer modeling. In this thesis paper we used Optisystem 15 for the simulation purpose [27].

4.1.1 Opti System

OptiSystem is an innovative optical communication system simulation package for design, testing, and optimization of virtually any type of optical link in the physical layer of a broad spectrum of optical networks [24].The system model has three sub system Transmitter, FSO channel/FO channel and receiver as shown in the **Fig4.1 and Fig 4.2**

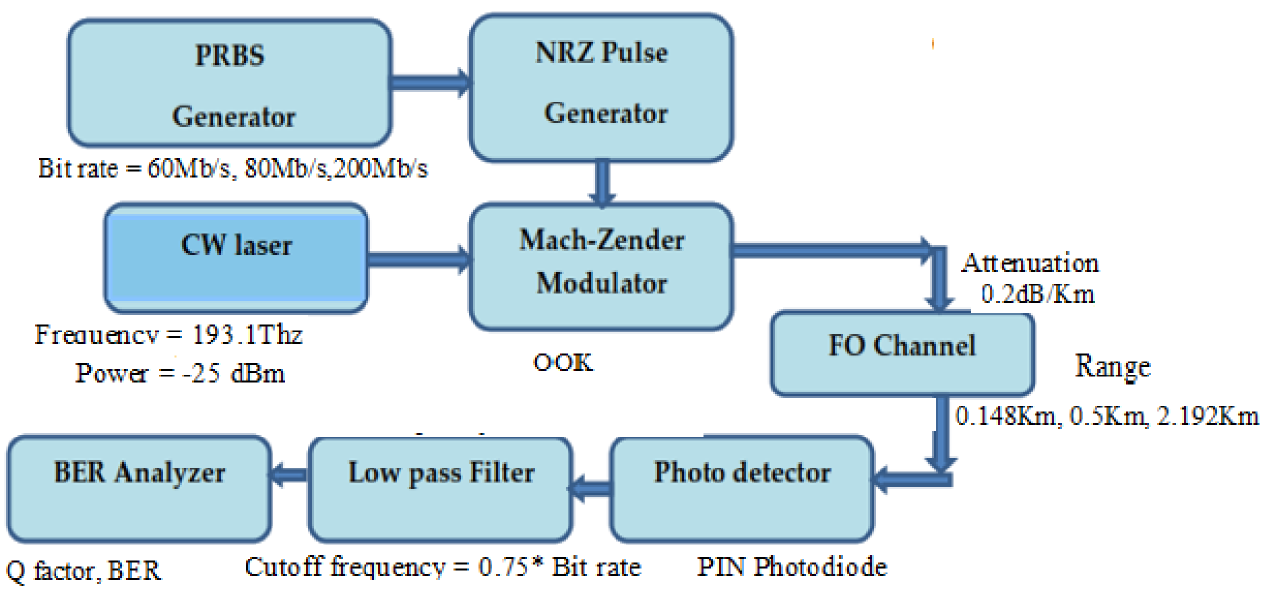

Fig 4.1: Block diagram of T_X /R_X FO system [21].

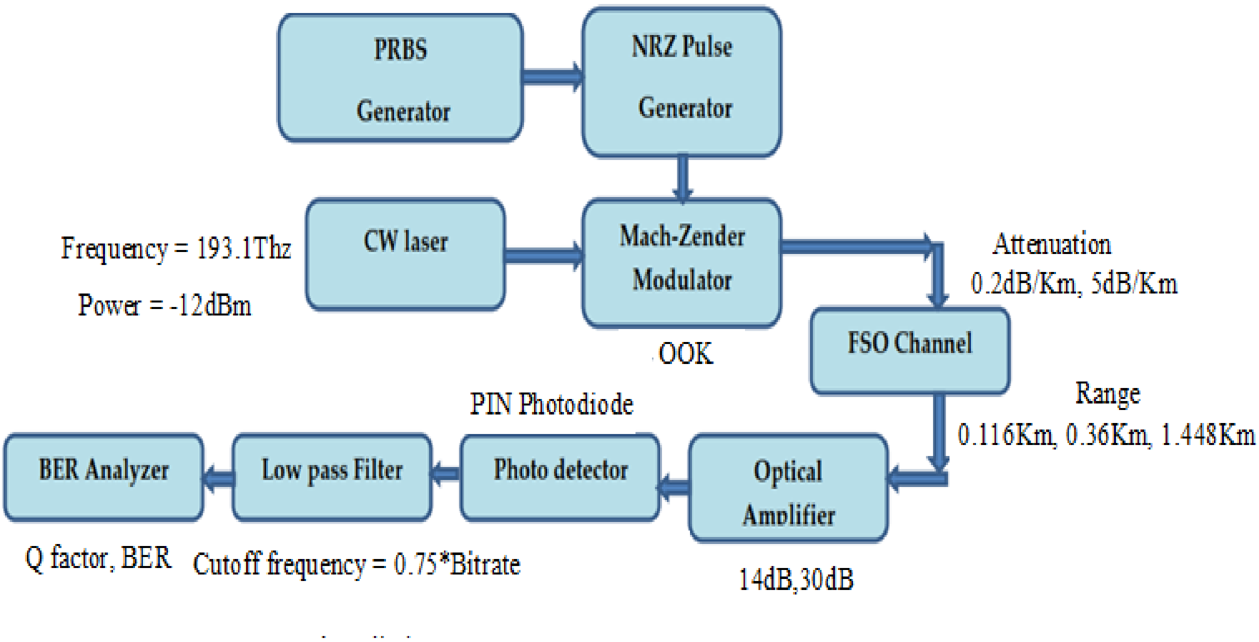

Fig 4.2: Block diagram of T_X /R_X FSO system [21].

Here in FSO system design we should increase the input power of CW (Continuous wave) laser from -25dBm to -12dBm in order to get a signal at the receiver side.

4.1.2 Sub System of FSO Model

From Transmitter side we have PRBS(Pseudo random bit sequence) generator, CW laser, NRZ(Non return to zero)pulse generator, Mach-Zhender modulator FSO channel is present which comprises of a link range, Attenuation factor, Tx and Rx aperture diameter and beam divergence On the receiver side we got, photodetector, low pass filter, Optical amplifier and BER analyzer.

4.1.3 Sub System of FO Model

From Transmitter side we have PRBS generator, CW laser, NRZ pulse generator, Mach-Zender modulator, Fiber optics channel contrast to wire transmission, in which an electric current flows through a copper conductor, in optical fiber transmission an electromagnetic (Optical) field propagates through a fiber made of a non-conducting dielectric. On the receiver side we got photodetector, low pass filter and BER analyzer.

4.2 System Model Considerations

There are some parameters which affect the performance of system and need to be considered while designing the system. Some are discussed below [26].

4.2.1 Modulation Techniques

Modulation technique is used according to the best usage of FSO channel capacity. Commonly used modulation schemes are on off keying (OOK), Pulse Position Modulation (PPM), Pulse Width Modulation (PWM), Differential Phase Shift Keying (DPSK) and Quadrature Amplitude Modulation (QAM) [28]. In conventional FSO, OOK is used for Intensity Modulation (IM). Modulated data representation is done by presence (on) of light and absence (off) of light. OOK is simple to implement but it has the poor energy efficiency. Further PPM was investigated for good energy efficiency, but it lacks in bandwidth efficiency. PPM and PWM are usually known as synchronous modulations as they map the input bit on a symbol of fixed duration. Various phase, frequency and amplitude modulations i.e. Phase Shift Keying (PSK), Frequency Shift Keying (FSK), Amplitude Shift Keying (ASK), Quadrature Shift Keying (QPSK), DPSK can be used for better capacity. DPSK mitigate the scintillation effect and doubles the spectral efficiency [28]. QAM is the latest proposed scheme in FSO. It is very effective for generating high data rates and also resistant to fading.

Table 4.1 List of Modulation Scheme [28].

Modulation technique	Remark
OOK	Simple but low power efficiency
PPM	Power efficiency is better than OOK but poor bandwidth efficiency
PWM	Resistant to ISI than PPM
DPSK	High energy efficiency
QAM	Resistant to fading

4.2.2 Photo detectors

Photo detectors are used to detect the intensity of light and convert the optical power to electrical. Avalanche Photo Diode (APD) and P-i-N (PIN) diode are the two types of photo detectors are used. PIN is used for the low range and APD is used for high range communication. PIN is less expensive but it has limited receiver performance. On the other side APD has high current gain due to the phenomenon of impact ionization. Drawback with the APD is that it generates the excess noise in the output. Study involves the use of PIN photo detectors according to the requirement of our design [26].

4.2.3 Transmission Windows

Optical transmissions uses wavelengths that are in the near-infrared portion of the spectrum, just above the visible, and thus undetectable to the unaided eye. Typical optical transmission wavelengths are 850 nm, 1310 nm, and 1550 nm. Both lasers and LEDs are used to transmit light through free space optics. Lasers are usually used for 1310-nm or 1550-nm and LEDs are used for 850-nm or 1300-nm [17].

