Design and Performance Analysis of Free Space Optical Communication over Various Optical Filtering for 5G System

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Major advisor: Dr. Demissie Jobir

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A Final Thesis Submitted to the Department of Electronics

And Communication Engineering

School of Electrical Engineering and Computing

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

Office of Graduate Studies

Adama Science and Technology University

June, 2022

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Declaration

I hereby declare that this Master Thesis entitled "Design and Performance Analysis of Free Space Optical Communication Over Various Optical Filtering for 5G System'' is my original work. That is, it has not been, submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are, used for this thesis have been, duly acknowledged through citation.

Habtamu Sida Urgessa ______________________ _______________

Name of the student Signature Date

Recommendation

I/we, the advisor(s) of this thesis, hereby certify that I/we, have read the revised version of the thesis entitled "Design, and Performance Analysis of Free Space Optical Communication Over Various Optical Filtering for Fifth Generation System'' prepared under my/our guidance by Habtamu Sida Urgessa submitted in partial fulfillment of the requirements for the degree of Master's of Science in Electronics, and Communication Engineering. Therefore, I/we recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Approval Page for M.Sc. Thesis

I/we, the advisors of the thesis entitled "Design and Performance Analysis of Free Space Optical Communication Over Various Optical Filtering for 5G System'' and developed by Habtamu Sida, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Habtamu Sida Urgessa have read and evaluated the thesis entitled "Design and Performance Analysis of Free Space Optical Communication Over Various Optical Filtering for 5G System'' and examined the candidate during open defense. This is, therefore, to certify that the thesis is, accepted for partial fulfillment of the requirement of the degree of Master of Science in Communication and Electronics Engineering.

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List of Abbreviations

APD	avalanche photodiode
AWG	Arrayed wave guide Grating
CNR	Carrier Noise Ratio
CFO	Carrier frequency offset
BER	Bit error rate
BBU	Base band units
BSTS	Boost Surveillance and Tracking System
DWDM	Dense Wave length Division Multiplexing
1G	First Generation
2G	Second Generation
3G	Third Generations
4G	Fourth Generations
5G	Fifth Generations
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FSO	Free space optics
FSOI	Free space optics inter connect
IFFT	Inverse Fast Fourier Transform
ISI	Inter symbol Interference
LAN	Local Area Network
LPF	Low pass filter
LTE	Long-term evolution
LCS	Laser Cross-Link Sub-system
MCM	Multi carrier Modulation
MZM	Mach-Zehnder Modulator
NASA	National Aeronautics and Space Administration
OFDM	Orthogonal Frequency Division Multiplexing
PSS	Phase shift surface
PAPR	Peak Average to Power Ratio
PSK	Phase Shift Key

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Key
SCM	Subcarrier Modulation xiv
WDM	Wave Division Multiplexing
WLAN	Wireless Local Area Network
OWC	Optical wireless channel
CV	Continuous wave
LED	Light emitted diode
SOA	Semiconductor amplifier
OSA	Optical spectrum analyzer
SNR	Signal to Noise Ratio
UMTS	Universal Mobile Telecommunication System

Abstract

FSO is a line-of-sight wireless communication technology that uses invisible beams of light to provide high-speed wireless connections that can send and receive voice, video, and data information. Free space optical communication has emerged as a best solution to high-speed transmission systems due to its higher bandwidth and higher data rates. To implement this intelligent network, by using MIMO, MIMO-OFDM and optical filters are, employed. When MIMO systems are, used significant capacity gain can be, observed as it exploits spatial multiplexing by having several transmit and receive antennas. MIMO-OFDM is the current technology used in the 5G wireless communication system. MIMO-OFDM is the current technology used in the 5G wireless communication system; hence, our approach to the evaluation of the capacity of the proposed FSO communication system with MIMO-OFDM will be very useful for providing a solution to the problem of the last mile bottleneck. Therefore, in this thesis, to analysis the performance we modeled MIMO- OFDM detection with (4-QAM, 16-QAM, 32-QAM, 64-QAM, 256-QAM) and utilizing different optical filters such us Gaussian, Rectangular, Trapezoidal, Bessel and Fabry perot. A comparison is carried out between our proposed scheme and reported counterpart. The performances have been, investigated by referring to different factors such us optical range (transmission distance), beam divergence, transmitter aperture diameter and receiver diameter. Different optical filters using pre post amplification provides high bandwidth for 5G application. If the length of the transmission is, increased largely, the signal is, dispersed which can be, explored as future work.

Key word: *FSO, 5G, MOMO-OFDM, Optical Filters*

CHAPTER ONE

1. Introduction

1.1. Background of the Study

FSO technology pioneered and championed by Cable Free optical wireless offerings has enabled the development of a new category of outdoor wireless products that can transmit voice, data, and video at bandwidths up to 1.25 Gbps (Janusz Mikołajczyk ,Zbigniew Bielecki et al., 2017). Free Space Optics connectivity does not require expensive fiber-optic cable and removes need for securing spectrum licenses for radio frequency RF solutions. FSO technology requires light. The use of light is a simple concept similar to optical transmissions using fiber-optic cables; the only difference is the medium. Light travels through air faster than it does through glass, so it is fair to classify FSO technology as optical communications at the speed of light. Laser link known as National Aeronautics and Space Administration (NASA) first established Ground/Orbiter Laser Communication Demonstration in 1995–1996 in conjunction with Jet Propulsion Laboratory (JPL). Demonstrations have established a full duplex FSO link with high data rates between various onboard space stations and ground stations, inter-satellite, etc.

With improved reliability and100 percentage availability. Besides FSO uplink/downlink, extensive research is, carried out. For FSO terrestrial links, i.e., link between two buildings to establish local area network segment that will provide last mile connectivity to the users. FSO communication is well suited for densely populated urban areas where digging of roads is cumbersome. Terrestrial FSO links can be, used either for short range (few meters) or for long range (tens of km). Short-range links provide high-speed connectivity to end users by interconnecting local area network segments that are, housed in building separated within the campus or different building of the company. Long-range FSO communication links extend up to existing metropolitan area fiber rings or to, connect new networks. These links do not reach the end user but they extend their services to core infrastructure. FSO communication system can also be, deployed within a building, and it is termed as indoor wireless optical communication (WOC) system. WOC communication is, considered as the next frontier for high-speed broadband connection due to its unique features: extremely high bandwidth, ease of deployment, tariff-free bandwidth allocation, low power (1/2 of radio frequency (RF) systems, less mass (1/2 of RF systems), small size (1/10 the diameter of RF antenna), and improved channel security. It has emerged a good commercial alternative to existing radio-frequency communication as it supports larger data rates and provides high gain due to its narrow beam divergence. It is capable of transmitting data up to 10 Gb/p/s and voice and video communication through the atmosphere/free space. Over the last few years, massive expansion in WOC technology has been, observed due to huge advances in optoelectronic components and tremendous growth in the market offering wireless optical devices. It seems to be one of the promising technologies for addressing the problem of huge bandwidth requirements and “last mile bottleneck.” There are many commercial applications of WOC technology, which includes ground-to-LEO, LEO-to-GEO/LEO-to-ground, GEO to-ground, LEO/GEO-to-aircraft, deep space probes, ground stations, unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs) etc. It also finds applications in the area of remote sensing, radio astronomy, space radio communication, military, etc. When WOC technology is, used over very short distances, it is termed as FSO interconnects (FSOI), and it finds applications in chip-to chip or board-to-board interconnections. FSOI has gained popularity these days.

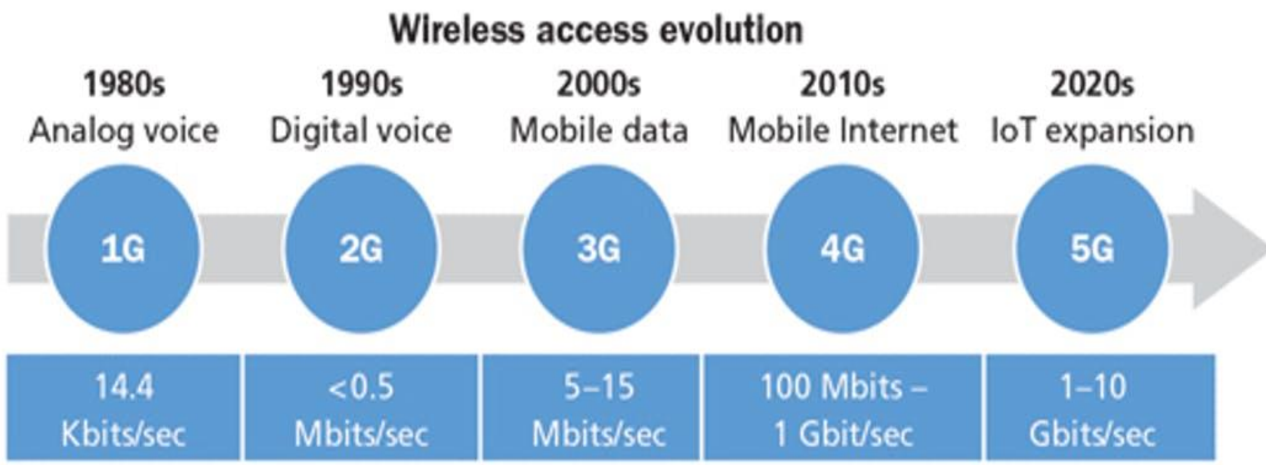

Figure 1.1 Wireless Access Evolution (Kara Mullaley, Corning Inc., Aug. 2, 2018).

1.1.1. 5G Wireless Technology

5G Technology stands for 5th generation mobile technology. 5G denote the next major phase of mobile telecommunication standards beyond the upcoming 4G standards. 5G technology is offering the service in Product Engineering, Documentation, supporting electronic transactions, etc. As the customer become more and more aware of the mobile phone technology, he or she will look for a decent package all together including all the advanced features a cellular phone can have. Hence the search for new technology always the main motive of the leading cell phone giants to out innovate their competitors.

The goal of a 5G based telecommunication network would ideally answer the challenges that a 4G model would present once it has entered widespread use. Wireless systems using orthogonal frequency division multiplexing (OFDM) with wide area coverage, high throughput at millimeter waves (10 mm to 1 mm) covering a frequency range of 30 GHz to 300 GHz, and enabling a 20 Mbps data rate to distances up to 2 km. The millimeter- wave band is the most effective solution to the recent surge in wireless Internet usage. These specifications are capable of providing wireless World Wide Web (WWWW) applications.

The WWWW allows a highly flexible network (flexible channel bandwidth between 5 and 20 MHz, optimally up to 40 MHz), and dynamic ad-hoc wireless network (DAWN). This technique employs intelligent antennae (e.g., switched beam antennae and adaptive array antenna) and the flexible modulation method, which helps in obtaining bidirectional high bandwidth, i.e., transfer of a large volume of broadcasting data in giga bytes, sustaining more than 60,000 connections and providing 25 Mbps connectivity. Users of 5G technology can download an entire film to their tablets or laptops, including 3D movies; they can download games and avail of remote medical services. With the advent of 5G, Piconet and Bluetooth technologies will become outdated (Dilsha M.D., Neenu Welson, 2015).

1.1.2. MIMO-OFDM

Wireless communications have, exploit the diversity technique since its inception and continues to capitalize on its multiple advantages in beyond fourth-generation standards. With the advent of full-dimension MIMO and massive MIMO, new paradigms are, being-targeted in the disruptive technology. Third-generation partnership project (3GPP) has also emphasized the advanced MIMO technology for achieving its vision of International Mobile Telephony IMT 2020. However, implementing multiple antennas can be cumbersome due to limiting factors such as size, cost, and hardware limitations. In such a scenario, where implementing multiple antennas is not feasible, the benefits of diversity can be reaped by employing cooperative communication. Single antenna mobiles can share their mobile stations giving rise to a virtual MIMO system. In this paper, we have analyzed the performance of cooperative mobile stations in a frequency selective channel. Orthogonal frequency division multiplexing (OFDM), known for its robustness against multipath fading, is the modulation technique employed to circumvent the hazardous effects of inter-symbol interference ISI (Himanshu Katiyar and Arun Kumar Singh , 2019).

1.2. Statement of the Problem

According the reports by the reputed international organizations studies

1. Increasing of global mobile data traffic, smart phone and computer users, consequently the problem of spectrum congestion become dominant shortly.
2. The infrastructural cost of optical fiber based links will be massive to deliver last mile connectivity consequently developing nations like those that Africa will be doomed to be financially unviable.
3. In existing 3G and 4G due to beam dispersion, Atmospheric absorption and shadowing many rural areas and buildings in many metropolitan cities where there is no network coverage and challenges in this technological world.

Therefore, using 5G FSO technology and increasing the performance can play a crucial role in bridging the gap between the bandwidth scarcity and cost effectiveness.

1.3. Objective of the Thesis

1.3.1. General Objectives

The general objective of this thesis is to design and evaluate the 5G free space optical communication system using optical filter for high security networks technology and achieve maximum quality factors in terms of optical range, transmit and receive aperture diameter.

1.3.2. Specific Objective

The specific objectives of the thesis:

1. To analysis, the performance of free space optical communication system by referring to different factors such as transmission distance (range), transmitting and receiving aperture diameter and beam divergence.
2. Validate the performance of the FSO system in terms of optical filters for different spatial locations and array sizes.

3. To compare among optical filters such as Bessel, Trapezoidal, Gaussian, Rectangular and Fabry perot, then report the best counterpart for fifth generation communication systems.

1.4. Hypotheses and Research Questions

Before 5G becomes a reality, the network infrastructure has to be in place to support the billions of devices and the trillions of megabits of data that will flood the network. Let, we look at how 5G will influence optical-fiber requirements. Cellular capabilities started rather simply, but as each generation expanded functionality, applications, and services the network infrastructure supporting them has grown increasingly complex. To achieve all that 5G offers, a denser, fiber-rich network infrastructure will be needed to deliver the key performance indicators: lower latency, longer battery life, higher data rates, ultra-high reliability and devices that are more connected. Why 5G is different? 5G enables the vision of a truly connected society with its impact being felt across virtually every industry. The Internet of Things (IoT) will transform the economy and the way we live our lives. 5G will similarly change and create new economic opportunities. What is the disaster of FSO communication? Performance is analyzes under turbulence conditions especially under rain conditions. The optical signal traveling through free Space is, affected by rain also.

1.5. Significance of the Study

Free Space Optics solutions offer various significance of normal RF signal wireless networks. Such, as Free Space Optics does not suffer from radio frequency interference or, band saturation license free operation, No software needed on client devices. Very high security level operation FSO is, certified in Governmental and Defense applications for transferring confidential and classified information inside installation is possible and it unaffected by operation through glass, and traditional microwave and, RF links cannot be, employed in such scenarios owing to high data rate requirements of 5G network. 5G networks promise to connect people and things through intelligent networks and applications, all generating an immense amount of data. It seeks to provide the best of all performance factors while simultaneously connecting more devices. These network advancements will enable and inspire a new wave of computing and technological innovation that will change the way we live and work. The other significance of optical filter at receiver side is that it provides the signal synchronization between the transmitted and received signal. It is mainly required to hold the samples of data at the sampling period without misinterpretation of 0's and 1's.

1.6. Scope of the Study

In order to achieve system performance for systems limited by inter symbol interference and noise, mat lab software evaluates metrics such as BER and Quality factor using numerical analysis or semi-analytical approaches and we have been. Again analyzing the performance of the system at different transmission distances and different optical filters by using different modulation techniques this can be in terms different variables such as SNR (signal-to-noise ratio), BER (bit error rate).

1.7. Limitation of the study

The limitation of this thesis is the difficulty of optisystem software no component of thesis part such as MIMO component is included in all version optisystem software and the version that included all components V.18 is not cracked. Therefore, it needs license. It is only works for one month on single computers.

1.8. Organization of the Study

This thesis is, divided into five chapters, each of which is, discussed in turn: Chapter 1 discusses the introduction parts, which consists of background, statement of problem, objectives, and specific objectives, significance of the study, scope of the study, Hypotheses and Research Questions, Limitation of the study and Organization of the Study. Chapter 2 presents the literature review and related works, which explain the concept of free space optical communication system and massive MIMO techniques. Chapter 3 presents the methodology of the study in terms of modeling and simulation of optical (MIMO, m-MIMO and MIMO-OFDM and filters) using coherent detection and direct detection receiver by using mat lab software. Chapter 4 the simulation results and discussions of the performance analysis of free space optical communication. Finally, conclusion and recommendation of the thesis is, discussed.