The two commonly used windows are 850 nm and 1550nm. 850 nm is highly reliable PIN photo detector, inexpensive transmitter and receiver components can be used for the operation in this window. 1550 nm window is well suited because of its low attenuation. Use of high speed laser technology and amplifiers to boost transmission power is done in this window. There are ranges of wavelengths at which the FSO operates best. Each range is known as an operating window. Each window is centered on the typical operational wavelength, as shown in Table 4.2.

Table 4.2 Optical Transmission Window [16].

Window	Operating wavelength
800 -900nm	850nm
1250- 1350nm	1310nm
1500-1600nm	1550nm

4.2.4 Aperture Size

Aperture size (diameter) of a lens is used in transmitter and receiver affect the transmission of laser beam. As we increase the aperture size, optical power also increases and helps in reduction of fading. Aperture size of receiver lens helps in calculating the geometric losses as a result of divergence of beam [26].

4.2.5 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 [1].

4.2.6. Eye Safety

Laser sources beyond a certain power threshold are harmful to the human body, in particular, the eyes. Thus,it is important to enforce a limitation on laser-emission power in optical wireless networks. Laser safety standards have been established, such as ANSI Z136.1 and IEC 60825-1. According to IEC 60825-1, the objective is to protect the human body from excessive laser radiation with wavelength ranging from 180 nm to 1 mm, by classifying lasers and laser products based on their degree of hazard. The optical beams in Class 1 and Class 2 (400-700nm) are considered completely safe except when direct and lengthy exposure is involved. Class 3 beams achieve a good power budget, but are not recommended to come in contact with the human body [14].

4.3 Mathematical Model Components

4.3.1 PRBS generator

PRBS refers to an algorithm that uses mathematical formulas to produce sequences of random numbers. It generate a sequence of numbers approximating the properties of random data.
This model generates a sequence of N bits [29].

Where $N = T_w B_r$……………………………………………………………………… (4.1)

$N_G = N - n_l - n_t$……………………………………………………………………………(4.2)

N = Number of sequence of bits

T_w=is the global Time window and B_r is the parameter Bit rate.

The number of bits generated is N_G, n_l and n_t are the number of leading zeros and the number of trailing zeros.

Operation mode controls the algorithm used to generate the bit sequence:

Probability: Random number generator is used, with parameter Mark probability specifying the probability of ones in the sequence

Alternate: Alternate sequence of ones and zeros is generated

Ones: A sequence of ones is generated

Zeros: A sequence of zeros is generated

Order: PRBS generator with Order k is used to generate a sequence with period of 2^K-1[1].

Time window = $S.L * 1/\text{Bitrate}$ …………………………………………………………….(4.3)

Number of S = $S.L * S_a/\text{bit}$ ………………………………………………………….……......(4.4)

$S.r = \text{Number of } S_a/T_w$……………………………………………………………………..(4.5)

Where $S.L$ = sequence length

S_a = number of samples

T_w = time window

$S.r$ = sample rate

- In this particular case, we indirectly define the simulation time window, the number of samples, and the sample rate using three parameters:
    - ✓ Bit rate
    - ✓ Bit sequence length

- ✓ Number of samples per bit

4.3.2 NRZ (Non-return-to-zero)

Refers to a form of digital data transmission in which the binary low and high states, represented by numerals 0 and 1, are transmitted by specific and constant DC (direct-current) voltages. NRZ modulation format is selected because of it's simplicity ,superiority and more distance coverage compared to RZ(Return to zero) modulation format[29].

4.3.3 CW Laser

A continuous wave laser that emits continuous laser beam with controlled heat output as beam durations and intensity. Operating frequency of 1550nm is selected due to it's low attenuation as well as the proliferation of high quality transmitter and detector components. In the CW case, the average output Power is a parameter that we specify. We choose CW laser over it's advantage on Quaci continuous wave laser and pulsed laser in terms of high power, small size, cost efficiency and availability. The Gaussian noise is modeled using the probability density function [7].

$$f(x) = \frac{1}{\sqrt{2\pi\delta_{x^2}}} * e^{-1/2\left(\frac{x-\mu}{\delta}\right)^2} \quad \ldots\ldots(4.6)$$

Where $f(x) =$ Probability density function

μ = mean

δ = Standard deviation [29].

4.3.4 MZM

Simulates a Mach-Zehnder modulator using an analytical model. The Mach-Zehnder modulator is an intensity modulator based on an interferometric principle. It consists of two 3 dB couplers which are connected by two waveguides of equal length. By means of an electro-optic effect, an externally applied voltage can be used to vary the refractive indices in the waveguide branches.

The different paths can lead to constructive and destructive interference at the output, depending on the applied voltage. Then the output intensity can be modulated according to the voltage.The equations that describe the behavior of the MZ modulator are [29].

$E_{out}(t) = E_{in}(t) \cdot \cos\big(\Delta\theta(t)\big) \cdot \exp(j \cdot \Delta\phi(t))$..(4.7)

Where Δθthe phase is difference between the two branches and is defined as:

$\Delta\theta(t) = {}^{\pi}/_{2}\,(0.5 - ER \cdot (M(t) - 0.5)$..(4.8)

With,

$ER = 1 - \frac{4}{\pi}\pi \cdot \arctan(\frac{1}{\sqrt{extract}})$..(4.9)

And

$\Delta\phi$ is the signal phase change defined as:

$\Delta\phi(t) = Sc.\,\Delta\theta(t).\,(1 + SF)/(1 - SF)$ ....(4.10)

Where the parameter SC is –1 if negative signal chirp is true, or 1 if negative signal chirp is false. Extract is the extinction ratio, SF is the symmetry factor, and modulation (t) is the electrical input signal. The electrical input signal is normalized between 0 and 1.We prefer to use MZM modulator because it minimize effect of dispersion and fast switching for high speed optical communication [29].

4.3.5 FSO Channel

It is a subsystem of two telescopes and the free space channel between them. It is best suited for the modeling of line of sight free space terrestrial links. This component allows for simulation of free space optical links. The component is a subsystem of transmitter telescope, free space and receiver telescope. Parameter range defines the propagation distance between transmitter and receiver telescope. The attenuation of the laser power depends on two main parameters: Attenuation and Geometrical loss. The first parameter describes the attenuation of the laser power in the atmosphere. The second parameter, Geometrical loss, occurs due to the spreading of the transmitted beam between the transmitter and the receiver [29]. The received power is given by:

$P_R = P_T(d_R^2/(d_T + \theta R)^2 10^{-\alpha R/10})$..(4.11)

P_R Received power (dBm)

P_T Transmitted power (dBm)

d_R Received aperture diameter (m)

d_T Transmitter aperture diameter (m)

α Atmospheric attenuation (dB/km)

θ Beam divergence (mrad)

R Range(km)

The directivity of Antenna is closely related to its gain. Antenna gain is given in the equation below.

Gain (optical) = $4\pi/\theta^2_{div}$(optical)…………………………………………………….......(4.12)

Where θ^2_{div} (optical) are the optical beam divergences are proportional to λ/D_R. Since the optical wavelength is very small, a very high directivity and improved gain are obtained. Where λ is the carrier wavelength and D_R the aperture diameter [11].

4.3.6 PIN Diode

Is a kind of photo detector, it can convert optical signals into electrical signals. There is a p-region an intrinsic region and an n-region. The p-region and n-region are comparatively heavily doped than the p-region and n-region of usual p-n diodes. The width of the intrinsic region should be larger than the space charge width of a normal p-n junction. High frequency response, being inexpensive, response time in nanosecond,good performance, small in size and low cost are the advantages of using PIN photodetector over other photodetectors like PN and Avalance photodetectors[28].

4.3.7 Low Pass Bessel Filter

The Bessel channel is low pass Bessel filter with cutoff frequency= 0.75*Bit rate and order equals to 4.on a very basic level equivalent to the Gaussian channel, and tends towards indistinct shape from channel organize increments.

While the time-space step response of the Gaussian channel has zero overshoot the Bessel channel has a little proportion of overshoot, yet in the meantime considerably not exactly essential recurrence territory channels. Diverged from restricted solicitation approximations of the Gaussian channel, the Bessel channel has better moulding element, compliment stage delay, and compliment bunch delay than a Gaussian of a comparative solicitation, anyway the Gaussian has cut down time deferral and zero overshoot. Basic typical for a Bessel channel is its maximally level get- together postponement, and not the adequacy response, it isn't right to use the bilinear change to change over the simple Bessel channel into an electronic shape. Bessel filter has better shaping factor, flatter phase delay.

Contrasted with constrained solicitation approximations of the Gaussian channel, the Bessel channel has better moulding variable, compliment stage delay, and compliment bunch delay than a Gaussian of a comparative solicitation [29].

4.3.8 BER analyzer

Used to observe minimum BER, Q factor, Eye diagram of the model.

4.3.8.1 BER (bit error rate)

Bit error rate equation show schematic of the fluctuating signal received by the decision circuit, these samples took at the decision instant to determine bit error through clock. The sampled value I fluctuates from bit to bit around an average value I 1 or 0 depending on whether the bit corresponds to 1 or 0 in the bit stream.

The decision circuit compares the sampled value with a threshold value ID and calls it bit 1 if I>ID or bit 0 if I<ID. Mistakes happen if I<ID for bit 1 because of receiver fuss. An error also Occurs if I>ID for bit 0. Both sources of errors can be included by defining the error probability as [24].

$\mathrm{BER} = \mathrm{P}(1)\mathrm{P}(0/1) + \mathrm{P}(0)\mathrm{P}(1/0) = \frac{1}{2}[\mathrm{P}(0/1) + (1/0)]$……………….………………(4.13)

$\mathrm{P}(0/1)$=condition probability of deciding 0 when 1 is sent, since

P(1)= P(0)=½, $\mathrm{BER} = \frac{1}{2}[\mathrm{P}(0/1) + (1/0)]$………………………..…….…………….....(4.14)

Common to assume Gaussian static for the current

$\mathrm{P}(0/1)$= Area below the decision level ID

$\mathrm{P}(1/1) = \frac{1}{\sqrt{2\pi\delta 0}}\int \mathrm{e}^{-(\mathrm{I}-\mathrm{I1})2/2\delta^2}\,\mathrm{dI} = 1/2\mathrm{erfc}\,((\mathrm{I1}) - \mathrm{ID})/\delta_1\sqrt{2}$……………………….....(4.15)

$\mathrm{P}\,(0/1) = \frac{1}{\sqrt{2\pi\delta 0}}\int \mathrm{e}^{-(\mathrm{I}-\mathrm{I0})2/2\delta^2} = 1/2\mathrm{erfc}((\mathrm{ID}) - \mathrm{I0})/\delta_1\sqrt{2}$……………………..……...(4.16)

4.3.8.2 Q factor

Where Q is quality factor can be written as [30].

$Q = \frac{\mathrm{I}_0 + \mathrm{I}_1}{\delta_0 + \delta_1}$………………………………………………………………….….(4.17)

And the equations that describe the behavior of it are:

Where δ_1^2 and δ_0^2 are respectively appropriate noise variance for the symbol 1 and 0, I_0 is sampled value of 0 ,I_1 is sampled value of 0. In practical the transmission quality achieved for values of Q >5.4

The equation for BER and Q factor are given by [24].

$$\mathrm{BER} = 1/2\ \mathrm{erfc}\ (Q/\sqrt{2}) \approx 1/\sqrt{2}Q\ \exp(-Q^2/2) \quad (4.18)$$

$$Q(\mathrm{dB}) = 10\log_{10} Q^2 \quad (4.19)$$

Where,

Q = Quality factor

Erfc = Error function

4.4 FSO Channel modeling

In FSO channel modeling we consider the receiver signal power, link margin, and data rate.

4.4.1. Link margin

Which is the ratio of available received power to the receiver power required to achieve a specified BER at a given data rate. Note that the "required" power at the receiver P_R(watts) to achieve a given data rate, R (bits/sec), we can define the link margin [31]. It can be calculated by observing received signal power at the receiver side [4]. It is an important factor to be observed that can affect the quality of an FSO link. Mathematical expression for link margin (LM) is given as [26].

$$\mathrm{LM} = 10\ \log P_R/S \quad (4.20)$$

In the above equation, P_R is a received signal power and S is receiver sensitivity. At receiver side, for signal to be detected its power should be greater than receiver sensitivity. Receiver sensitivity is a constant value in dBm given by manufacturer and ranging from -20 to -40dBm. So, received signal power must be evaluated for quality check of an FSO link [26].

4.4.2 Receiver Signal Power

Consider a laser transmitting a total power P_T at the wavelength 1550nm .the signal power received at the communications detector can be expressed as [31].

$$P_{rec} = P_{trans} D^2/\theta_{div}^2 L^2 \cdot 10^{-\gamma L/10} \tau_{trans} \tau_{rec} \quad (4.21)$$

Where D is the receiver diameter, θ is the divergence angle, γ is the attenuation factor (dB/m), $\tau_{trans}\tau_{rec}$ are the transmitter and receiver optical efficiency respectively [26].

4.4.3 Data Rate

Given a laser transmitter power P_{trans}, with transmitter divergence of θ, receiver diameter D, transmit and receive optical efficiency τ_{trans}, τ_{rec} the achievable data rate R can be obtained from [29].

$R = P_T \cdot \tau_{trans}\tau_{rec} \cdot 10^{-\gamma L/10} D^2/\pi(\theta/2)^2 L^2 E_p N_b$……………..…………………………......(4.22)

Where N_b is the receiver sensitivity measured by (photon/bits) or (dBm), $E_p = h_c/\lambda$ is the photon energy at wave length, where h_c is Planck's constant.

4.4.4 Geometric Attenuation

Practical performance of FSO system is also limited by geometric losses. These losses occur when the light beam spreads to a size larger than the receiver's aperture. Geometric loss is expressed by a ratio of the receiver's aperture diameter D_R and irradiated beam diameterD_T. This ratio can be determined by the formula [17].

$A_{geo} = [d_{Rx}/(d_{Tx}+\theta_{1})]^2$ …………………………………………..…….……….…...(4.23)

4.4.5 Atmospheric Attenuation

The following Beer's Law equation describes the atmospheric attenuation [24].

$\tau(R) = -P(R)/P(0) = e^{\wedge}(-(B)R)$……………………………………………...…….(4.24)

$\tau(R)$= transmittance at distance R

P(R)= laser power at R

P(0) = laser power at the source

β= attenuation or total extinction coefficient (per unit length)

4.4.6 Rain Attenuation

Rain is one of the factor for inducing attenuation in a FSO system. Rain has less impact than fog because wavelength of optical signal is very small as compared to rain drop [32]. The attenuation of optical signal due to rain is by scattering phenomenon. Specific optical attenuation increases linearly with increase in rain rate. Rainy season in A.A (Addis ababa)starts at the beginning of June and remains till the end of September with average rain intensity of 13mm/hr [3].

Rain attenuation (R_a)=1.076*R_3^2……………………………………………………..……….(4.25)

Where R is rain intensity.

Chapter 5

Simulation results and discussions

5.1 Simulation Results

In order to achieve the goal of this thesis paper, the system model shown in figure 5.1 and Fig 5.2 help us to evaluate comparative performance evaluation of FSO as a back up link for fiber optics by using the detection of BER analyzer Max Q factor, Min Bit error rate ,Eye diagram .We also use 2D graph reading to show the relation between Q factor vs power, Q factor vs range and 3D graph for relation between BER, range and data rate.