CHAPTER TWO

2. Theoretical Overview

Free Space Optics (FSO) is a technology that uses laser beams via a line of sight optical bandwidth connection to transfer data, video or voice communications across areas ranging typically from 100m to a few kilometers at throughput bandwidths up to 1.5Gbps at frequencies above 300GHz of wavelengths, typically, 785 to 1550nm. Using Free Space Optics wireless networks eliminates the need to secure licensing found with RF signal solutions and the expensive costs of laying fiber optic cable; principally the concept of transferring data via light is the same as with fiber optics just through a different medium. The basis of Free Space Optics communication is rather straightforward with a pair of transceiver units housing an optical receiver and transmitter, allowing the sending and receiving of data simultaneously, and an optical source with a focusing lens. The unit at one location transmits a beam of focused light carrying the information directly at the unit at the receiving location where the light beam is then, transferred to an optical fiber from a high sensitivity receiver.

2.1. Related Works

Approaches to the new Free Space Optics (FSO) Communication Technology market is, presumed to witness a robust expansion over the projected timeline attributed to the high need for digital connectivity and the augmented need for higher and resilient bandwidth. Moreover, the surging demands for fast and robust wireless connection and the extensive application of free space optics in 4G networks. However, factors such as smoke, fog, rain, and atmospheric turbulence increase the network system's volatility and are, anticipated to act as a restraining market factor throughout the projected timeframe. The optical signal is, attenuated in the atmosphere by absorption, scattering, scintillation, propagation geometrics and other phenomena. In practice, the total radiation attenuation A (λ) caused by atmosphere can be, calculated as:

$$A(\lambda) = \alpha_{fog}(\lambda) + \alpha_{snow}(\lambda) + \alpha_{rain}(\lambda + \alpha_{scattering}(\lambda), \text{ (dB/km)} \tag{2.1}$$

Where αx (λ) is attenuation caused by the mentioned weather conditions and λ is an operational Wavelength. Analysis of free-space optics development from these approaches the article presents state of work in technology of free-space optical communications (Free Space Optics – FSO). Both commercially available optical data links and their further development are, described. The main elements and operation limiting factors of FSO systems have been, identified. Additionally, analyses of FSO/RF hybrid systems application are included. During last decades, FSO systems became an important direction of optoelectronic technology applications. FSO is also known as fibreless photonics. To obtain a broadband communication channel, high frequency (HF) modulated light pulses are, used to transmit data through the atmosphere (Janusz Mikołajczyk1), Zbigniew Bielecki1) et al., 2017).

Important FSO systems' applications are e.g. ad-hoc mobile communications during crises, so-called "last mile" links in urban areas, a special data transfer e.g. between ships and land, and secret military data links. It was, shown that a command center would be able to send information to vehicles or soldiers at a distance of "line-of-sight" with a transmission rate from 25 Mbps to 1.25 Gb/p/s.The main disadvantage of the FSO system is its high sensitivity on weather conditions (atmospheric attenuations). Different weather phenomena like fog, snow and rain, turbulence, are able to scatter and to absorb the optical signal. As a result, both range and data rate of data transmission channel are, reduced. To minimize the influence of these negative factors, characterization of various weather conditions and selection of so-called atmosphere transmission windows are required.

Design and planning of optical transport network for 5G and beyond Driven by the increasing number of mobile devices and the use of smart mobile applications, mobile technology is, continuously and rapidly advancing. 5G wireless technology is in progress to address the increasing demands for high capacity, Low latency Ubiquitous mobile access. The transport network will require undergoing an evolutionary change with a complete rethink of the design and deployment strategies. Challenges and weakness we observed from this paper higher cell densities, Costlier transport connectivity Fulfill diverse requirement of x G mobile, providing cost-effective transport network become a complex problem (Dr. Chathurika Ranaweera, Prof. Christina Lim et al., 2018).

Performance analysis of radio over optical fiber system with OFDM using multiplexing from these techniques an integration of microwave and optical networks, which its uses optical fiber as a backbone technology because of the tremendous advantages it offers. However, the performance of RoF systems can deteriorate severely because of nonlinear effects of the channel. In addition, Orthogonal Frequency Division Multiplexing (OFDM) is, being, proposed as, a standard for broadband wireless networks for deployment with RoF systems to facilitate overall system performance. The increased of demand for high-speed data rate and high capacity of bandwidth because of recent developments in technology in bandwidth for access networks. Nowadays, there is an urgent need in optical communication to meet the service requirements of ultra-large capacity and ultra-high speed for wireless access network because of its spectrum availability and digital signal processing equipment. However, the current wireless signals suffer from uncompromising loss along the existing transmission channel in addition to loss of free space. RoF system is a very important technique for the wireless access network, where it is, used to transmit millimeter and microwave waves by optical fiber for short and long distances. It is also used to support the current 4th generation mobility network and WLAN (1 Faris Mohammed Ali, 2Eman Abd Almalik Abd Ali et al., 2018).

Beam Domain Optical Wireless Massive MIMO Communications with Transmit Lens. Optical wireless communication systems rely on optical radiations to transmit information with wavelengths ranging from infrared to ultraviolet including the visible light spectrum (H. Elgala, R. Mesleh et al., Sept. 2011.). Base station (BS) commonly employs light-emitting diodes (LEDs) as optical transmitters to convert the electrical signals to optical signals. Recently, laser diodes (LDs) are, considered as potential sources for optical communication due to high modulation bandwidth, efficiency, and beam convergence (F. Zafar, M. Bakaul et al., Feb 2017). To achieve high data rate in optical communications, multiple separate LED/LD arrays are, usually utilized in the BS to provide higher data rate by means of spatial multiplexing. As a result, multiple-input multiple-output (MIMO) technique is a natural progression for optical. Communication systems. As the nature of optical downlink communication is broadcast network, multiple UTs should be, well supported. BSs simultaneously transmit signals to all UTs, resulting in the so-called multi-user interference, consequently degrades the performance. Thus, multi-user MIMO (MU-MIMO) has been, studied and several pre-coding schemes have been proposed, which are different from conventional RF systems since only real-valued non-negative signals can be transmitted (L. Zeng, D. O'Brien et al., Dec. 2009.).

2.2. Fundamentals of FSO Communication System

FSO is a wireless technology that uses light as a medium of transmission between a pair of transceivers and the systems are categorize under optical wireless and consider an emerging high-speed point-to-point broadband technology. FSO systems can be used for terrestrial applications such as inter building connections, backhaul for cellular systems, high quality video surveillance in a city and redundant links for fiber optic. It can be, deployed over a few kilometers link distances. Over the years, FSO technology has gained acceptance in enterprise campus network. FSO provides high bandwidth with fast installation time compare with fiber optic. It is also, to date, have free licensing of frequency and high secure compare with radio. Particles suspended in the air due to different weather phenomena such as fog, rain and haze are usually interacting with the photons of optical wavelength causing scattering of the optical signal. Scattering of the optical signal cause attenuation, thereby reducing the overall availability of FSO communication system. In addition to the weather impact, the FSO channel is, affected by scintillation due to atmospheric turbulence. The effect of scintillation can be, compensated by using diversity schemes. In tropical regions, the effect of scintillation is almost negligible due to low refractive index structure of turbulence. Moreover, multiuser diversity can improve the capacity performance of FSO channel over strong turbulence. Pointing errors due to misalignment between the two FSO installed headers can also cause additional loss. Practically, this loss can be, incurred over more than 3 km FSO link distance. Pointing loss is, related to the design of the FSO equipment and can be, accomplished by installing FSO headers on solid parts of the building with active auto-tracking system. The auto-tracking system normally uses close loop feedback control mechanism to keep the receive beam on target. These external and internal parameters can affect the performance and link availability of FSO link. Practically, link availability is, used to measure the quality of service of a communication system. Therefore, it is important to explain the availability concept and how it will be, predicted. The availability can be, defined as the time that a link is in operation. It is, mostly described and represented in percentage over a yearlong period. It can be, modeled based on deriving mathematical models or statistical analysis of past data. In addition, it can be, estimated by calculating the link budget of an FSO communication system. Thus, the availability prediction methods in the present work are, based on statistical data and FSO link budget (Ahmed Basahel, Md. Rafiqul Islam et al., 2018).

2.3. Availability Prediction Methods

As we mentioned that availability of a terrestrial FSO communication link could be, predicted using local weather statistics or FSO link budget. In this section, two methods of availability estimations will be, demonstrated as follow:

2.3.1. Availability Prediction Using Local Weather Fade Statistics

Link Availability can be, modeled based on statistical analysis of long-term local weather data. The longer period of collecting data, the more accurate the prediction models can be, derived. Availability prediction model is varying from one region to another. Each region derives its model, which best represent, its region and fit with its local weather data. For example, in a tropical climate, rain is the most constant factor that occurs most of the year. Normal haze also is, considered as a parameter that influences the optical signal. The availability prediction model can be, derived and presented as follow:

$$\text{Pout}\ (\%) = \alpha exp^{(9|b.Fm|)} \tag{2.2}$$

$$\alpha = \begin{cases} 4.409, & d \leq 1km \\ 165.4(d)^{-6.599} + x, & 1\text{km} < \text{d} \leq 5\text{km} \end{cases} \tag{2.3}$$

$$\text{b} = 0.3147(\text{d})^{-0.9964} \tag{2.4}$$

Where *Pout* is the outage probability, *a* & *b* are constant coefficients and *Fm* is fade margin (Db). From above model, link availability (*A*) for FSO can be, predicted as (*1-Pout*). This model is, developed based on tropical climate. The atmospheric attenuation due to rain and haze were, predicted based on the rain rate and visibility data measured of the climate. Cumulative distribution function (CDF) of predicted attenuation was, obtained using equal probability correlation of CDF of measured data and predicted attenuation models (Ahmed Basahel, Md. Rafiqul Islam et al., 2018).

2.3.2. Availability Prediction Using FSO Link Budget

The other method, which can be, used to predict FSO link availability, is using FSO link budget. For a typical terrestrial FSO system install in tropical region, the link budget equation can be, presented as follows:

$$\text{Pr} = \text{Pt} - \text{Geometrical loss} - \text{Atmospheric loss} - \text{Optical loss} \tag{2.5}$$

Where, pt & pr are transmitting and receive power in (dB) and Geometrical loss can be obtained as:

$$\text{Geometrical loss (dB)} = 20\log 20\log_{10}{}^{\frac{\text{d}\theta}{\text{D}}} \tag{2.6}$$

Where θ is the divergence angle (m rad) and *D* is the diameter of the receiver lens (m). The atmospheric attenuation due to haze can be determined using Beer-Lambert law as follow:

$$\tau = exp^{(-\sigma\text{d})} \tag{2.7}$$

Where σ km^{-1} is the scattering coefficient and obtained based on visibility V data. Whereas, atmospheric attenuation due to rain can be, obtained as:

$$A\%\,p\,(\mathrm{dB}) = 5.433187d(\gamma R)(R\%p^{-0.377})(exp^{(-0.102d)}) \quad (2.8)$$

Where γR is the specific rain attenuation (dB/km) and R is the rain rate (mm/hr). Determining all potential losses that may occur during the communication link is an indispensable part of the deployment of FSO system. Geometrical and optical / equipment losses in FSO are considered to be constant losses. Geometrical loss depends on the FSO system parameters and link distance. Regardless the cost efficiency of FSO system, various FSO system parameters will result in different availabilities. At the FSO receiver side, excess power after deducting all constant losses from transmitted power that launched from the transmitter will be, considered a link margin. This margin will be, allocated for any atmospheric weather influence within the propagating optical link. In other words, the link margin identifies the allowable atmospheric attenuation that is still available. The link margin will be for the additional loss due to rain or haze for optical link. The rise in FSO link distance will increase the total loss. The link availability can be, obtained if the received power does not exceed the specific receiver sensitivity for the required link distance. The flow chart of the availability prediction method using FSO link budget is, shown in Fig. (2.1) Link budget calculations for FSO system.

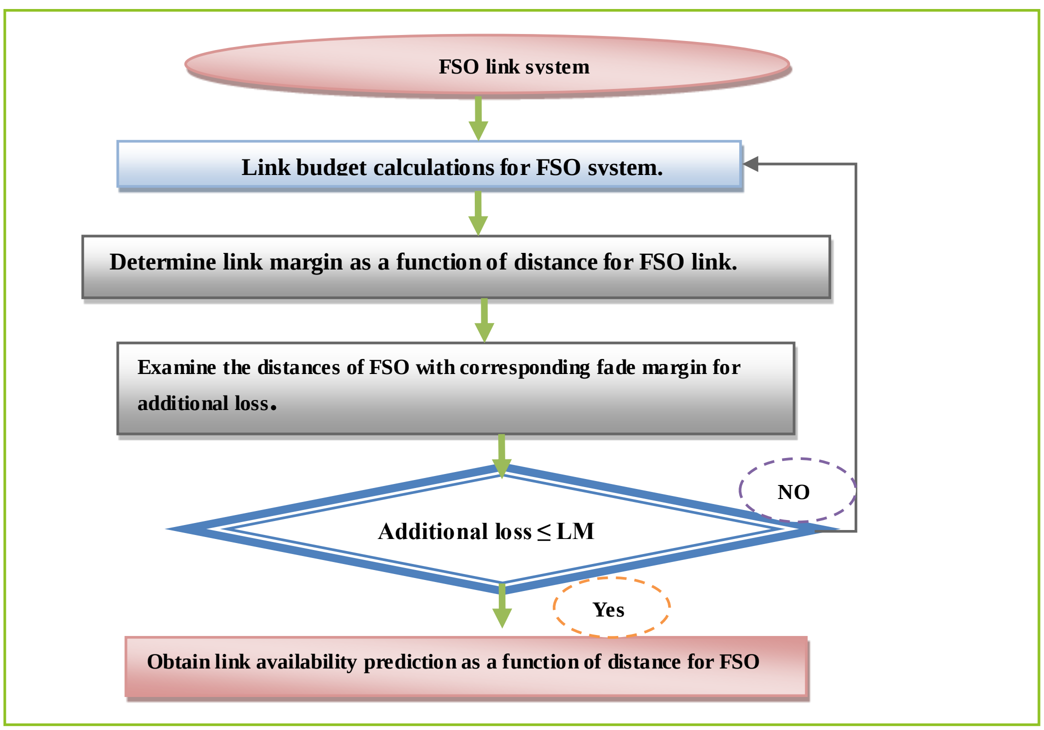

Figure 2.1 Flow Chart of FSO Availability Prediction Using Link Budget Method

2.4. The basic Features of FSO Communication System

1. High-Bandwidth Availability: FSO has a 2000THz data bandwidth, which offers a very high channel capacity.

2. Narrow Beam Width: As FSO, uses laser at the transmitter end, the beam width is very narrow which provides high-level secrecy that cannot be, achieved by RF communication.

3. Unlicensed Spectrum: FSO communication takes place in ISM band, which is an unlicensed band. Hence, FSO is free from spectrum distribution, which makes it convenient and cost-effective.

4. Low Installation Coast: The installation cost of FSO is very low as compared to RF for the same data rate.

5. Easy Deployment and Redeployment: The installation time in FSO is very low.

2.5. Application Area of FSO Communication

1. Inter-Campus Connectivity: There is a heterogeneous network traffic (i.e., voice, data, fax, multimedia traffic, etc.) that overwhelm the typical connections, be it in the school/university campuses or the corporations. FSO systems have the capability of providing ultrahigh speeds with low cost unlike dedicated fiber optic connections.

2. Monitoring and Video Surveillances: Nowadays, video cameras are deployed almost everywhere it may be in the supermarkets, airports, malls, and so on for public safety and in military applications. Deployment of video cameras is easy. However, the conventional wireless technology is incapable of providing high throughput required for video streams. FSO technology supports high-quality video transmission, thereby proving to be an efficient alternative.

3. Back-haul for Cellular Systems: In cellular systems, FSO can prove to be of high use in carrying the traffic of cellular telephone with high speed as well as fast data rates from antenna towers to the PSTN, thereby increasing the speed of transmission.

4. Redundant Link and Disaster Recovery: As FSO links can be, deployed easily and in less time, this advantage of FSO can prove to be extremely helpful in natural disasters, terrorist attacks, and emergencies in which the communication infrastructure may have been, damaged or became unreliable. The practical example of the FSO deployment as a redundant link was witnessed after 9/11 terrorist attacks in New York City, where FSO links were rapidly deployed in the area for financial corporation’s which were left out with no landlines.

5. Storage Area Network (SAN): SAN is a network that provides access to consolidated block-level data storage. FSO links can, be used to form a SAN.

6. Point-to-Point and Point-to-Multipoint Communication: FSO communication is possible in point-to-point links, for example, between two shops, two buildings, and in point-to-multipoint links, for example, from satellite to ground for short as well as long-distance communication.

2.6. The Block Diagram of FSO Communication System

The block diagram of typical FSO link is, shown in the figure like any other communication technologies the FSO essentially comprises of three parts: the transmitter, channel and receiver.