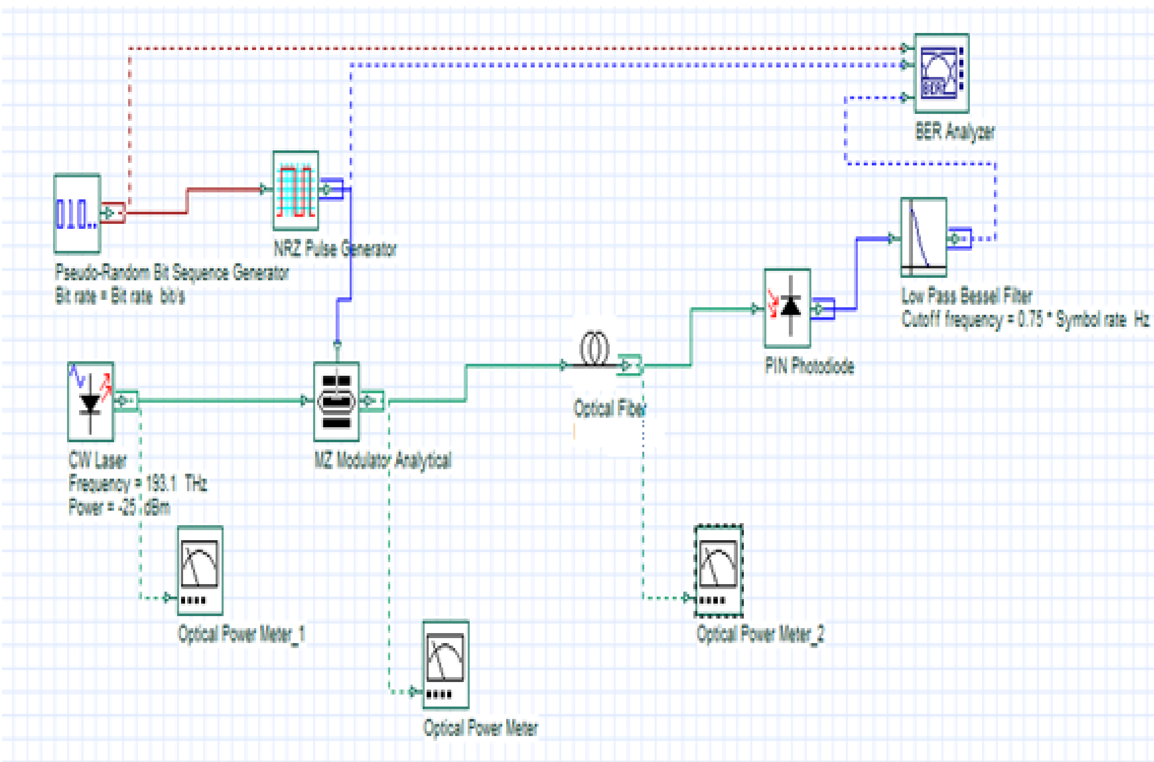

Fig 5.1: Simulation Model of Fiber Optics

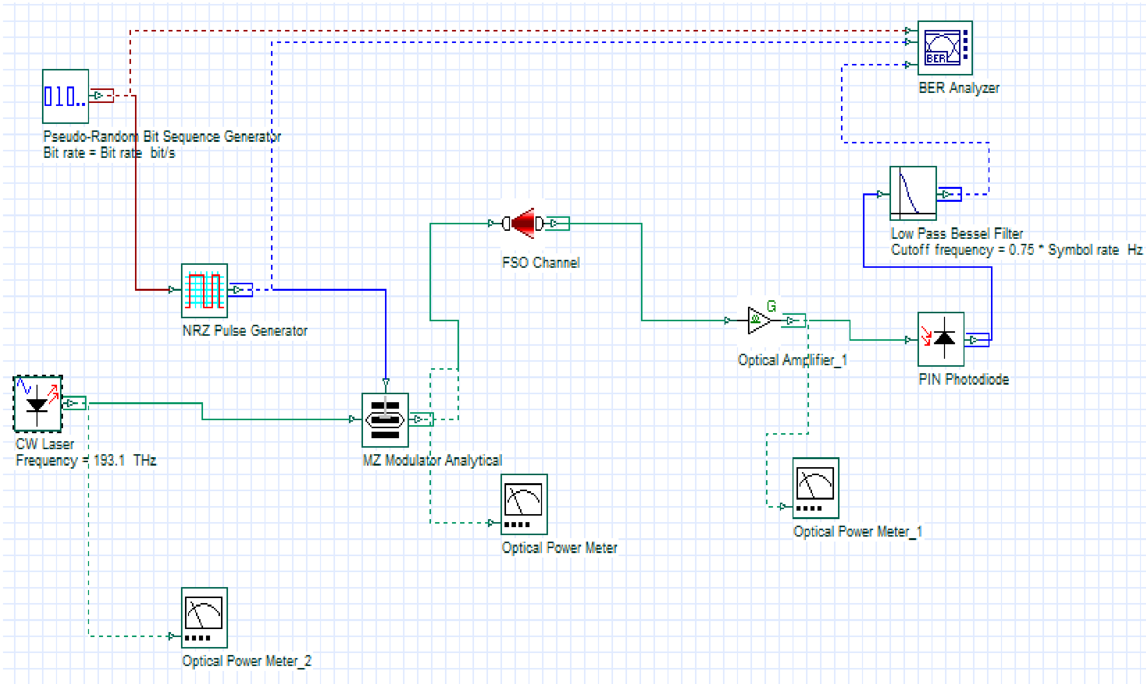

Fig 5.2: Simulation Model of Free Space Optics

Table 5.1 Simulation Parameters

Data Rate	80Mb/s,60Mb/s,200Mb/s
Input power	-25dBm,-12dBm
Reference wavelength	1550nm
Modulator	MZM
Transmitter Aperture diameter	5cm
Receiver Aperture diameter	20cm
Beam divergence	2mrad
Optical detector	PIN
Pulse generator	NRZ
Range	0.148km,0.5km,2.192km (FO) 0.116km,0.36km,1.448km (FSO)

Below we will see and discuss the simulation results which is an eye diagram reading of FO and FSO designs for six different ranges and three different data rate requirement applying input power of -25dBm in FO link and -12dBm in FSO link.

5.1.1 Eye diagram for FO channel

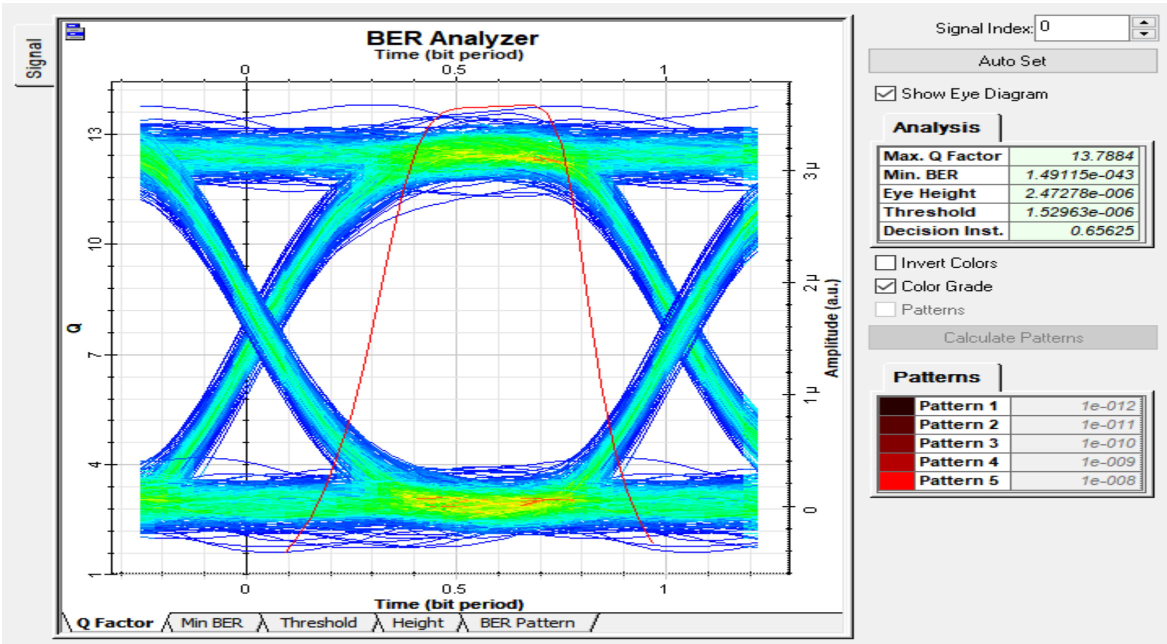

Fig 5.3: Eye diagram for 80Mb/s data rate at a distance of 0.148Km and attenuation 0.2dB/km

(P_{in} = -25dBm)

Here from the right side of the table we can read Max Q factor of 13.78 is achievable at Min BER of 1.49e-043.And we have widest an open eye.

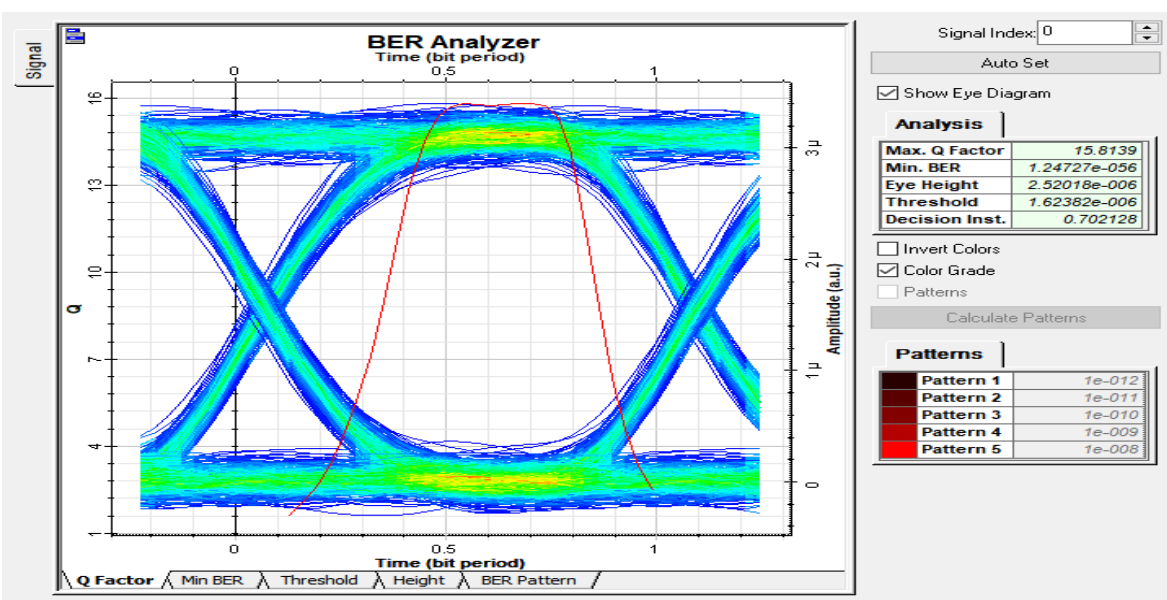

Fig 5.4: Eye diagram for 60Mb/s data rate at a distance of 0.5Km and attenuation 0.2dB/km

(P_{in}= -25dBm)

The value of Max Q factor 15.81 achieved due to reduced requirement of data rate of 60Mb/s the increment of Q factor shows better reduction of BER which is 1.24e-56.