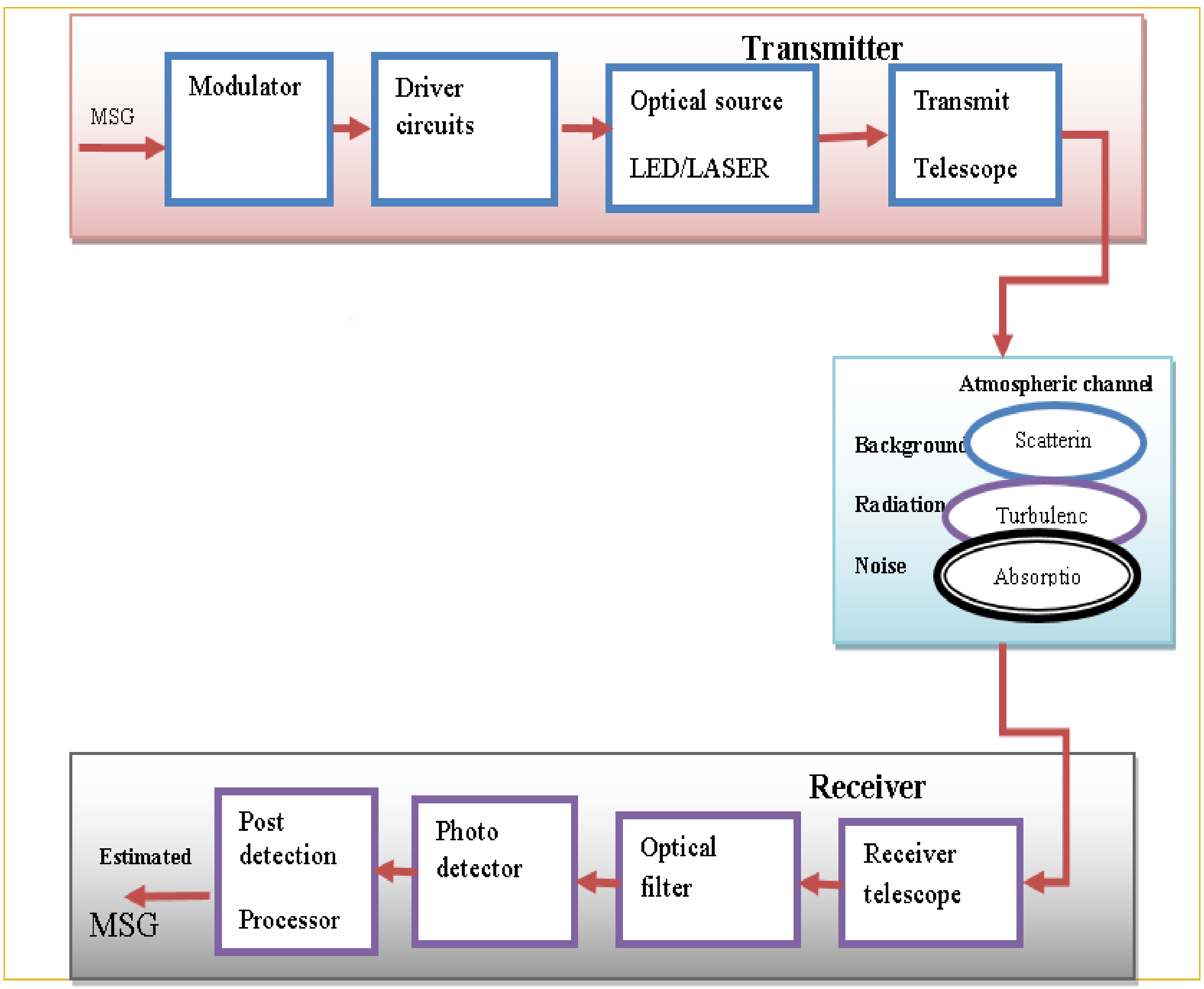

Figure 2.2 Block diagram of FSO. Communication System.

2.6.1. System Description

The general block diagram of FSO is, shown in Fig. above it simply comprises: transmitter, channel, and receiver. The transmitter sends modulated laser beam through free space, which is, received, demodulated, and detected at the receiver. In an FSO system, the message signal is, modulated in the modulator block that essentially is an intensity modulation (IM). Several modulation techniques have been, implemented on FSO system such as OOK, BPSK, QPSK, and PPM. In the intensity modulation, the modulated signal is, used to vary the intensity of the light coming out of the laser source. The transmitter telescope directs the modulated laser beam toward the receiver telescope. The receiver comprises a photo detector that can be a PIN or an APD. The photo detector converts the light signal into corresponding electrical signal so that it can further be demodulated, and processed. As FSO is a LOS communication, there should be no obstruction between transmitter and receiver. The architecture of FSO can be, summarized as:

i. Transmitter

The transmitter system is composed of four subsystems. The first subsystem is the Pseudo-Random Binary Sequence (PRBS) generator. A pseudorandom binary sequence (PRBS), pseudorandom binary code or pseudorandom bit stream is a binary sequence that, while generated with a deterministic algorithm, is difficult to predict and exhibits statistical behavior similar to a truly random sequence. The second subsystem is the Non-Return-to-Zero (NRZ) encoder that encrypts information. In telecommunication, a non-return-to-zero (NRZ) line code is a binary code in which ones are represented by one significant condition, usually a positive voltage, while zeros are represented by some other significant condition, usually a negative voltage, with no other neutral or rest condition. The third subsystem is the optical transmitter (laser generator).The fourth subsystem is the Mach–Zehnder modulator that modulates the intensity of the light source according to the output pulse generator. A Mach-Zehnder modulator is, used for controlling the amplitude of an optical wave. If a voltage is, applied across one of the arms, a phase shift is, induced for the wave passing through that arm. When the two arms are, recombined, the phase difference between the two waves is, converted to an amplitude modulation. The transmitter telescope collects climate and directs optical radiation towards the receiver telescope at the other end of the channel. Summary of commonly used sources in FSO systems are:

Within the 700-10000nm wavelength band there are a number of transmission windows that are almost transparent with an attenuation of <0.2dB/km. The majority of FSO system are designer to operate in the 780-850nm and 1520-1600nm spectral windows 780nm-850nm is most widely used because device and components are readily available in this wave length range and at low cost. The 1550nm band is attractive for a number of reasons

1. Compatibility with third window wavelength-division multiplexing networks.

2. Eye safety (about 50 times more power can be, transmitted at 1550nm than at 850nm).

3. Reduced solar background and scattering in light haze/fog. Consequently, at 1550nm a significantly more power can be, transmitted to overcome attenuation by fog. However, the drawback of the 1550nm band is slightly reduced detector sensitivity, higher component cost and a stricter alignment requirement. (≈10000nm) Quantum cascaded laser: is expensive and relative new, very fast and highly sensitive, better fog transmission characteristics, components not readily available and no penetration through the glass. Near Infrared (LED) is cheaper simple driver circuit, lower power and lower data rate.

ii. Channel

The communication channel between the transmitter and the receiver is the free space that is air. The modulated light signal is, degraded in the channel. Atmospheric turbulences such as fog, rain, snow causes the scattering absorption and fading of the transmitted signal that, eventually degrades the performance of the FSO system.

iii. Receiver

The optical receiver is composed of an avalanche photodiode (APD), optical amplifiers, the filter (Law Pass Bessel Filter) to filter the high frequency of unwanted signals, and 3R (reduce, reuse and recycle) regenerator to determine the electrical signal embedded. The receiver devices are direct detection based devices that, directly detect the instantaneous power of the collected optical field as it arrives at the receivers.

1. The RX telescope: collects and focuses the incoming optical radiation on to the photo detector.

2. An optical band: pass filter to reduce the amount of background radiations

3. A photo-detector: PIN or APD that converts the incident optical field into an electrical signal. Germanium is only detectors are, generally not used in FSO because of their high dark currant.

4. Post-detection processor/decision circuit-where the necessary amplification, filtering and signal processing necessary to guarantee a high fidelity data recovery are, carried out. Due to detector capacitance effect, higher speed detectors are, inherently smaller in size (70µm and µm for 2.5gbps

and 10 gbps, respectively) with a limited field-of-view (FOV) that requires accurate alignment. FOV of the receiver is the ratio of the detector size to the focal length (Jaganthan and Ionov).

FOV = d/f =dF #/D; where d is the detector diameter f is the effective focal length, and D the receiver aperture. The quantity F# is the f-number. For a 75μm size detector, with F#=1 and D =150mm telescope, the FOV = ≈0.5mrad. The commonly used photo detector for in the contemporary laser communication systems are:

Table 2.1 FSO phto detector

Material/structure	Wavelength[nm]	Responsively	Typical sensitivity	Gain
Silicon PIN	300-1100	0.5	-34dBm@155Mbps	1
Silicon PIN, with trans-impedance amplifier		0.5	-26dbm@1.25gbps	1
InGaAsPIN	1000-1700	0.9	-46dbm@155mbps	1
SilconAPD	400-1000	77	-52dbm@155mbps	150
InGaAsAPD	1000-1700	9	-33dbm@1.25gbps	10
Quantum-well and Quantum-dot detectors	10,000	-----	-------	------

The receiver detection process can be, classified into two:

i. Direct Detection

Direct detection can only detect the amplitudes of the signals when receiving the receive terminal. Different from coherent detection which can extract amplitude, frequency, and phase information from an optical carrier, direct detect system can only modulate optical wave via intensity modulation. Generally, direct detection is, used for short reaches and point-to-point connections in metro networks. By leveraging PAM4, direct detection can now transport 100Gbit/s and can reach distances of up to 80km while complying with requirements for optical signal-to-noise ratio. With the benefit of small size, simplified structure, and low consumption, intensity modulation direct detection (IM/DD) communication system becomes the ideal option for short-distance optical communication. In addition, recent technological advances have been prompting direct detection to apply in metro DCI networks.

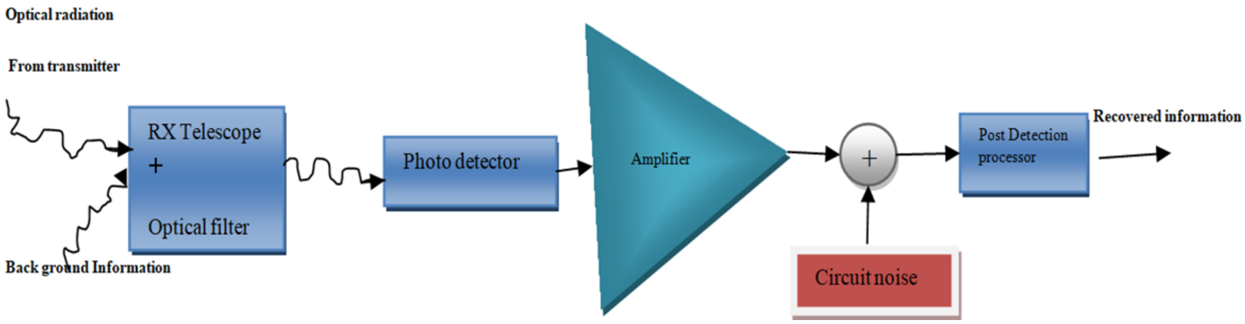

Figure 2.3 Direct detection of optical receiver

ii. Coherent detection

Coherent detection is an optical signal detection technique that is useful both in fiber-optic communication systems and in optical measurement and sensors. It uses a local oscillator at the receiver, enabling 100Gbit/s transport on a single wavelength for long-haul DWDM networks. With the capability to do coherent detection, an optical receiver can track the phase of an optical transmitter to extract any phase and frequency information carried by a transmitted signal. Though coherent detection is a concept derived from wireless communication systems, it has been widely used in optical fiber communications, consequently bringing great influence to long-haul optical networks. However, for 100G metro DCI, the increased cost and power consumption of coherent detection are the other troubling problems.

2.7. FSO Communication system Challenges (FSO Attenuation)

The most important phenomena that affect the performance of a FSO link are absorption, scattering, and atmospheric turbulence. In this thesis we studies the effect of environmental parameters such as rain, fog, haze, snow, and dust on the performance of optical wireless communications using different channels (1TX/1RX, 2TX/2RX, and 4TX/4RX) at different wavelengths (850nm-1550nm). Fog is the most hostile factor to FSO link due to the fog particles, which are having nearly the same wavelength as wavelength of light. The atmospheric attenuation coefficient is, calculated depending on visibility and the wavelength of the incident beam according to

$$\alpha = \frac{3.91}{v}\left(\frac{\lambda}{\lambda 0}\right)^{-q} \tag{2.9}$$

Where, λ indicates transmission wavelength (nm), V indicates visibility (km), $\lambda 0$ indicates visibility reference

Wavelength=550nm, and q indicates the size distribution of the scattering particles.

According to Kruze model

$$q = \begin{cases} 1.6 & V>50km \\ 1.3 & 6km<V<50km \\ 0.585v^{\frac{1}{3}} & V<6km \end{cases} \qquad (2.10)$$

Using (2.10) can determine the attenuation of the transmitted signal (α) for different weather conditions. The atmospheric attenuation (τ) in dB can be, calculated as follows

$$\tau = 4.3429*\alpha*L \qquad (2.11)$$

Where L is distance between transmitter and receiver. Rain is one of the factors for inducing attenuation in a FSO system. Rain has less impact than fog because wavelength of optical signal is very small as compared to raindrop. In addition, attenuation of rain can be, calculated as follows:

$$A\ rain = 1.076*R^{0.67}(dB/km) \qquad (2.12)$$

Where is the rain rate in mm/h.

2.8. Log Distance Path Loss or Log Normal Shadowing Model

Log distance path loss model is a generic model and an extension to free space model. It is, used to predict the propagation loss for a wide range of environments, whereas, the Free space model is restricted to unobstructed clear path between the transmitter & the receiver.

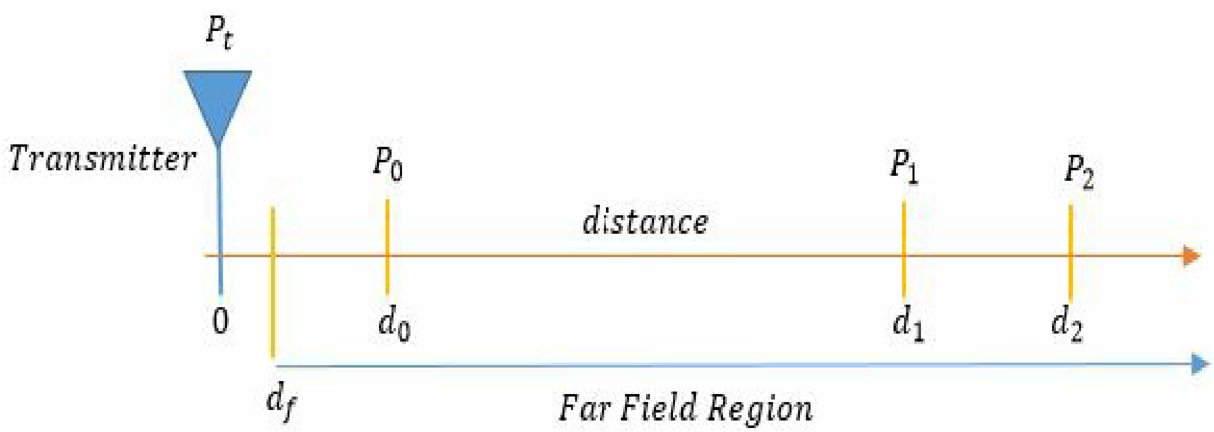

Figure 2.4 Log Distance Path Loss or Log Normal Shadowing Model (Viswanathan, Mathuranathan, 2013)

In the far field region of the transmitter (d ≥) d_f, if PL (d_0) is the path loss measured in dB at a distance d0 from the transmitter, then the path loss (the loss in signal power measure in dB when moving from distance (d_0 to d) at an arbitrary distance d > isd_0 given by

$$PL_{d0} \rightarrow d^{(dB)} = PL(_{d_0}) + 10\text{n}log10^{\left(\frac{d}{d_0}\right)} + \text{x} \qquad d_f \leq d_0 \leq \text{d} \tag{2.13}$$

PL (d0) = Path Loss in dB at a distance d_0

PLd->d0 = Path Loss in dB at an arbitrary distance d

n = Path Loss exponent. See the table below that gives the path loss exponent for various environments.

χ = A zero-mean Gaussian distributed random variable (in dB) with standard deviation – σ. This Variable is, used only when there is a shadowing effect. If there is no shadowing effect, then this variable is zero. Taking log of the Normal (Gaussian)-variable results in the name "Log-Normal" fading. Usually to model real environments the shadowing effects cannot be, neglected. If the shadowing effect is, neglected, the Path Loss is simply a straight line. To add shadowing effect a zero-mean Gaussian random variable with standard deviation – σ is, added to the equation. The actual path loss may still vary due to other factors. Thus, the path loss exponent (modeling the slope and the standard deviation of the random variable should be, known precisely for a better modeling. The Path Loss Exponent (PLE) table given below is for reference only. It may or may not fit the actual environment we are trying to model. PLE is an important parameter and it affects the system performance drastically. Usually PLE is, considered to be, known a-priori but mostly that is not the case. Care must be, taken to estimate the PLE for the given environment before.

Table 2.2 Log Distance Path Loss or Log Normal Shadowing Model parameter (Viswanathan, Mathuranathan, 2013)

Environment	Path loss exponent(n)
Free space	2
Urban area cellular radio	2.7 to 2.8
Shadowed urban cellular radio	3 to 5
Inside building line of sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factory	2 to 3

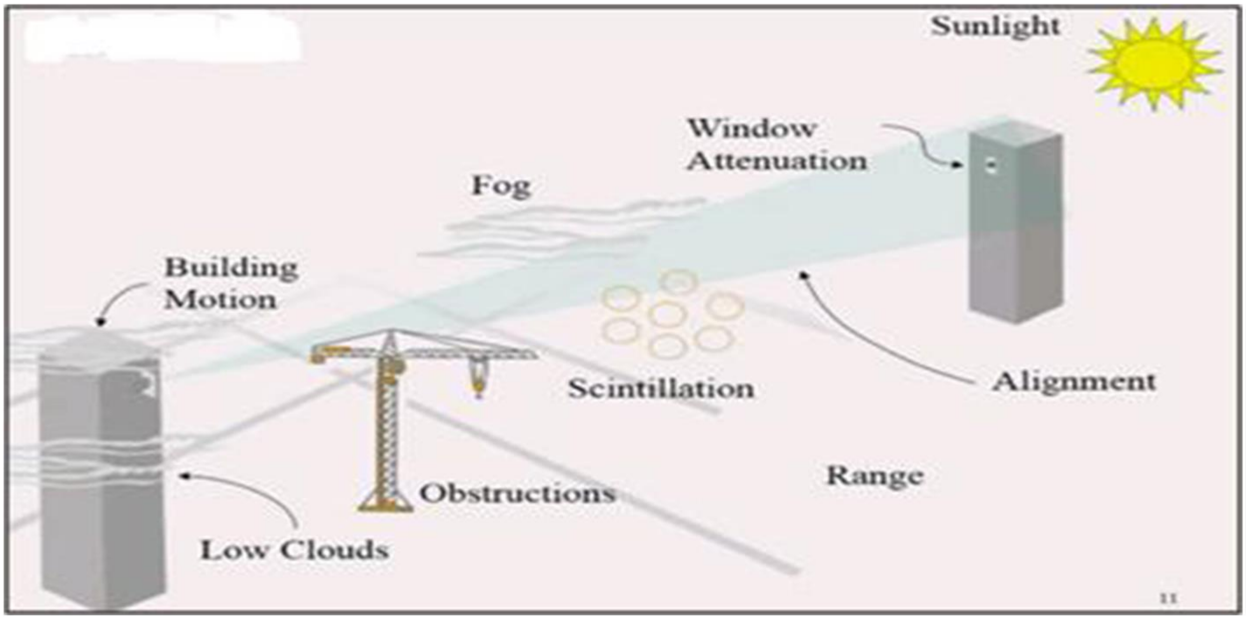

Figure 2.5 Challenges faced by an FSO system under turbulence condition (Farouk Kh. Shaker,Mazin Ali et al., 2019).

2.9. Techniques of to Improve FSO Channels

1. Study the Basic Parameters of FSO System
2. Comparison between SISO and MIMO Techniques
3. Optimal Design of MIMO Technique
4. Design Multi beam FSO Communication Links
5. Multichannel FSO Communication System

2.9. 1. Study the Basic Parameters of FSO System

The first step in designing a wireless communication system knows what happens to the signal when travels through these mediums, this task are, usually accomplished by measuring or simulating the channel impulse response. The enormous bandwidth promising by FSO communications is available only under clear atmospheric conditions. However, this is not a realistic situation, the great potentials of FSO communications and suitable measures should be, used in transmitter and receiver designs, using mat lab simulation software, FSO systems have been, designed and studied the effect of wavelength, beam divergence angle and data rate on the performance of the system under different weather conditions.

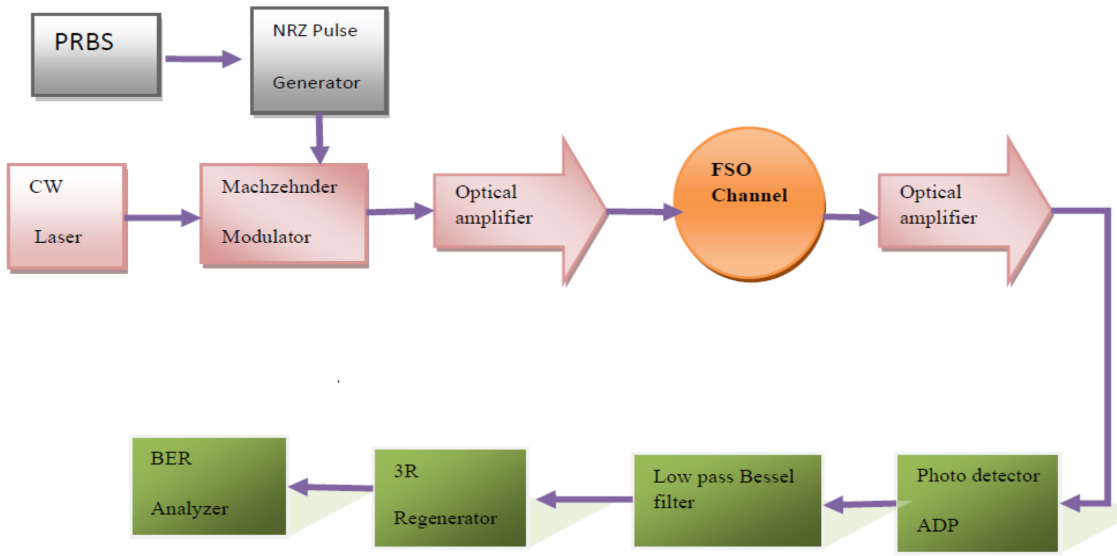

Figure 2.6 Block diagram of Single Input-Single Output (SISO) FSO system shown in figure (Hosam Abd Elrazek Mohamed Ali ,1,2 El-Sayed Soliman A. et al., 2019).

2.9.2. Comparison between SISO and MIMO Techniques

From case1, in clear weather and haze or rain the SISO system operate good without problem but when the weather get worse like fog or snow the link will be failed, so MIMO technique used to improve the communication. In figure (2.6) shown block diagram of MIMO system with two transceiver, some of components use just in MIMO technique like a fork which is use to duplicate the number of output ports so that each of the signals coming out from fork's output has the same value with the output signal from the previous component connected to it. Fork produced multiple beam of laser, these laser beams are, combined by the power combiner. At the receiver, side power coming from FSO channel by a power combined and then fed to the optical receiver. Optical power meter and BER analyzer are two visualizes used in the simulation. One Gbps used as a data rate and made a comparison between this system and the previous one (SISO system) with used same properties for both systems for distance of communication equal to 1Km.

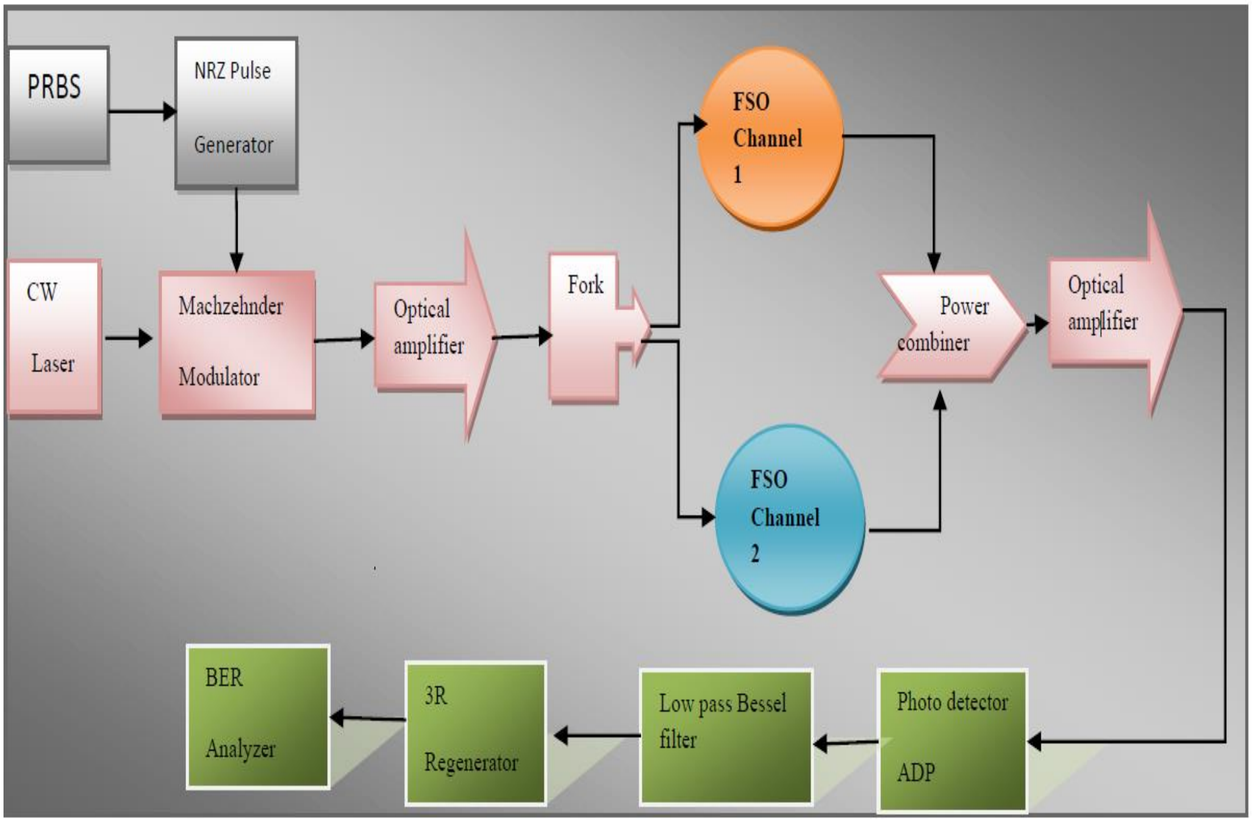

Figure 2.7 Block diagram of MIMO (Hosam Abd Elrazek Mohamed Ali ,1,2 El-Sayed Soliman A. et al., 2019)

2.9.3. Optimal Design of MIMO Technique

In this case optimal design has been done by using four transmitters and four receivers (4Tx/4Rx) FSO system to increase an efficiency of communication, after that we made a comparison between it and (2Tx/2Rx)system which mention in previous case. In the other words, there are two systems. The first one is MIMO with two transceiver and the other one is also, MIMO but with four transceiver (which considered as an optimal design). In this work different weather condition have been, applied to observe the behavior of systems under variable atmosphere effect by calculating link margin for every condition (the link margin value shows how much margin a system has at a given range to compensate for absorption, scattering and scintillation losses).

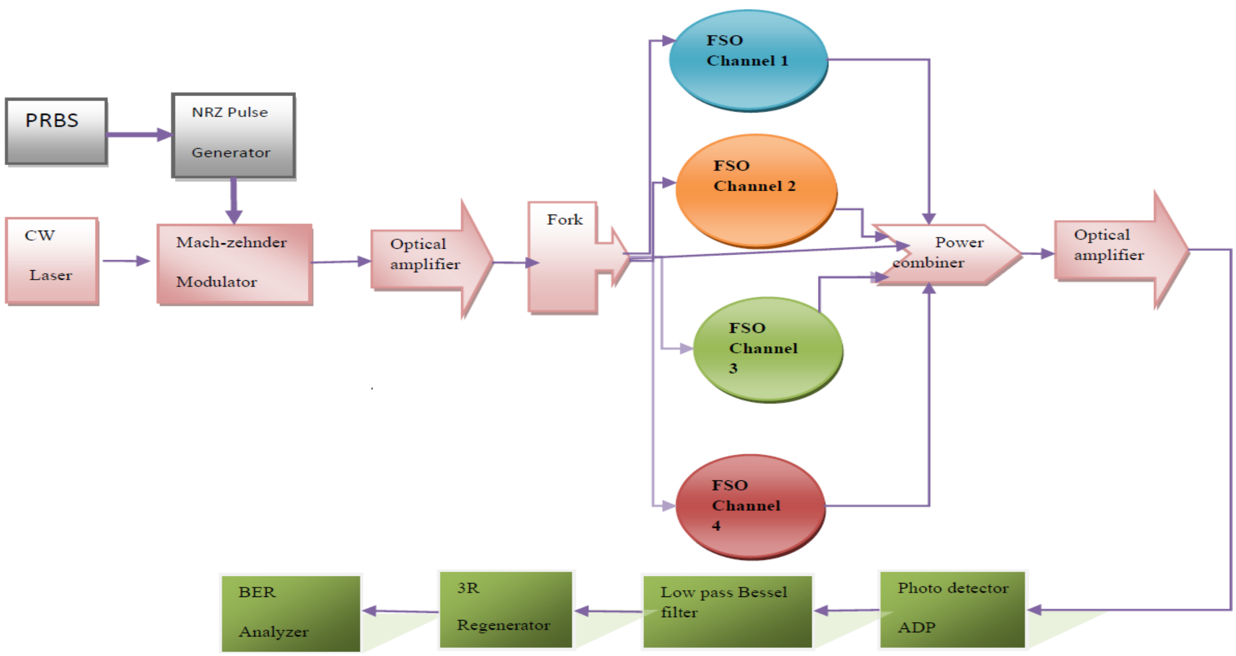

Figure 2.8 Block diagram of optimal MIMO design with four transceiver (Hosam Abd Elrazek Mohamed Ali ,1,2 El-Sayed Soliman A. et al., 2019).

2.10. Design Multi beam FSO Communication Links

To design multi beam FSO communication links a hybrid wavelength division multiplexing WDM)/multi beam architecture can be, used. Multi beam hybrid WDM can be, used for FSO communications to improve data rate in the presence of atmospheric turbulence. The transmitter consists of a continuous wave laser, Mach-Zehnder modulator, data generator, and a de multiplexer. A number of continuous WDM channels spaced by a set of a number of channels is integrated to the de multiplexer and then transmitted to the destination through the atmospheric channel. In the receiver all beams are collected and separated into a single beam profile using a de-multiplexer. An avalanche photo detector (APD) photodiode is, used to convert optical signal into electrical signals and is, filtered to recover the data. This technique can offer a potential solution to the last-mile problem to achieve high capacity, increased transmission distance, and high data rate in multiples of Gbit/s range. The transmitter consists of laser diodes at operating at 1550 nm wavelength, one optical WDM multiplexer, one optical splitter, and spatially diverse lenses.

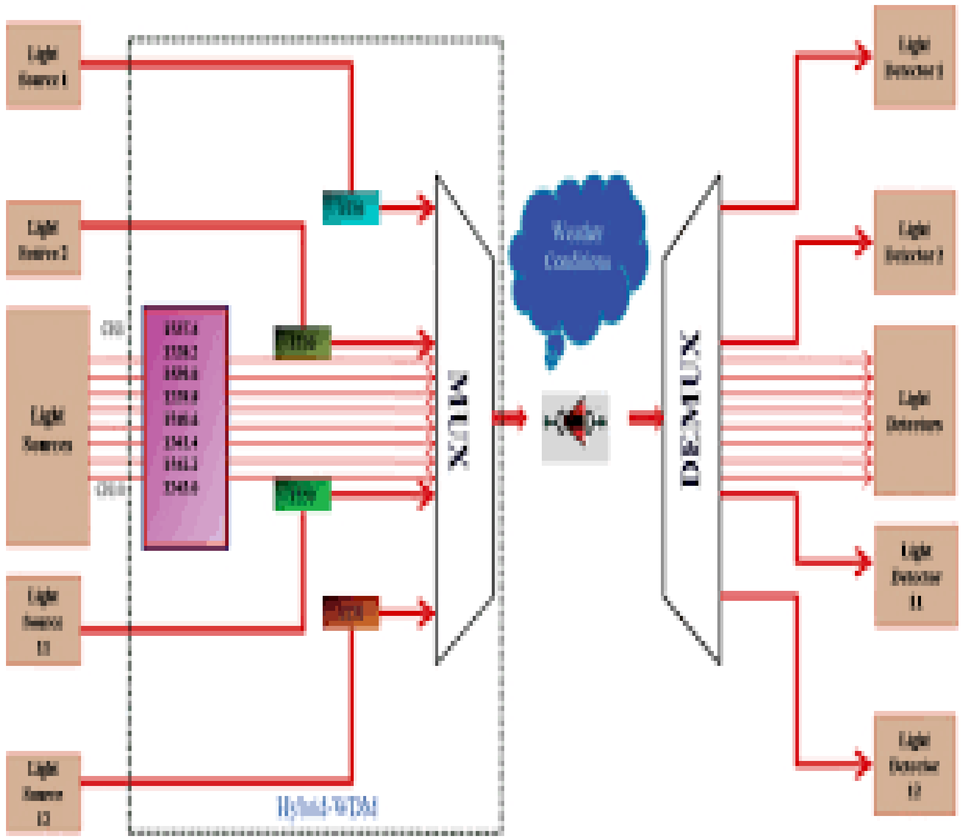

Figure 2.9 Hybrid WDM-FSO modes (S. Robinson, S. Jasmine, 2016).