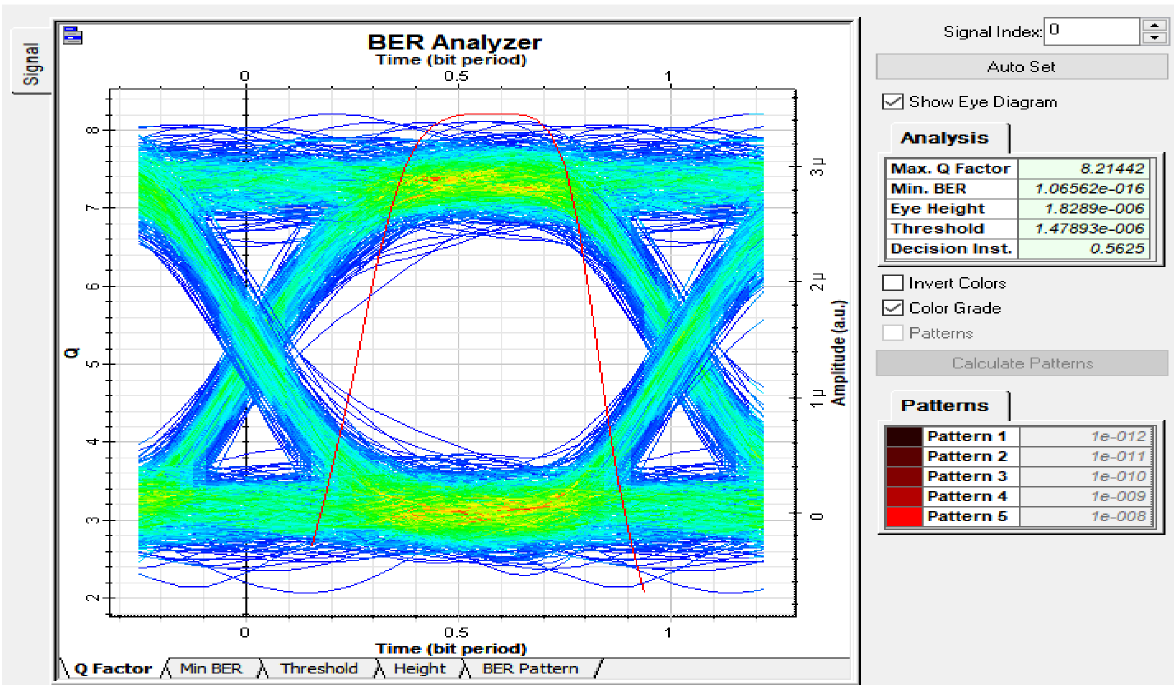

Fig 5.5: Eye diagram for 200Mb/s data rate at a distance of 2.192 Km and attenuation 0.2dB/km (P_{in} = -25dBm)

The desired data rate 200 Mb/s at a distance of 2.192 km with a constant input power caused a reduction of Max Q factor to 8.21 this shows the inverse relationship of Q factor & distance and direct relationship of & BER(1.07e-16).

Table 5.2 Detection of BER analyzer for FO link (Attenuation of 0.2dB/km)

BER Analyzer Reading	0.148km 80Mb/s	0.5km 60Mb/s	2.192km 200 Mb/s
Max Q factor	13.75	15.81	8.21
Min BER	1.49e-043	1.24e-056	1.06e-016
P_{in}	-25dBm	-25dBm	-25dBm
P_{out}	-28.36dBm	-28.26Bm	-28.68dBm

5.1.2 Eye diagram of FSO channel

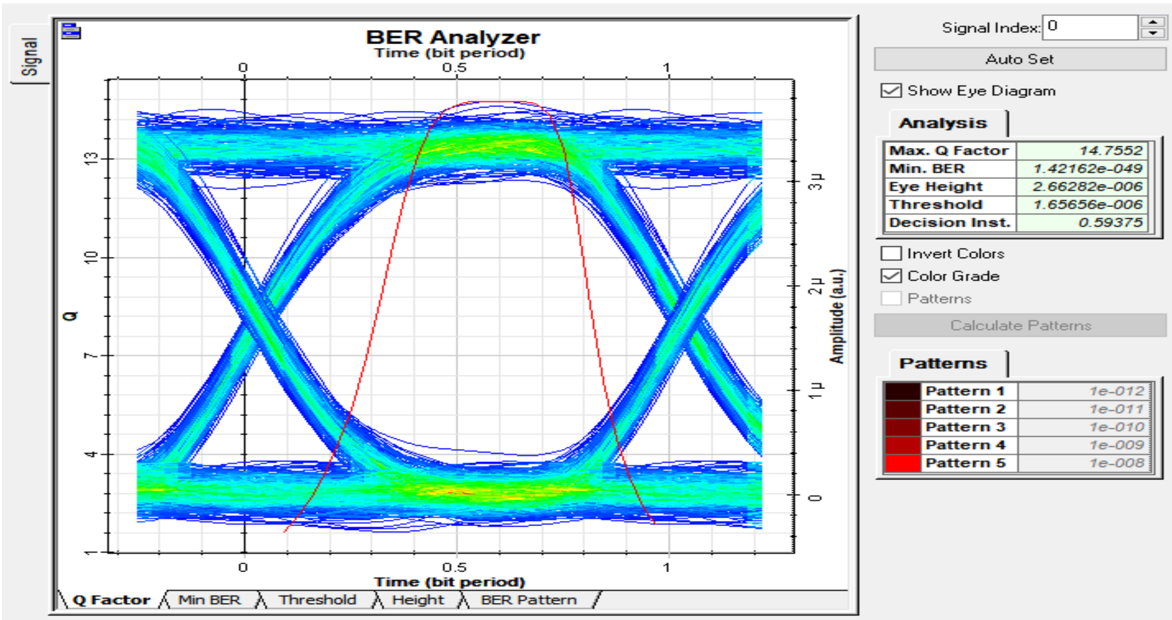

Fig 5.6: Eye diagram for 80Mb/s data rate at a distance of 0.116Km and attenuation 0.2dB/km

(P_{in} = -12dBm)

Here in FSO design Max Q factor 14.75 and BER value of 1.42e-49 is attained at cost of increasing an input power from -25dBm to -12dBm.

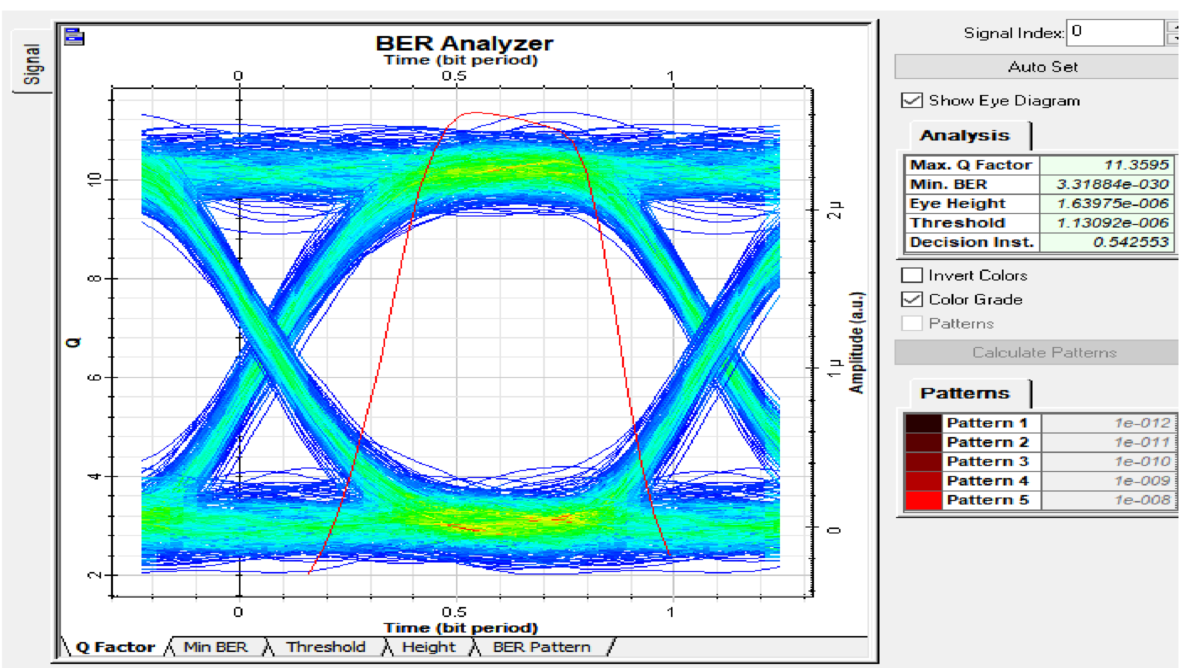

Fig 5.7: Eye diagram for 60Mb/s data rate at a distance of 0.36Km and attenuation 0.2dB/km

(P_{in}= -12dBm)

In this eye diagram we can read that the increment of distance cause the reduction of Q factor from 14.75 to 11.35 and increment of BER from 1.42e-49 to 3.31e-30. This acceptable value of Q factor is possible at the cost of increasing input power from -25 dBm to -12dBm.