2.11. Multichannel FSO Communication System

Multichannel FSO communication system using compact (maximum one square-foot), two-dimensional antennas with multiple communication links between them has been explored. High bandwidths of hundreds of Gbit/s are considered. Addressing the multichannel interference issues for such arrays to reduce per channel capacity by efficient array design and employing optical orthogonal codes (OOCs) for FSO communication multi-Gbit/s bandwidths have been achieved (Satish Kumar Modalavalasa1, Rajan Miglani1 et al., 27 August 2021). This unique concept technology can be, applied directly to multi hop broadband access networks or mesh networks and in backhaul to connect wireless base stations. This is therefore a practical potential solution for the last-mile problem. The basic principles for designing a multi-channel FSO system is that the effective bandwidths are, increased with the number of channels. A 10 x10 two-dimensional array should be capable of providing 100 Gbit/s in aggregate capacity with a 1 Gbit/s single transceiver system. The performance of this type of two-dimensional arrays with multiple transmitters and receivers will depend on the number of design factors such as the distance between the arrays, divergence angle of the light source, and package density of the transceivers on the surface of the array. A multichannel system with K+1 simultaneously operating channels, in the performance FSO communication system analysis, with a Gaussian beam profile and on-off keying modulation for the transmitting information bits, a threshold value IT for the receiver's output, a Gaussian shot noise with a power density No were assumed. They modeled the array communication channel as a binary asymmetric channel and the capacity was, estimated as a function of bit error probability. The channel capacity of their array considered the package density on each of the arrays, distance between arrays, and divergence angle of the transmitting light source. The array capacity C is, given by:

$$C = \max p_1 \; H(p_1 p_e) - p_1 H(p_e) \tag{2.14}$$

Where H is the entropy, $p1$ is the input symbol [one or zero] probability distribution, and Pe is the probability of error. The probability of error for multi element FSO communication is, given by

$$p_e = Q\left(\frac{\mathrm{IT}}{2\sqrt{\frac{1}{2}\sum_{k=0}^{K-1} e^{-\left(\frac{4\Theta k}{\Theta}\right)^2} + \frac{\mathrm{NoTb}}{4}}}\right) \tag{2.15}$$

Where the signal from the transmitter was limited by the boundary of [0-≤ t ≤ Tb] for binary 0 or binary1. In Eq. (2.15) Ɵk is the angle of transmission from the kth interferer and Ɵ is the divergence angle of the beam. Q is the usual Q-factor in a Gaussian distribution. When including OOC to minimize the inter array interference for the communication system, for an orthogonal code of weight N and length F, the probability of error is then given by

$$\mathrm{Pe} = Q\left(\frac{IT}{2\sqrt{\left(\frac{N^2}{2F}\right)\left(1-\frac{N^2}{2F}\right)\sum_{k=0}^{K-1} e^{-\left(\frac{4\Theta k}{\Theta}\right)^2} + \frac{\mathrm{NoTb}}{4}}}\right) \tag{2.16}$$

The capacity of the FSO communication system for the array and including OOC can be, calculated from eq. (2.16) for capacity. Their results show that an array without OOCs can be, used for shorter distances (≈150 m) with single laser, and the arrays can be used over longer distance (≈500m) using VCSELS laser array. It was also, shown that by proper design of the pattern for the transceivers packing and implementing optical orthogonal codes on these arrays, capacity close to 1 can be achieved. A helical array design has shown to achieve better capacity. The multichannel FSO communication systems with two-dimensional arrays backhaul can therefore provide a practical solution to offer hundreds of Gbit/s in solving the last-mile problem.

2.12. Massive MIMO Free Space Optical Communication

Free space optical (FSO) communication has established a reputation for itself as a next-generation network capable of delivering high-speed data services. In light of the upcoming, launch of 5G services. To evaluate the performance of the FSO system for the implementation of 5G technology. The link analysis reveals the weak fog events in coastal areas effective link range of up to 10km can be, achieved while maintaining bit error rate of 10^{-1}. Despite dominant foggy conditions in hilly, plains and desert areas, the proposed FSO link significantly limits the degrading effects of channel. Conventionally, MIMO systems have been used to increase the data transmission rates; as in FSO systems, the MIMO approach has been used to improve the probability of correct data reception by transmitting the same information through multiple lines-of sight channels. The optical carriers used in MIMO systems are, tuned at a particular wavelength, and this selection could affect the system properties. Therefore, wavelength selection is a crucial part of the FSO system design. Wavelength diversity refers to the use of different transmission wavelengths and these diverse subcarriers, while propagating through channels, undergo different levels of fading. However, if the information received over different channels is, combined at the receiver, the detection probability of correct information increases. The block diagram for the proposed MIMO-FSO system is, illustrated in Figure (2.8), where the different blocks of the system are, placed according to their functional positions. Since wavelength diversity and spatial diversity have a proven track as performance enhancement catalysts in the FSO system, in this thesis, the use of wavelength diversity along with MIMO systems has been, proposed to provide seamless last mile connectivity. It is important to underline here that FSO signals have to deal with absorption, scattering, and geometrical loss of orientation while propagating. All of these factors contribute toward atmospheric attenuation, which can be, summed as follows:

DB/km = (absorption + scattering + geometrical loss).

Although the inclusion of multiple sub-carrier wavelengths helps improve reception quality, it forms a wideband signal after multiplexing and consumes greater amounts of bandwidth in contrast to the transmission of data over a single carrier. This trade-off between system resources and performance is an exception for next-generation optical networks, as optical links by default possess huge spectral bandwidth. In addition, the wavelength diversified MIMO-FSO system could be, improved further by incorporating the SOA (Semiconductor Optical Amplifiers) and optical filter based link compensation.

Semiconductor Optical Amplifier (SOA): is a semiconductor element that amplifies light. Antireflective processing is, applied on both facets of a semiconductor laser to eliminate the resonator structure. When light enters from outside the semiconductor, the light is, amplified by stimulated emission. SOA is, used for amplifying an optical signal. SOAs are included in the optical transceiver modules used for communication between data centers to amplify the optical signal in the 1.3 um band used for Ethernet communication in order to compensate for transmission loss.

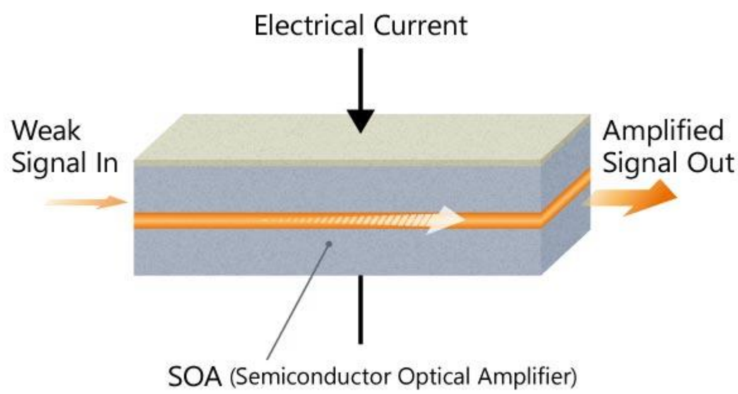

Figure 2.10 Block diagram of SOA (semiconductor optical amplifier) (Satish Kumar Modalavalasa1, Rajan Miglani1 et al., 27 August 2021).

2.13. MIMO-OFDM FSO System

MIMO-OFDM systems are the norm in current wireless systems 5G, WLAN due to their robustness to frequency-selective channels and high data rates enabled. With ever-increasing demands on data rates supported, these systems are getting more complex and larger in configurations with increasing number of antenna elements, and resources allocated. With antenna arrays and spatial multiplexing, efficient techniques to realize the transmissions are necessary Beam forming is one such technique, which is, employed to improve the signal to noise ratio (SNR) that ultimately improves the system performance, as measured here in terms of bit error rate (BER). In MIMO-OFDM single-user system where the maximum number of antenna elements on transmit and receive ends can be 1024 and 32 respectively, with up to 16 independent data streams. It models a spatial channel where the array locations and antenna patterns are in corporate into the overall system design. For simplicity, a single point-to-point link (one base station). The performance of FSO communication can be, improved by using Multiple-Input Multiple-Output (MIMO). When MIMO systems are, used significant capacity gain can be, observed as it exploits spatial multiplexing by having several transmit and receive antennas. At high data rate, for dispersive channel, Inter Symbol Interference (ISI) plays a vital role. Due to the effect of ISI, the capacity of the MIMO system severely degrades. The OFDM provides a solution to this problem. In OFDM, the original signal is, modulated by orthogonal tones. The entire stream is, divided into many parallel sub streams. Hence, the symbol duration is increased and the effect of Inter Symbol Interference (ISI) is, mitigated. OFDM has high spectral efficiency and simple frequency domain equalization. The implementation of OFDM can be, easily carried out by using IFFT at the transmitter and FFT at the receiver. Thus, it provides a cost effective solution to combat the fading caused by atmospheric turbulence in FSO transmission. The use of OFDM in conjunction with MIMO is an attractive technology to meet up the needs of future broadband wireless communication. MIMO-OFDM is the current technology used in the 5G wireless communication system; hence, our approach to the evaluation of the capacity of the proposed FSO communication system with MIMO-OFDM will be very useful for providing a solution to the problem of the last mile bottleneck. However, there is a difference in using MIMO and OFDM in optical communication. The signals are unipolar by nature so we use either DC biased OFDM or clipped OFDM in the optical domain. In this work, we have evaluated the capacity (bits/sec/Hz) of MIMO-OFDM FSO and MIMO FSO in the presence of ISI. The effect of increasing the order of MIMO is also, shown in the results. To model the atmospheric turbulence lognormal channel model is, used, which is suitable for weak turbulence condition. The MIMO-OFDM system is a popular technique in wireless environment to mitigate the effect of fading. Fig. (2.11) shows a typical block diagram of the MIMO-OFDM FSO system. A conventional MIMO system offers enhancement in the capacity in comparison to the Single Input Single Output channel. However, at high bit rates due to ISI the capacity of a MIMO system is limited. To eliminate the effect of ISI and enhance the capacity we use OFDM in conjunction with MIMO. In this work, to evaluate the ergodic capacity, of MIMO-OFDM FSO communication system, we are using an *Mt x Mr* MIMO with OFDM.

i. Transmitter

The transmitter part of the system has *Mt* FSO transmitters. The bits from information source are, first modulated by QPSK/QAM modulation scheme and mapped into symbols (not shown in the figure). These symbols are, and then de multiplexed according to number of transmitters. The message at each transmitter is now parallel sub streams of the original signal. These sub streams are the inputs of serial to parallel converter, which takes N (number of subcarriers) of these symbols as input and produces N output symbols corresponding to the original signal. These N output signals are, put through IFFT for OFDM modulation. The output of the OFDM modulator is the time domain symbol corresponding to the frequency domain input symbol. These symbols are, then converted from parallel to serial and transmitted by all the *Mt* by FSO transmitters. The FSO transmitter's uses either laser diode or light emitting diodes to transmit the optical signal.

ii. Atmospheric Channel

The signals propagate through the atmosphere where they are, distorted due to the effect of turbulence. The lognormal channel model is, used in this work to model the atmospheric turbulence. In this model, the variations of the medium are, assumed as individual cells of air or eddy of different diameters and refractive indices. The intensity fluctuations are, called scintillation, one of the most important factors that limit the performance of an atmospheric FSO communication link. The most widely accepted Kolmogorov gives theory of turbulence is, given by Kolmogorov. This theory assumes that kinetic energy from large turbulent eddies, characterized by the outer scale L0, is transferred without loss to the eddies of decreasing size down to sizes of a few millimeters characterized by the inner scale l0. The inner scale represents the cell size at which energy is dissipated by viscosity. The refractive index varies randomly across the different turbulent eddies and causes phase and amplitude variations to the wave front.

iii. Receiver

After the signal passes through the channel, the faded signal with superimposed noise on the *Mt* transmitted signals is, received by the FSO receiver array. At the receiver optical detectors, like an avalanche photo diode detect the signals. These detected signals after converting into parallel sub channel are, put through Fast Fourier Transform (FFT) for OFDM demodulation. The fading caused by atmospheric turbulence produces ISI. This ISI can be, taken into account by changing the delay spread into a number of interfering symbols.

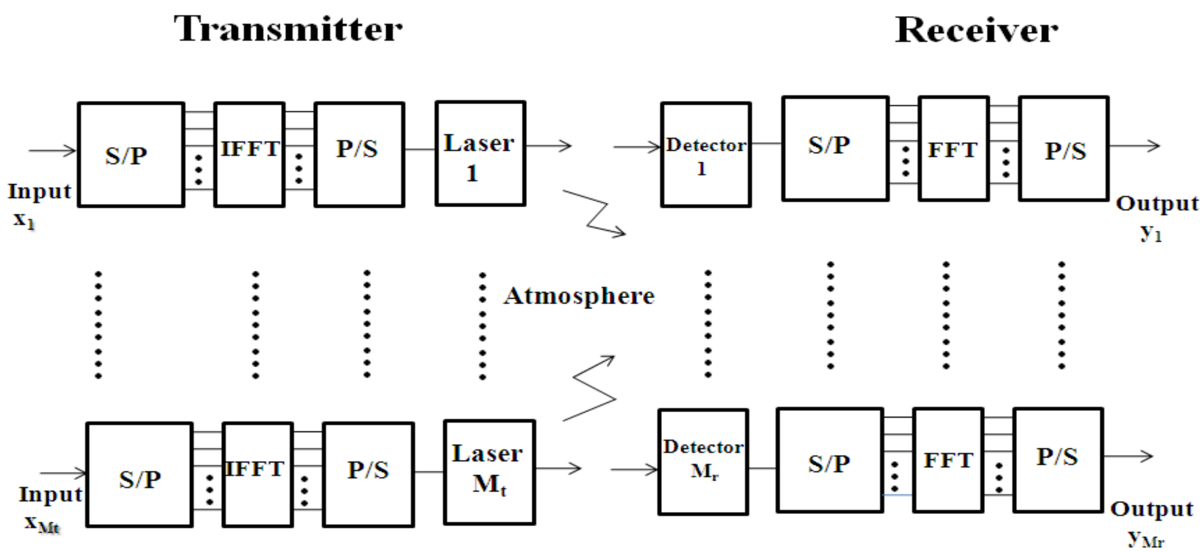

Figure 2.11. Block diagram of MIMO-OFDM FSO system (Manish Sharma1, D. Chadha1 et al., 2013)

2.13.1. Capacity Analysis

$$I = I_0 exp^{(x)} \tag{2.17}$$

I=intensity

$$\tilde{y} = \tilde{H}\tilde{x} + \tilde{n} \tag{2.18}$$

$$\tilde{y} = \widetilde{E_2}\tilde{H}\widetilde{E_1}\tilde{x} + \widetilde{E_2}\tilde{n} = \tilde{H}`\tilde{x} + \tilde{n}` \tag{2.19}$$

Where, $\widetilde{E_1}$ is IFFT transformation matrix given by:

$\widetilde{E_1} = (\widetilde{E_{1,j}}) \otimes I_{M_t}$, ; $e_{i,j} = exp^{(j2\pi i\ j/N)}$; i,j = 0,1,2….N – 1, $\widetilde{E_2}$ is FFT transformation matrix given by

$\widetilde{E_2} = (\widetilde{E_{1,j}}) \otimes I_{M_r}$, ; $e_{i,j} = exp^{(j2\pi i\ j/N)}$; i, j = 0,1,2….N – 1, N is number of subcarriers**,** I_{Mt} represents the M_t x M_t identity matrix and IMr represents an Mr x Mr identity matrix. The characteristic of the channel is, taken into account by changing the delay spread into a number of interfering symbols represented by L. The channel matrix is given by (P. Uthansakuand and M. E. Bialkows,“, 2004)as:

The channel capacity of conventional MIMO and MIMO-OFDM

$$C = E\left(\log_2 \det\left(I_m + \frac{\rho}{M_t}\widetilde{H}\widetilde{H}^{\dagger}\right)\right) \quad (2.20)$$

$$C = E\left(\log_2 \det\left(I_m + \frac{\rho}{M_t}\widetilde{H}`\widetilde{H}`^{\dagger}\right)\right) \quad (2.21)$$

where E (.) denotes expectation, m is min (Mr, Mt), ρ is an average signal to noise ratio (SNR) at each receive antenna and" $\widetilde{H}$" is the channel matrix which incorporates the subcarriers of OFDM, number of interfering symbols and random numbers generated according to the channel model, i.e., Lognormal channel. †denotes conjugate transpose of a matrix.