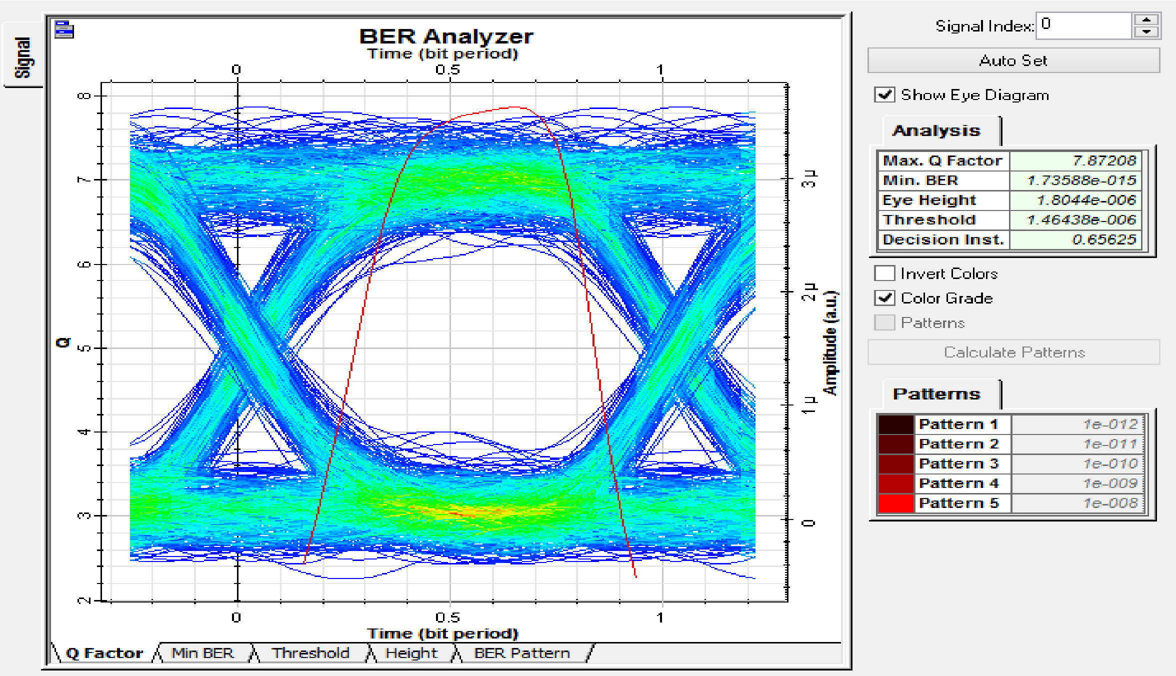

Fig 5.8: Eye diagram for 200Mb/s data rate at a distance of 1.448 Km and attenuation 0.2dB/km (P_{in} = -12dBm) using Op Amp (14dB)

The highest the data rate requirement at the longest distance couldn't be applicable without usage of optical amplifier even if we use the amplifier and the highest input power this is an eye diagram reading that we get the lowest Max Q factor and highest BER. This indicate that the performance of FSO design highly affected if both distance and data rate shows an increment.

Table 5.3 Detection of BER analyzer for FSO link (Attenuation of 0.2dB/km)

BER analyzer Reading	0.116km 80 Mb/s	0.36km 60 Mb/s	1.448km 200 Mb/s using Op amp (14dB)
Mac Q factor	14.75	11.35	7.87
Min BER	1.42e-049	3.32e-030	1.74e-015
P_{in}	-12 dBm	-12dBm	-12dBm
P_{out}	-28.04dBm	-29.78Bm	-39dBm

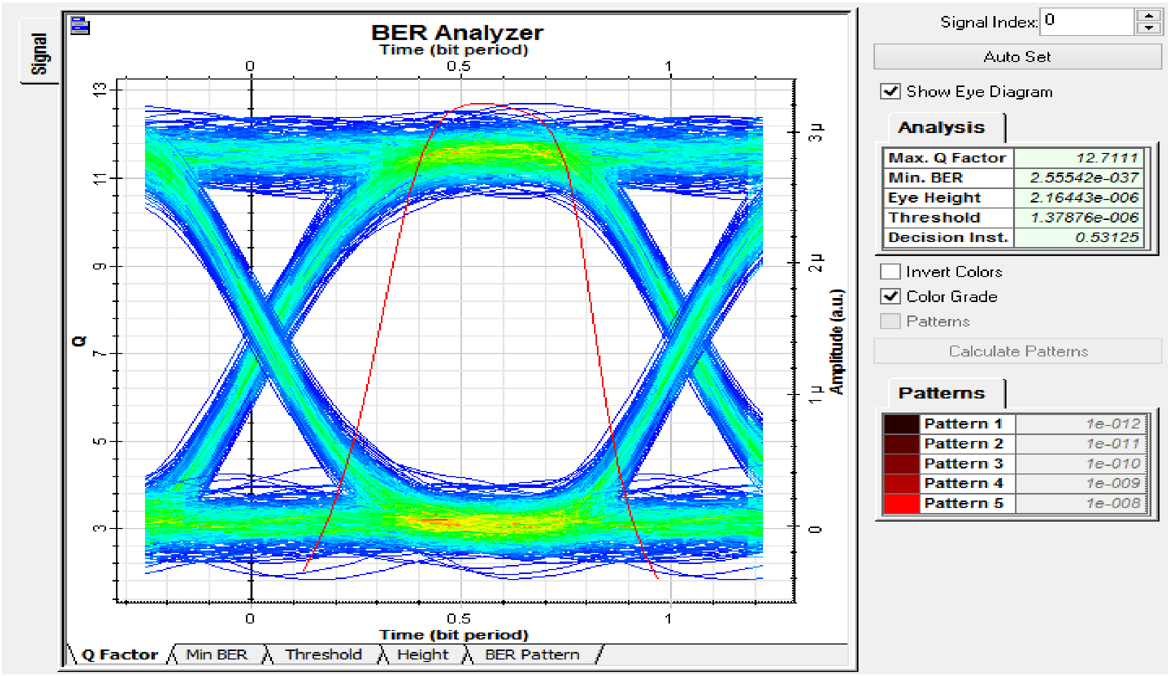

Fig 5.9: Eye diagram for 80Mb/s data rate at a distance of 0.116Km and attenuation 5dB/km (P_{in}= -20dBm)

Considering attenuation of 5dB/km caused by rain implies that FSO design affected during summer time but that doesn't mean the design is not functional it's just contribute for the reduction of Q factor from 14.75 to 12.71 and increment of BER from 1.42e-49 to 2.55e-37.