2.13.2. Channel Sounding

For a spatially multiplexed system, availability of channel information at the transmitter allows for pre-coding to be, applied to maximize the signal energy in the direction and channel of interest. Under the assumption of a slowly varying channel, this is, facilitated by sounding the channel first, where in for a reference transmission, the receiver estimates the channel and feeds this information back to the transmitter. For the chosen system, a preamble signal is, sent over all transmitting elements and processed at the receiver accounting for the channel. The receiver elements perform pre-amplification, OFDM demodulation, frequency domain channel, estimation and calculation of the feedback weights based on channel diagonalization using singular value decomposition (SVD) per data subcarrier. For conciseness in presentation, front-end synchronization including carrier and timing recovery are, assumed. The weights computed are, hence fed back to the transmitter, for subsequent application for the actual data transmission.

2.13.3. Data Transmission

This process includes channel coding, bit mapping to complex symbols, splitting of the individual data stream to multiple transmit streams, pre-coding of the transmit streams and OFDM modulation with pilot mapping, and replication for the transmit antennas employed. For pre-coding, the preamble signal is, regenerated to enable proper channel estimation. It is prepended to the data portion to form the transmission packet which is then replicated over the transmit antennas.

2.13.4. Transmit Beam Steering

Phased Array System offers components appropriate for the design and simulation of phased arrays used in wireless communications systems. For the spatially aware system, the signal transmitted from the base station is steered towards the direction of the mobile, to focus the radiated energy in the desired direction. This is, achieved by applying a phase shift to each antenna element to steer the transmission. We uses a linear or rectangular array at the transmitter, depending on the number of data streams and number of transmit antennas selected.

2.13.5. Receive Beam Steering

The receiver steers the incident signals to align with the transmit end steering, per receive element. Thermal noise and receiver gain are applied. Uniform linear arrays with isotropic responses are, modeled to match the channel and transmitter arrays. The receive antenna pattern mirrors the transmission steering. Beam steering is a technique for changing the direction of the main lobe of a radiation pattern. In radio and radar systems, beam steering may be accomplished by switching the antenna elements or by changing the relative phases of the RF signals driving the elements. In recent days, the beam steering is playing significant role in 5G communication because of quasi-optic nature of 5G frequencies. In acoustics, beam steering is, used to direct the audio from loudspeakers to a specific location in the listening area. This is, done by changing the magnitude and phase of two or more loudspeakers installed in a column where, the combined sound is added and, can celled at the required position. Commercially, this type of loudspeaker arrangement is, known as a line array. This technique has been around for many years but since the emergence of modern Digital Signal Processing technology, there are now many commercially available products on the market. In optical systems, beam steering may be accomplished by changing the refractive index of the medium through which the beam is transmitted or by the use of mirrors, prisms, lenses, or rotating diffraction gratings.

2.13.6. The Winner ii Channel Model Spatially Defined m- MIMO

Channel that allows you to specify the array geometry and location information. We use the typical urban microcell indoor scenario with very low mobile speeds. The two scattering based channels use a single-bounce path through each scattered where the number of scatters is user-specified. For this we uses the number of stutterers is set to 100. The 'Scattering' option models the scatters placed randomly within a circle in between the transmitter and receiver, while the 'Scattering models their placement completely randomly. The models allow path loss modeling and both line-of-sight (LOS) and non-LOS propagation conditions. We assumes that non-LOS propagation and isotropic antenna element patterns with linear geometry. Apply a spatially defined channel to the steered. The same channel is, used for both sounding and data transmission, with the data transmission having a longer duration controlled by the number of data symbols parameter.

2.13.7. Signal Recovery

The receive antenna array passes the propagated signal to the receiver to recover the original information embedded in the signal. Similar to the transmitter, the receiver used in a MIMO-OFDM system contains many stages, including OFDM demodulator, MIMO equalizer, QAM demodulator, and channel decoder. For the MIMO system modeled, the displayed receive constellation of the equalized symbols offers a qualitative assessment of the reception. The actual bit error rate offers the quantitative figure by comparing the actual transmitted bits with the received decoded bits.

2.14. Antenna Selection MIMO-OFDM Wireless Systems and Model

We consider a point-to-point MIMO-OFDM system with K subcarriers, n_T transmit antennas, and n_R*receive* antennas. The number of equipped transmit RF chains is n_{RF}, $n_{RF} \leq n_T$. A simplified block diagram of the system is shown in Fig.(2.12) At the transmitter, the input data stream is, mapped onto a unit-energy M-QAM (M-ary quadrature amplitude modulation) or M-PSK (M-ary phase shift keying) constellation. The subcarrier allocation block takes in a data frame of u = (u(0), u(1),..., u(K -1), and then allocates the data symbol $u(k)$,0 $\leq k \leq K$ -1, to the selected antenna, denoted as i_kAssociated with the k th sub carrier.

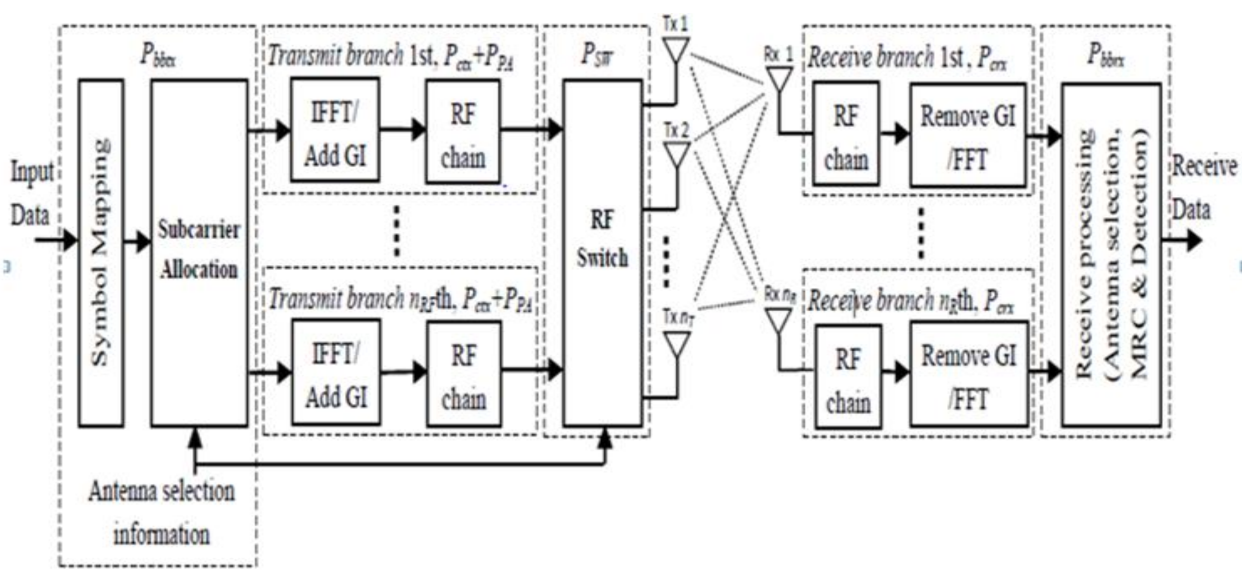

Fig. 2.12 A simplified block diagram of an antenna selection MIMO-OFDM wireless system (N. Phuc. Le, F. Safaei & L. Chung., 2016).

Vector x (k) = ((k), x_2 (k)… x_{nT} (k))^T is assigned the data symbol, whereas the others are zero square. The output sequences from the subcarrier allocation block are then fed into *K*-point IFFT (inverse fast Fourier transform) blocks. Each time-domain OFDM signal is then, added with a guard interval (GI) before being, transmitted via its corresponding transmit antenna. Note that the transmit branch corresponding to the output of the subcarrier allocation block that is not allocated any data symbol is turned off to save energy. At the receiver, the received signal at each antenna is fed into the FFT block after the GI is removed. The received signal in the frequency domain corresponding to the k_{th} subcarrier can be expressed, as

$$Y(k) = \sqrt{P_t}H(K)x(k)+n(k) = \sqrt{P_t}h_{ik}(k)u(k) +n(k), \quad (2.22)$$

Where,

H(k) denotes the sub channel matrix associated with the k_{th} subcarrier where its entries are denoted as $h_{j,i}$,i = 1,2,…, n_T, j = 1,2,…, n_{ik}(k) indicates the effective channel vector obtained by selecting the column of H(k) that is corresponding to selected transmit antenna i_k on the kth subcarrier, and P_t is an equal transmit power allocated to each data subcarrier. Note that the total transmit power in one OFDM symbol is

P_T = KP_t Also vector y (k) = (y_1(k), y_2 (k),... y_{nR}(k))^T and

n(K) = (n_1 (k), n_2 (k),…. y_{nR} (k))^T,where y_j(k) and n_j(k) denote that received signal and the noise at the j_{th} receive antenna, respectively. Here, the noise is, modeled as a Gaussian random variable with zero-mean and variance square. Assume that the receiver uses an MRC (maximum ratio combining) method for signal detection, the detected signal at the k_{th} subcarrier.

CHAPTER THREE

3. System Model and Description

The approach for design and performance analysis of free space optical communication over various optical filtering for fifth generation system has been, design and simulate using mat-lab with optical filters.

2.8. Methods

This thesis has been, conducted according to the following steps:

Step1: Studying the basic theory, architectures and related subjects.

Step2: Revising the existing work in the literature, which is, related to the FSO communication.

Step3: Identifying the parameters which required for modeling of our system

Step4: Modeling our system by using mat lab

Step5: Testing of the proposed system, this is simulated.

Step6: Results are, analyzed by using QAM modulation and BER.

Step7: Compare and contrast our result by using different modulation and classify them into main categories depending on their performance.

Step8: Compare this work with other related work to get the final deduction.

2.9. The General Mathematical Models of MIMO Channel

The basic MIMO channel model and its core requirements, multilink channel sounding techniques, MIMO technology classification, and MIMO channel modeling are, presented in this section. First, the generalized MIMO channel model and MIMO channel modeling techniques are, introduced. Second, the concept of multilink channel sounders is, presented briefly. This section also covers the single-sounder sequential measurements, single-sounder multi node measurements, and multi-sounder measurements. Further to this, we high light the basic classification of MIMO channel models point-to-point, multiuser MIMO, and massive MIMO, and provided a concise description of the multiuser MIMO for the uplink and downlink scenarios. Wireless Communications and Mobile Computing.

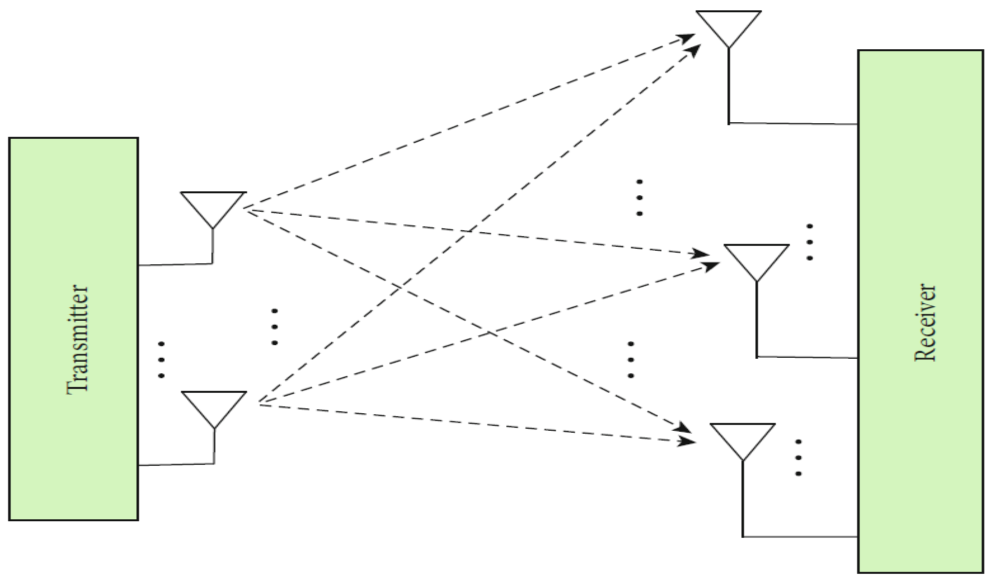

Figure 3.1. Basic MIMO channels showing multiple transmit and receive antennas (Agbotiname Lucky Imoize , Augustus Ehiremen Ibhaze et al., 2021).

2.9.1. Basic MIMO Channel Model

The traditional single antenna communication system lacks the required spatial degree of freedom provided by multiple antennas. In MIMO communication systems, the presence of multiple antennas can be of great advantage. The spatial degree of freedom provided by these antennas can be, appropriately harnessed to boost the capacity and expand the system's coverage through optimal scheduling of multiple users to simultaneously, share the spatial channel. As illustrated in Figure 3.1 the channel gives useful information about transmitting and receiving antennas in a simple MIMO channel. Considering the case of an $n \times m$ MIMO channel system, where m and n represent the respective numbers of transmitting and receiving antennas the linear time-variant MIMO channel could be, modeled as shown in [3.1], using an $n \times m$ channel matrix (P. Almers, E. Bonek, A. Burr et al., 2007).

$$H(t, \tau) = \begin{pmatrix} h_{11}(t,\tau) & h_{12}(t,\tau) & h_{13}(t,\tau) & \cdots & h_{1m}(t,\tau) \\ h_{21}(t,\tau) & h_{22}(t,\tau) & h_{23}(t,\tau) & \cdots & h_{2m}(t,\tau) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ h_{n1}(t,\tau) & h_{n2}(t,\tau) & h_{n3}(t,\tau) & \dots & h_{nm}(t,\tau) \end{pmatrix} \tag{3.1}$$

Where $h_{nm}(t,\tau)$ is the time-variant channel impulse response between the m^{th} transmit antenna and the n^{th} receive antenna. The channel matrix in (3.1) includes antenna-type effects, configuration, orientation, and frequency filtering. This knowledge could be instrumental in formulating a general multiple input multiple output relationship between the length- *m* transmit signal vector *s*(t) and the length- *n* receive signal vector *y*(t) given in (3.2).

$$y(t) = H(t,\tau)s(t-\tau)d\tau + n(t) \quad (3.2)$$

Where n (t) gives the accompanying noise plus interference. For a time-invariant channel, the dependency of the channel matrix t reduces to zero. Therefore, H $(\tau) = H(t,\tau)$for instance, if the channel has a flat frequency, meaning there will be one single tap denoted by H, then reduces to (3.3).

$$y(t) = Hs(t) + n(t) \quad (3.3)$$

2.9.2. Channel Model Requirements

In simple terms, mobile radio propagation models have diverging requirements to meet. On the one hand, the models should be very robust to provide adequate information about the propagation Channels properties. Here, the models' deficiencies should be, stated such that there is no ambiguity in applying the models to the desired propagation environments. On the other hand, the models should be, designed with simplicity for easy application, rapid implementation, and less computational complexities. Channel models developed in the past focused only on the aspects of key interests at the time. Such models might not give an accurate prediction of the radio channels if other environmental characteristics are considered. Given this, some existing models tend to present data on the received signal level and other key performance indicators (KPIs) (A. L. Imoize, K. Orolu et al., 2020). Typical example of such model is Okumura-Hata model (P. Almers, E. Bonek, A. Burr et al., 2007).

2.10. Multilink Channel Sounding Techniques

In the past, the capabilities of most channel sounders are limited to single link measurements. As the number of links increases, there arises a need to design innovative solutions to characterize multilink propagation experimentally. In recent years, some techniques have been, developed to measure multiple links.