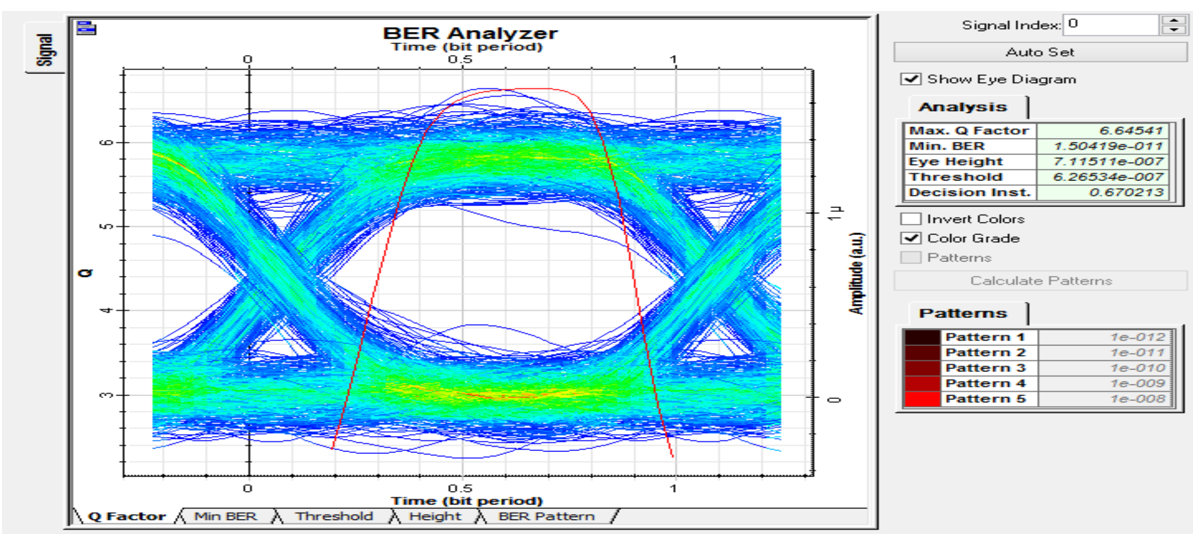

Fig 5.10: Eye diagram for 60Mb/s data rate at a distance of 0.36Km and attenuation 5dB/km (P_{in} = -12dBm)

We can see that eye opening shrink and we found minimum Q factor(6.64). This shows the effect of rain attenuation in signal quality and increment of distance minimize received power of FSO design.

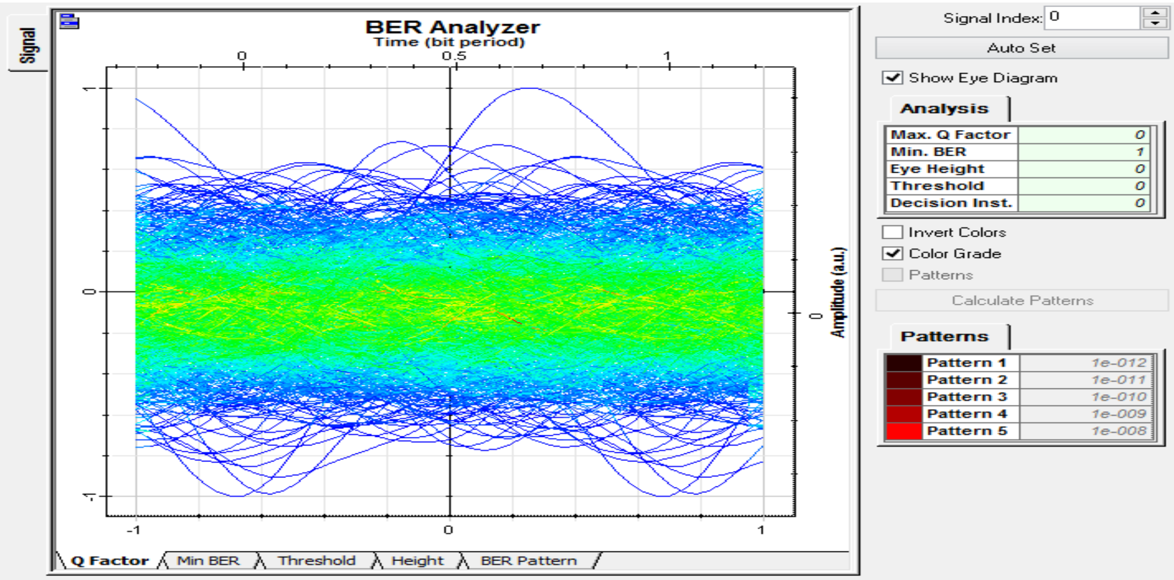

Fig 5.11: Eye diagram for 200Mb/s data rate at a distance of 1.448 Km and attenuation 5dB/km (P_{in} = -12dBm)

From this eye diagram we can read that at the highest distance and data rate requirement rain attenuation caused failures of FSO link. And have a maximum distortion.

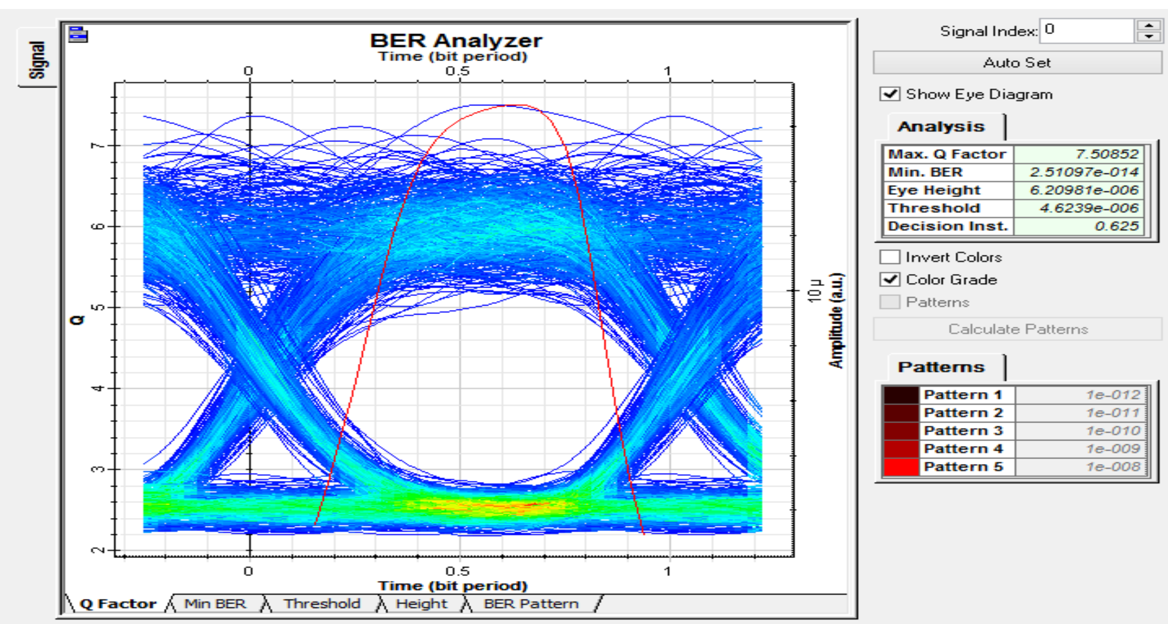

Fig 5.12: Eye diagram for 200Mb/s data rate at a distance of 1.448 Km and attenuation 5dB/km (P_{in} = -12dBm) using Op Amp (30dB)

To enhance the received power or Q factor from 0 to 7.5 we used Op Amp at 30dB at the presence of rain attenuation effect. And it's possible to minimize the distortion of opening eye diagram.

Table 5.4 Detection of BER analyzer for FSO link (Rain attenuation of 5dB/km)

BER Analyzer Reading	0.116km 80 Mb/s	0.36km 60 Mb/s	1.448km 200 Mb/s Op Amp(30dB)
Max Q factor	12.71	6.64	7.50
Min BER	2.55e-037	1.50e-011	2.51 e-014

From the 2D graph and 3D Bar graph we will notice the relation between Q factor vs BER and Range vs Data rate vs Q factor for both FO and FSO link.

5.1.3 2D graph

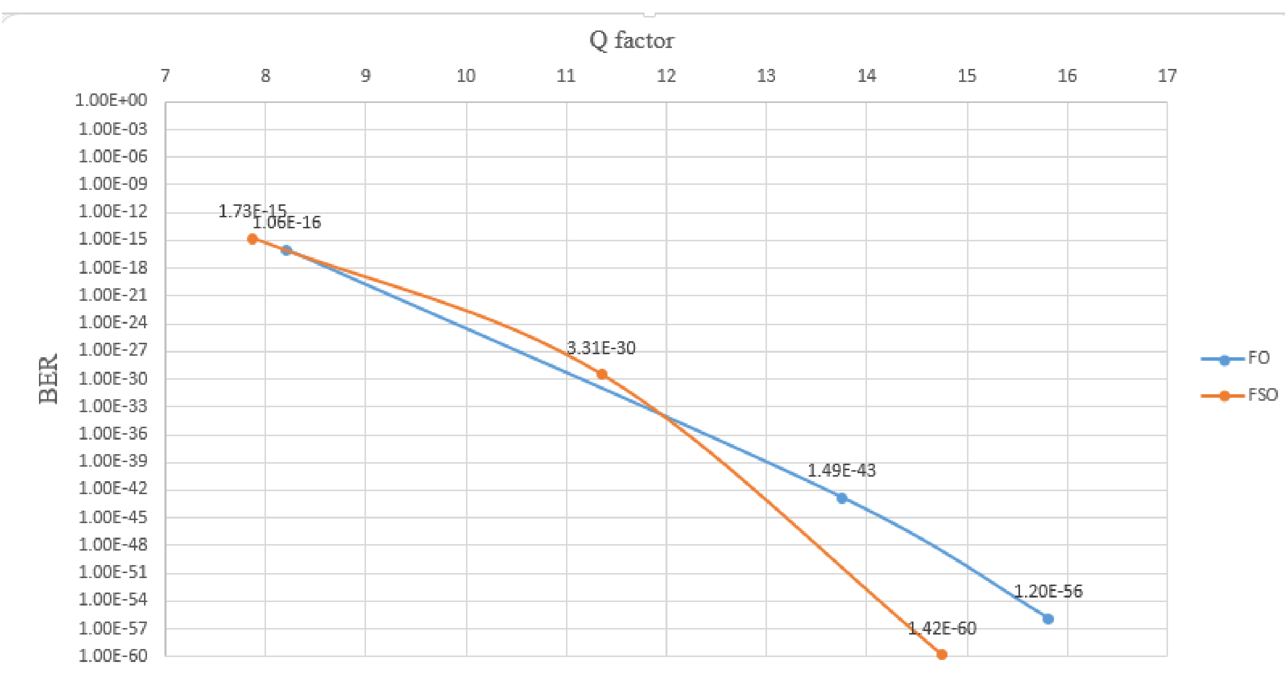

Fig 5.13: BER vs Q factor for FO and FSO link

Here in 2D graph we see inverse relationship of Q factor and BER, Maximum Q factor is also achievable in FO link and the maximum BER value in FSO link is caused to have minimum value of Q factor.

5.1.4 3D graph

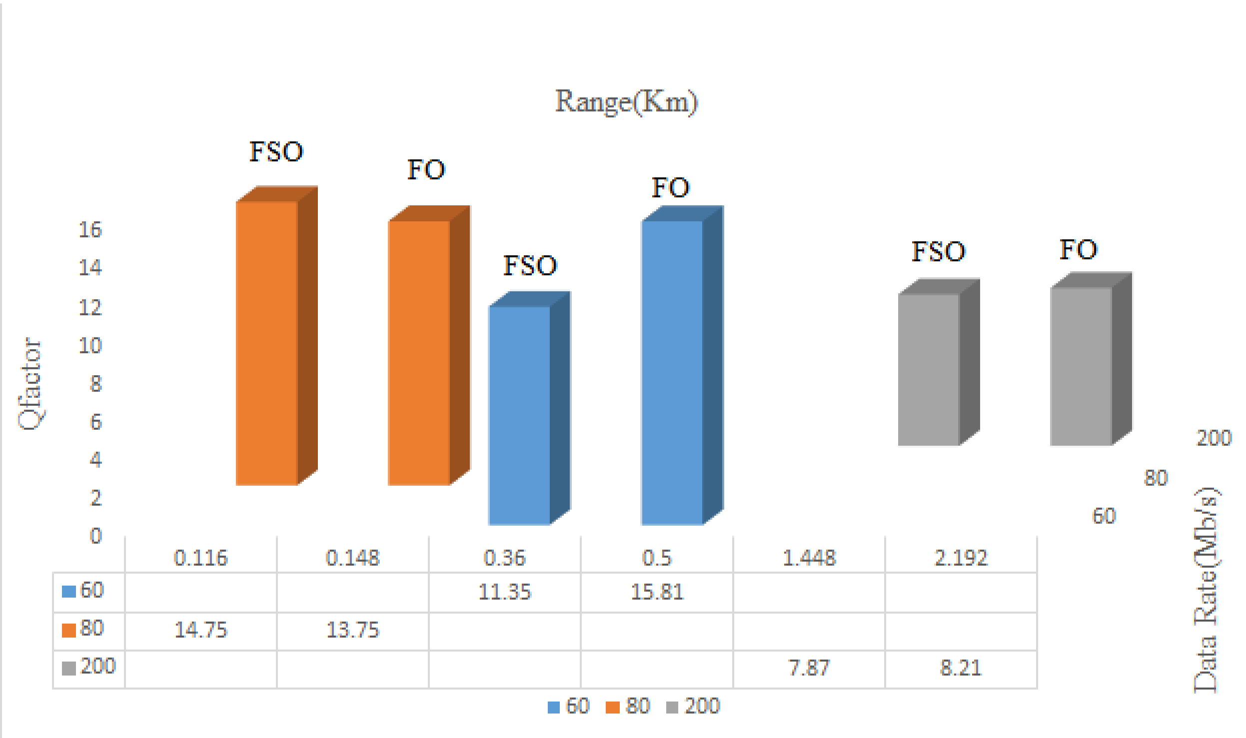

Fig 5.14: Range vs Data rate vs Q factor for FO and FSO link

From the above graph we can read that at a cost of increasing the input power from -25dBm to -12dBm FSO link has a greater Q factor value of 14.75 at range of 0.116km & 80Mb/s data rate requirement. At both medium and large ranges FO link gives us a better Q factor value of 15.81 and 8.21 respectively while it compares with FO link which has 11.35 and 7.87 Q factor value at medium and large distances.

5.2 Discussions of simulations result

For the performance measurement and comparison of both FO and FSO we check the detection of BER analyzer, reading of 2D graph, 3D graph and Optical power meter using a simulation software called OptiSystem 15. From FO link simulation result in fig 5.3 and 5.5 we noticed that at a distance of 0.148km, 2.192km the Max Q factor values are 13.75 and 8.21 respectively it means the shorter the range between $T_x$and R_x the greater value of Q. We also realized there is more bit error rate in transmitting higher value of data rate.

When we come to transmitting power, in order to transmit the higher data rate in our case 200Mb/s at a distance of 1.448km it needs a greater transmission power which is -12dBm using Op Amp (14dBm) relative to lower requirement of data rate with shorter range. The greater Q value implies that we have better received power.

For the FSO link at clear air (typical value of attenuation of 0.2db/km) is taken. It is known that the measure cause of attenuation for FSO link is rain other than fog, but in our scenario since A.A objected to fog averagely 1 day /year [3]. We choose the link performance during rainy season. The data from international telecommunication union tells us A.A has average rain intensity of 13mm/hr. Rain attenuation is (R_a)=1.076*R_3^2≈5dB/ km [3]. So taking this in to consideration we add rain attenuation in FSO link and found less Q factor values for all 3 different link ranges. For this explanation we can refer to figure 5.9, 5.10 and 5.11.

Referring fig 5.6,5.7 and 5.8 the first two link ranges(0.116km and 0.36 km) even if the value of Q decreases the link still perform well but for the last link at a distance of 1.448 km the link performance failed and the Q values comes to less than 5.4(acceptable value of Q factor) means the received signal is going to be very noisy in order to mitigate this problem we add Op Amp (14dB) to receive better signal at the receiver with Q factor 7.5.

For those different link distances and data rates FO link requires much less power than FSO link. For both FSO and FO link the receiver sensitivity range is between -20 dBm to -40 dBm. In this thesis paper we took -40dBm.From the reading of optical power meter we realized the received power decrease while the link distance increase. The BER result from FSO link at a distance of 0.116 km(80Mb/s) and 0.36 km(60 Mb/s) respectively showed us the direct relationship of bit error rate and distance between transmitter and receiver.

Chapter 6

Conclusion and Recommendation

6.1 Conclusion

The goal of this thesis paper is to analyze and compare the performance of FSO link with FO link by observing the detection of BER analyzer like Q factor, BER and reading of optical meter. The selected transmitter is -25 dBm and -12 dBm CW laser diode with wavelength of 1550 nm. In the design of FSO link we take the ranges between the transmitter (Bole exchange) and receivers (Sapphire Hotel, Best Western Addis Hotel, Sky light Hotel) are 0.116km, 0.36km and 1.448 km at the maximum desired data rate of 80 Mbps,60 Mbps and 200Mbps respectively. In the system model we use the modulation scheme OOK and low pass Bessel filter.

To choose the wavelength and power of the laser diode, eye safety was the main consideration. A class I laser with 1550 nm wave length can be used without eye protection goggles. However, the range of power from -28dBm to -12dBm limited the performance of both FSO and FO link. An Op Amp is used to mitigate the performance degradation caused by rain attenuation. The beam divergence of 2 mrad , a telescope with the transmitter aperture diameter of 5cm and receiver aperture diameter of 20cm used to capture the transmitted signal. The photodetector used in this project was PIN photodetector.

All parameters of the components were applied in the software and the effect on the link of the transmitted signal was observed. It was seen that the most FSO link degradation occurs due to rain attenuation.

Finally from the simulation results we understand that even if FO link perform better than FSO at a much less value of input power considering the cost, and time efficeiency it’s better to prefer FSO as a backup link because it can perform like FO link at a cost of input power.

6.2 Recommendation

In this thesis, FSO link performance analysis and comparison with fiber optics were discussed. The design of FSO system used as a .backup link for fiber optics connectivity which already implemented on three different buildings found around the area of Bole Medhanialem. In future works integration of FSO system with optical fibers could be included.

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