2.10.1. MIMO Technology Classification

MIMO technology can be, classified as point-to-point, multiuser, and massive MIMO. These are, briefly described as follows.

i. Point-to-Point: This MIMO technology is the simplest of the three (T. L. Marzetta, E. G. Larsson, H. Yang et al., 2016).The BS is installed with an antenna array communicating with other terminals that are having an antenna array. The various terminals are, multiplexed in an orthogonal manner, using time- and frequency-division multiplexing techniques. Practically, point-to-point MIMO's usefulness can be limited even with massive arrays at the link terminals due to three key factors. First, the terminal equipment is quite complex, and it requires independent RF chains per antenna and the use of advanced digital signal processing techniques to separate the data streams. Second, the propagation environment should support minimum base stations and terminal antennas' independent streams. In a real-life scenario, this is difficult to achieve, mainly when compact arrays are used. Last, the spectral efficiency scales slowly with the minimum base station and terminal antennas near the cell edge, where ordinarily many of the terminals are located and where SNR is practically low due to severe path loss in the propagation paths (T. Marzetta, 2015).

ii. Multiuser MIMO: In multiuser MIMO (MU-MIMO), an antenna can provide network services to several UEs utilizing the same frequency resources. MU-MIMO has some advantages over the point-to-point MIMO (P2PMIMO). MU-MIMO can use only single-antenna terminals. It is practically less, affected by the propagation environment's dynamics, unlike point-to-point MIMO, which is easily, affected by the conditions of line of sight. However, the practicality of MU-MIMO is, limited by two factors. The base station and the terminals must know the channel state information (CSI) on the downlink (G. Caire, N. Jindal et al., 2010). This can be very expensive, as enormous resources are required to transmit pilots in both directions efficiently. Second, advanced signal processing is highly needed for the BS and UEs for high spectral efficiency. Several wireless communication-related companies like Nokia Siemens, Intel, and Agilent Technologies, among others, treat multiuser MIMO as an adoptable candidate technology given by the Samurai project report (B. Badic, A. F. Cattoni, M. Dieudonne et al, 2012). The system is more feasible for mobile devices with low complexity and few reception antennas. To this end, an introduction to the multiuser MIMO downlink is, given in (Q. H. Spencer, C. B. Peel et al., 2004). Here, two algorithms comprising a signal processing with various types of transmitter beam forming and dirty paper coding (Costa, 1983) to solve the problem of signal interference from other users are, well explained in simple terms.

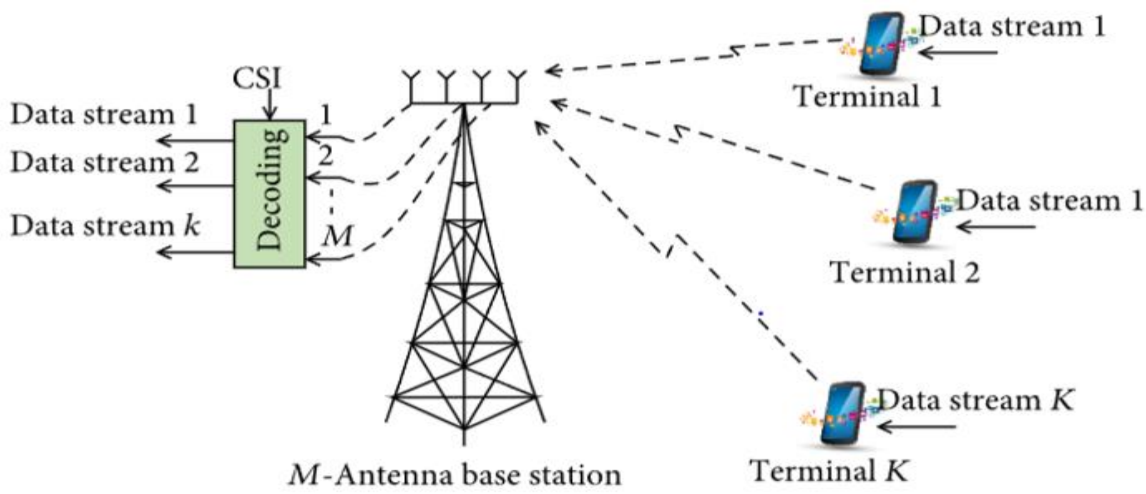

Figure 3.2a Uplink (Noha Hassan †ID and Xavier Fernando *,, 2017)

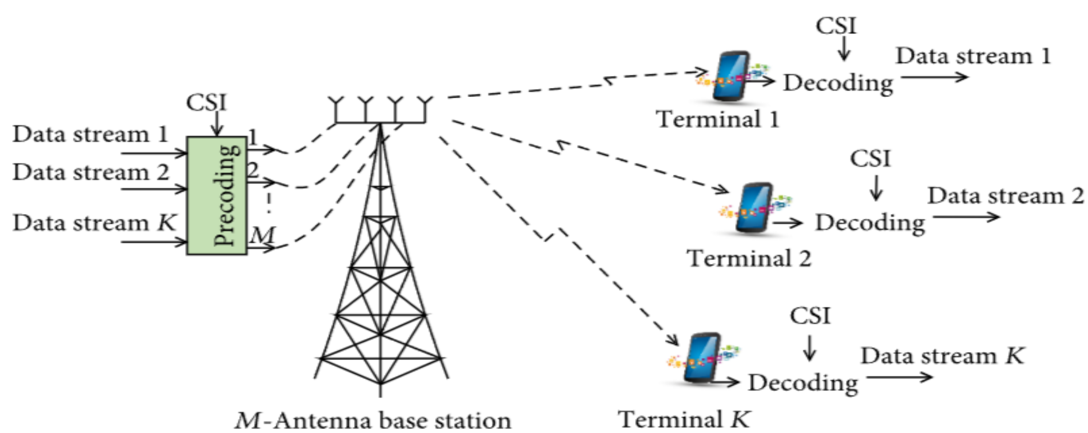

Figure 3.2b Downlink (Noha Hassan †ID and Xavier Fernando *,, 2017)

iii. Massive MIMO

A useful and scalable version of multiuser MIMO is, referred to as massive MIMO (m-MIMO). Massive MIMO is different from MU-MIMO in three instances.

1. Massive MIMO requires that only the BS needs to know about the channel state information.
2. The number of base stations is typically more significant than the number of terminal antennas.
3. There is no stringent requirement for complex signal processing techniques. This is because simple linear signal processing can be, done on the uplink and downlink as indicated in several works (Agbotiname Lucky Imoize , Augustus Ehiremen Ibhaze et al., 2021).

2.11. BER Analysis of Rayleigh Fading Channels in Mobile Communication

In the study of communication systems the classical additive white Gaussian noise channel, with statistically independent Gaussian noise samples corrupting data samples free of inter-symbol interference (ISI), is the usual starting point for understanding basic performance relationships. The primary source of performance degradation is thermal noise generated in the receiver. The external interference received by the antenna is significant than thermal noise. This external interference can sometimes be, characterized as having a broadband spectrum and is, quantified by a parameter called antenna temperature. The model of free space treats the region between transmit and receive antennas as being free of all objects that might absorb or reflect radio frequency energy. It also assumes that, within this region, the atmosphere behaves as a uniform and non-absorbing medium. In this idealized free-space model, the attenuation of RF energy between the transmitter and receiver behaves according to an inverse-square law. For most practical channels, where signal propagation takes place in the atmosphere and near the ground, the free space propagation model is inadequate to describe the channel and predict system performance. In a wireless mobile communication system, a signal can travel from transmitter to receiver over multiple reflective paths; this phenomenon is, referred to as multipath propagation. The effect can cause fluctuations in the received signal's amplitude, phase, and angle of arrival, giving rise to the terminology multipath fading. Another name, scintillation is used to describe the multipath fading caused by physical changes in the propagating medium, such as variations in the density of ions in the ionosphere layers that reflect high frequency (HF) radio signals. Names, fading and scintillation refer to a signal's random fluctuations or fading due to multipath propagation. The main difference is that scintillation involves mechanisms (e.g., ions) that are much smaller than a wavelength. The end-to-end modeling and design of systems that mitigate the effects of fading are usually more challenging than those whose sole source of performance degradation is AWGN (Vinay Panwar,Sanjeet Kumar, 2012).

2.11.1. Types of Fading

There are two types of fading effects, which characterize mobile communications

1. Large-scale fading represents the average signal power attenuation or path loss due to motion over large areas.

2. Small-scale fading refers to the dramatic changes in signal amplitude and phase that can be, experienced because of small changes in the spatial separation between a receiver and transmitter.

2.11.2. Bit Error Rate

Bit error rate is a key parameter that is, used in assessing systems that transmit digital data from one location to another. BER is applicable to radio data links, Ethernet, as well as fiber optic data systems. When data is, transmitted over a data link, there is a possibility of errors being introduce into the system. If this is so, the integrity of the system may be, compromised. As a result, it is necessary to assess the performance of the system, and BER provides an ideal way in which this can be, achieved. BER assesses the full end-to-end performance of a system including the transmitter, receiver and the medium between the two. BER is, defined as the rate at which errors occur in a transmission system. In simple form;

$$\text{BER} = \frac{\text{number of bits in error}}{\text{total number of bits sent}} \tag{3.4}$$

BER expression is by

$$\text{BER} = \int_0^\infty P_{b\left(\frac{E}{r}\right)P(r)dr} \tag{3.5}$$

$P_{b\left(\frac{E}{r}\right)}$ =the conditional error probability

$P(r)$= the pdf of the SNR

2.12. Performance Analysis BER vs Eb/No

i. BPSK and D-BPSK Detection

In coherent detection, the receiver derives its demodulation frequency and phase references using a carrier synchronization loop. Such synchronization circuits may introduce phase ambiguity in the detected phase, which could lead to erroneous decisions in the demodulated bits.

ii. QPSK Transmitter and Receiver

The receiver addresses practical issues in wireless communication, such as carrier frequency and phase offset, timing drift and frame synchronization. QPSK is modulation scheme that allows one symbol to transfer two bits of data. There are four possible two-bit number (00, 10, 11), and consequently we need four phase offsets. Again, we want maximum separation between the phase options.

iii. M-phase-shift keying (M-PSK)

M-PSK is, employed in some of digital cellular standards and communication geostationary satellite system. MPSK employs a set of M equal-energy signals to represent M equi-probable symbols. This constant energy restriction [i.e., the constant envelope constraint] warrants a circular constellation for signal points.

Table 3.1 BER vs Eb/No

Modulation	Detection Method	Bit Error Rate(pb)
BPSK	Coherent	0.5ercf($\sqrt{\frac{Eb}{No}}$)
QPSK	Coherent	0.5ercf($\sqrt{\frac{Eb}{No}}$)
M-PSK	Coherent	$\frac{1}{m}$erfc($\sqrt{\frac{mEb}{No}}$sin($\frac{k}{M}$))
M-QAM[m = even]	Coherent	(m = even) $\frac{2}{m}$(1-$\frac{1}{\sqrt{M}}$)erfc ($\sqrt{\frac{3mEb}{2(M-1)No}}$)
D-BPSK	Non-coherent	$0.5e^{\frac{-Eb}{No}}$
D-QPSK	Non- coherent	Q1(a, b) – $0.5I_0(ab)e^{-0.5(a^2} + b^2)$ Where a = $\sqrt{\frac{2Eb}{No}}\,(1-\frac{1}{\sqrt{2}})$ b = $\sqrt{\frac{2Eb}{No}}\,(1+\frac{1}{\sqrt{2}})$ Q1(a, b) = Marcum Q-function Io(a, b) = Modified Bessel- function

2.13. Inter-symbol Interference and Equalization

The all-pass assumption made in the AWGN (or non-dispersive) channel model is rarely practical. Due to the scarcity of the frequency spectrum, we usually filter the transmitted signal to limit its bandwidth so that efficient sharing of the frequency resource can be, achieved. Moreover, many practical channels are band pass and, in fact, they often respond differently to inputs with different frequency components, i.e., they are dispersive. We have to refine the simple AWGN (or non-dispersive) model to accurately represent this type of practical channels. One such commonly employed refinement is the dispersive channel model.

$$R(t) = u*h_c(t) + n(t) \tag{3.6}$$

Where,

U(t)-the transmitted signal

h_c(t)-the impulse response of channel

N(t) = AWGN with power spectral density $d_o/2$

In essence, we model the dispersive characteristic of the channel by the linear h_c(t) filter. The simplest dispersive channel is the band-limited channel for which the channel impulse response h_c(t) is that of an ideal low pass filter. This low pass filtering smears the transmitted signal in time causing the effect of a symbol to spread to adjacent symbols when a sequence of symbols is, transmitted. The resulting inter-symbol interference (ISI) degrades the error performance of the communication system. There are two major ways to mitigate the detrimental effect of ISI. The first method is to design band limited transmission pulses that minimize the effect of ISI. We will describe such a design for the simple case of band-limited channels. The ISI free pulses obtained are called the Nyquist pulses. The second method is to filter the received signal to cancel the ISI introduced by the channel impulse response. This approach is, generally known as equalization (Al-janabi, Hussen Dheaa kamil, 2012).

2.14. An optical filter

Filter is a device that selectively transmits light of different wavelengths, usually implemented as a glass plane or plastic device in the optical path, which are either dyed in the bulk or have interference coatings. The optical properties of filters are, completely described by their frequency response, which specifies how the magnitude and phase of each frequency component of an incoming signal is, modified by the filter (Christi K. Madsen, Jian H. Zhao, 1999). Filters mostly belong to one of two categories. The simplest, physically, is the absorptive filter; then there is interference or dichroic filters. Many optical filters are used for optical imaging and are manufactured to be transparent; some used for light sources can be translucent. Optical filters selectively transmit light in a particular range of wavelengths, that is, colors, while absorbing the remainder. These are more usually older designs traditionally used for photography; filters with more regular characteristics are, used for scientific and technical work. In astronomy optical filters are used to restrict light passed to the spectral band of interest, e.g., to study infrared radiation without visible light which would affect film or sensors and overwhelm the desired infrared. Optical filters are also essential in fluorescence applications such as fluorescence microscopy and fluorescence spectroscopy. There are many different kinds of filters, including Gaussian, Bessel, Trapezoidal, Rectangular and Fabry perot

For Gaussian, filter function given by

$$H(f) = \alpha e^{-ln\sqrt{2}(\frac{(f-fc)2N}{B})} \tag{3.7}$$

Where H(f) is the filter transfer function, α is the parameter Insertion loss. fc is the filter center frequency defined by the parameter Frequency, B is the parameter Bandwidth, N is the parameter Order and f is the frequency.

For Bessel function given by

$$H(f) = \alpha \frac{do}{BN(s)} \tag{3.8}$$

α is the parameter Insertion loss, N is the parameter Order, is an nth-order Bessel polynomial of the form expressed as,

Trapezoidal filter

$$H(f) = \alpha 10\left(\frac{1-A}{10B-BOdB}\right)(f-fc) \tag{3.9}$$

Where, H(f) is the filter transfer function, α is the parameter Insertion loss. fc is the filter center frequency defined by the parameter Frequency, B is the parameter Bandwidth at the cutoff magnitude, B0dB is the parameter Zero dB bandwidth, and f is the frequency.

Rectangular

$$H(f) = \alpha\left(\frac{1-R)}{1-R*e^{2\pi l\left(\frac{f-fc}{B}\right)}}\right) \quad (3.10)$$

For fabry-parot the transfer function is given by

$$H(f) = \alpha\left(\frac{1-R)}{1-R*e^{2\pi l\left(\frac{f-fc}{B}\right)}}\right) \quad (3.11)$$

Where, H (f) is the filter transfer function, α is the parameter Insertion loss. fc is the filter center frequency defined by the parameter Frequency, B is the parameter Bandwidth, and f is the frequency. With FSR is the parameter free spectral range.

To implement and analysis of the simulation result based on table 3.2 parameter setup

Table 3.2 Simulation parameters

Parameter	Value
NFFT Number of subcarriers	256
Cyclic prefix	64
Transform	FFT
Convolution Code Rate	1/2, 2/3, 3/4…………
Modulation order	2,4,8,16,32,64,256
Simulated environment	Rayleigh channel (NLSOS)
Detection techniques	Minimum mean square error (MMSE0
Number of transmit antenna	32
Number of received antenna	16
Bits Per Subcarrier	2: QPSK, 4: 16QAM, 6: 64QAM, 8:256QAM
Distance for mobile	300m
Specified angle(azimuth & elevation)	-(90,90),(-90,90)degrees respectively

Table 3.3 Maximum quality factor for previous model and our modified model with different optical filters in relation to the range

Maximum Q Factor						
Range (cm)	Previous model	Proposed model (Bessel)	Proposed model (Trapezoidal)	Proposed model (Gaussian)	Proposed model (Rectangular)	Proposed model (Fabry perot)
0	550.4	177.99	178.98	194.99	179.99	213.99
100	490.56	282.49	267.02	314.2	280.02	319.3
200	381.8	332.99	315.9	368.6	330.2	362.12
300	253.8	359.02	335.01	398.4	345.89	376.99
400	275.3	376.43	350.45	413.66	363.45	389.5
500	175.3	243.9	286.5	256.1	225.61	195.47
600	120.1	155.7	185.1	164.2	149.94	135.8
700	83.32	102.9	125.03	102.6	98.92	87.9
800	58.98	67.9	86.01	68.9	65.25	60.54
900	38.29	44.83	68.9	57.89	43.37	45.7

Table 3.4 Maximum quality factor for our proposed model with different optical filters in relation to transmitter aperture diameter

Maximum Q Factor					
TX. aperture Diameter (cm)	Proposed model (Bessel)	Proposed model (Trapezoidal)	Proposed model (Gaussian)	Proposed model (Rectangular)	Proposed model (Fabryperot)
0	177.99	178.98	194.99	179.99	213.99
10	282.49	267.02	314.2	280.02	319.3
20	332.99	315.9	368.6	330.2	362.12
30	359.02	335.01	398.4	345.89	376.99
40	376.43	350.45	413.66	363.45	389.5

Table3.5 Maximum quality factor for our proposed model with different optical filters in relation to Receiver aperture diameter.

Maximum Q Factor					
RX. Aperture Diameter (cm)	Proposed model (Bessel)	Proposed model(Trapezoidal)	Proposed model (Gaussian)	Proposed model (Fabryperot)	Proposed model(Rectangular)
0	238.4	246.4	266.32	278.32	238.4
10	335.32	325.9	371.2	363.89	336.32
20	367.43	355.8	405.99	387.43	360.89
30	382.2	363	421.99	398.45	370
40	389.4	360	431.45	405.98	375

Table 3.6 Maximum quality factor for the previous model and our modified model with different optical filters in relation to beam divergence.

Maximum Q Factor						
Beam div. (mrad)	Previous model	Proposed model (Bessel)	Proposed model (Trapezoidal)	Proposed model (Gaussian)	Proposed model (Rectangular)	Proposed model (Fabry perot)
0	318	413	364	387	340	320
2	270	347	317	330	296	268
4	226	290	269	275	253	226
6	191	245	235	235	220	191
8	163	210	204	198	185	163

CHAPTER FOUR

3. Results and Discussions

Shadow effect is the large-scale fluctuation of the signal envelope due to large (with respect to a wavelength) objects obstructing the propagation paths between the transmitter and the receiver.

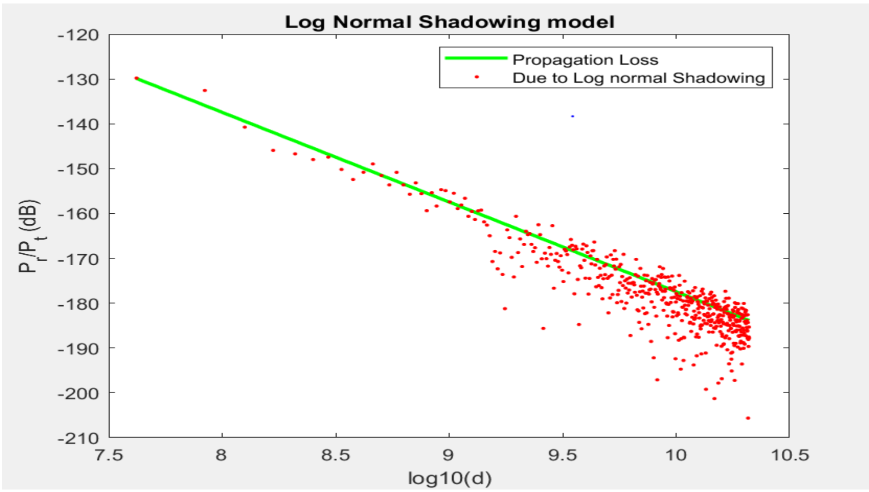

Figure 4.1 Shows Log distance/Log Normal Shadowing Path Loss model

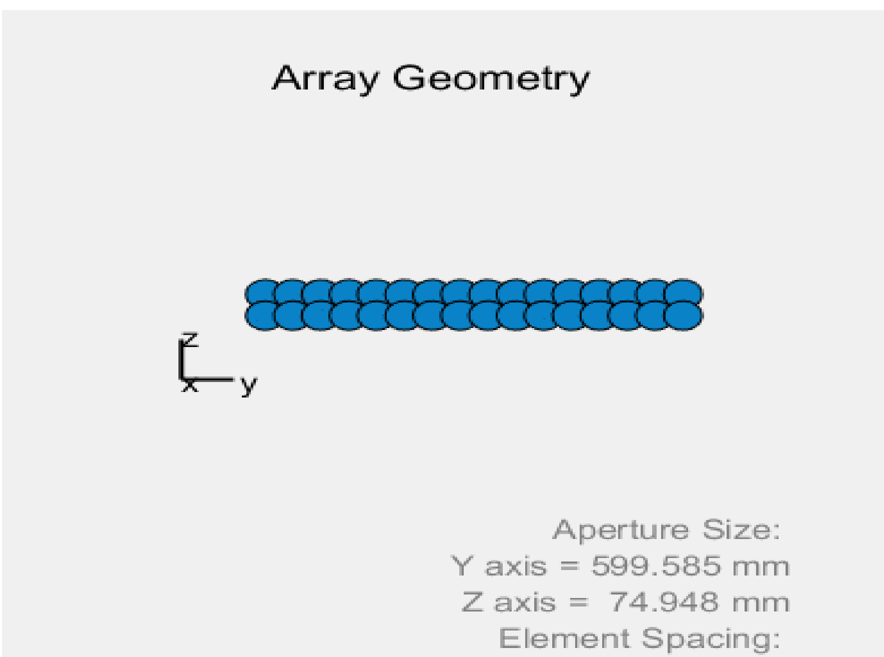

Figure 4.2 Transmit array geometry pattern

In a transmit array antenna is a structure capable of focusing electromagnetic radiation from source antenna to produce a high-gain beam. In the implementing using MIMO and MIMO-OFDM Pre-coding with Phased Arrays and different type of filters are used the result shows how phased arrays are, used in MIMO and MIMO-OFDM communication system employing beam forming and the models the radiating elements that comprise a transmitter and the front-end receiver components, for a MIMO-OFDM communication system

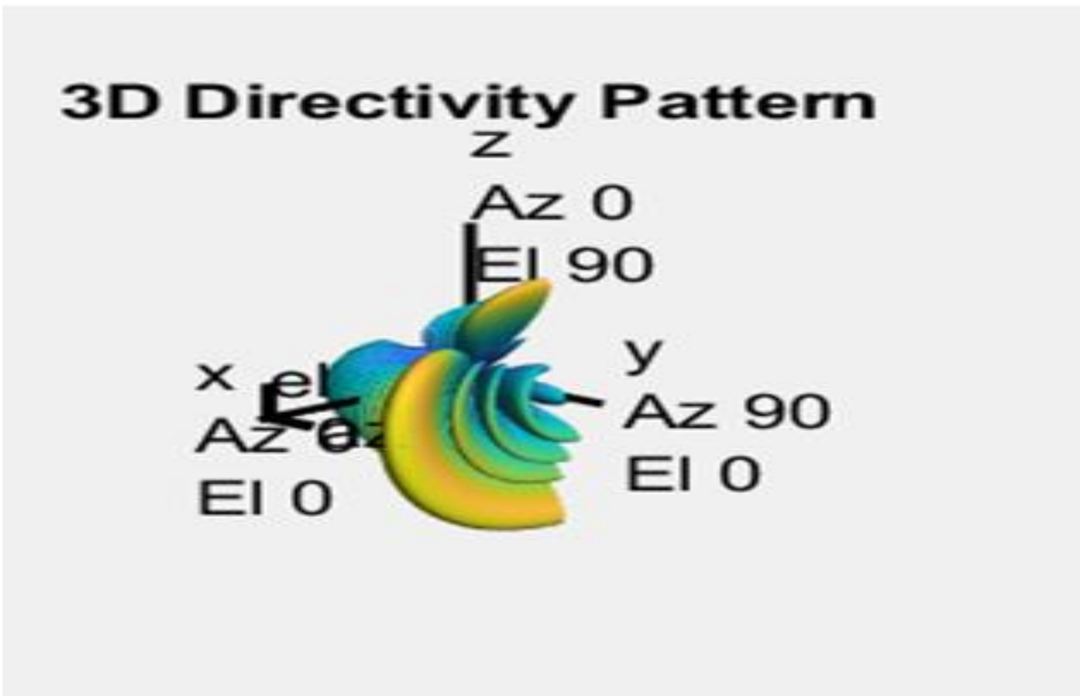

Figure 4.3 Transmit array response pattern

An array response vector as function of direction for a particular array in terms of element pattern and positions. This result will show reconstruction of 3-D radiation from two orthogonal slices. Pattern reconstruction for an Omni-directional and directional antenna will be, considered. For an Omni-directional antenna, we can reconstruct the 3-D pattern using vertical Slice alone. When only the elevation pattern data is, provided, function assumes Omni directionality of the antenna with symmetry about the z-axis (i.e., azimuthal symmetry). Reconstruction using both vertical Slice & horizontal Slice data points can also be, done for the above case. The reconstructed pattern will not vary. Thus, for any Omni-directional antenna 3-D pattern can be, reconstructed with enough data points from orthogonal slices along the theta direction. The reconstructed radiation pattern looks like the 3-D radiation pattern, which can be, obtained using the pattern function

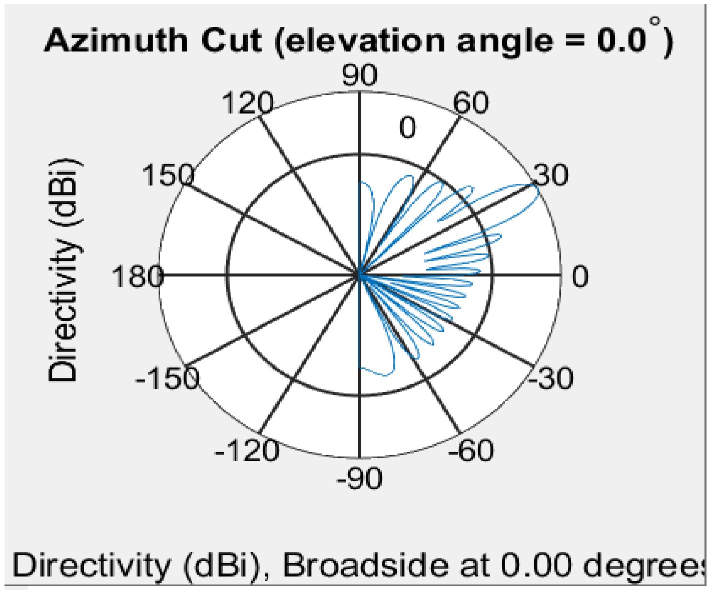

Figure 4.4 Transmit array azimuth pattern

The azimuth plane pattern is, formed by slicing through the 3D pattern in the horizontal plane, the x-y plane in this case, just as you would slice through a bagel. Notice that the azimuth plane pattern is non-directional, that is, the antenna radiates its energy equally in all directions in the azimuth plane. The radiation pattern of the half-wave dipole is maximum perpendicular to the conductor, falling to zero in the axial direction, thus implementing an omnidirectional antenna if installed vertically, or (more commonly) a weakly directional antenna if horizontal.

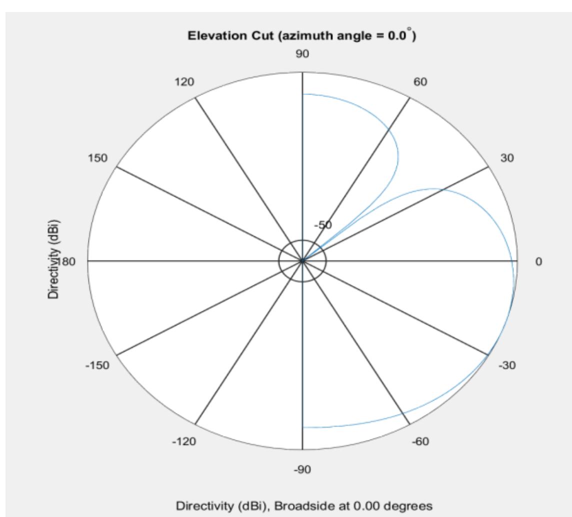

Figure 4.5 Transmit array elevation pattern

A transmit array antenna (or just transmit array) is a phase-shifting surface (PSS), a structure capable of focusing electromagnetic radiation from a source antenna to produce a high-gain beam. In electromagnetics, an antenna's gain is a key performance parameter, which combines the antenna's directivity and radiation efficiency. In a transmitting antenna, the gain describes how well the antenna converts input power into radio waves headed in a specified direction. In a receiving antenna, the gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power.

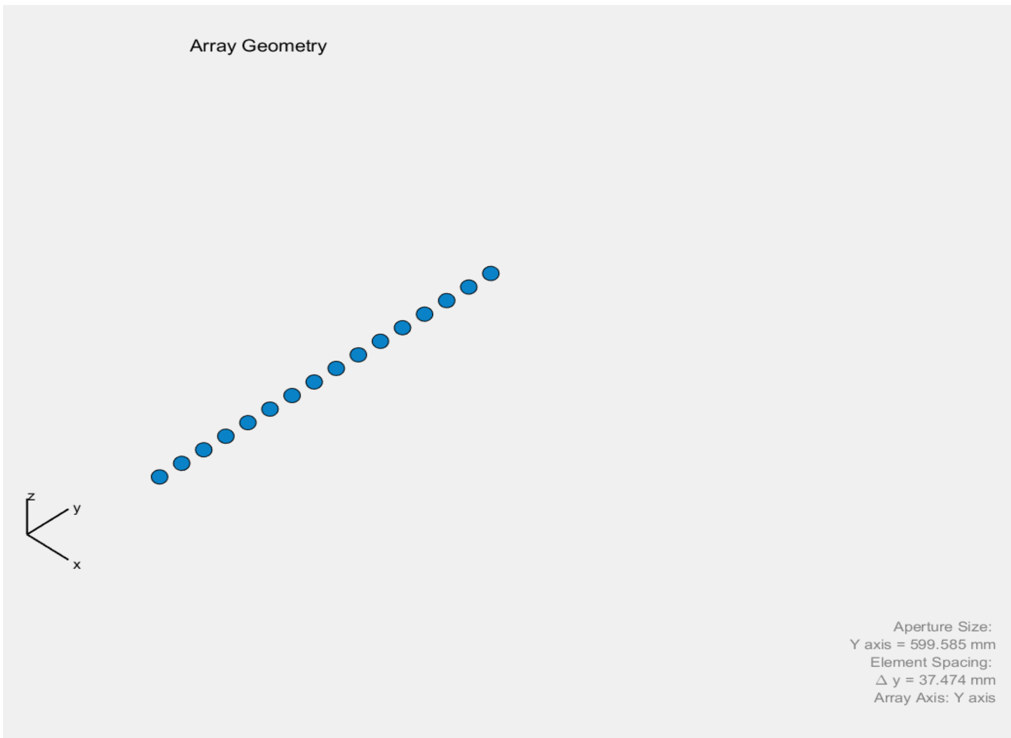

Figure4.6 Receive array geometry

In a receiving antenna, the gain describes how well the antenna converts radio waves arriving from a specified direction into electrical power.

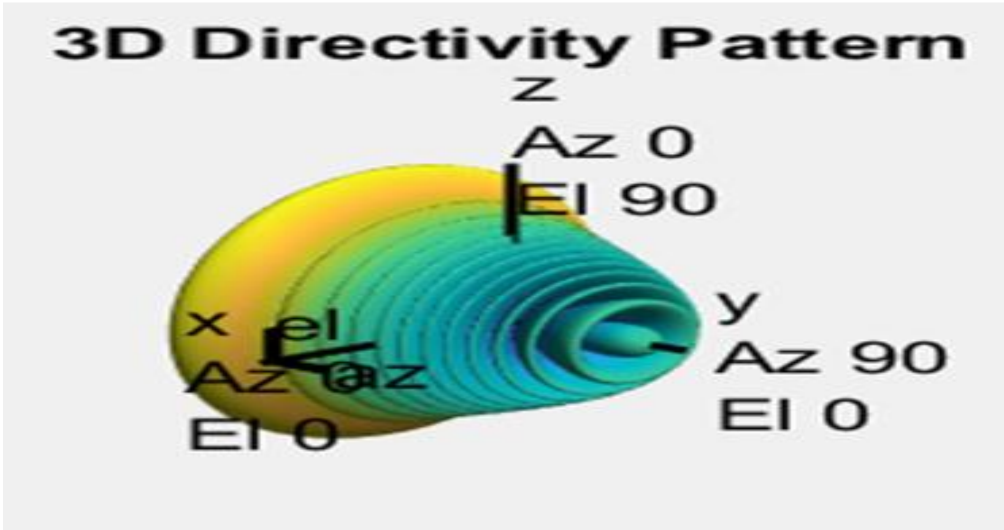

Figure 4.7 Receive array response pattern

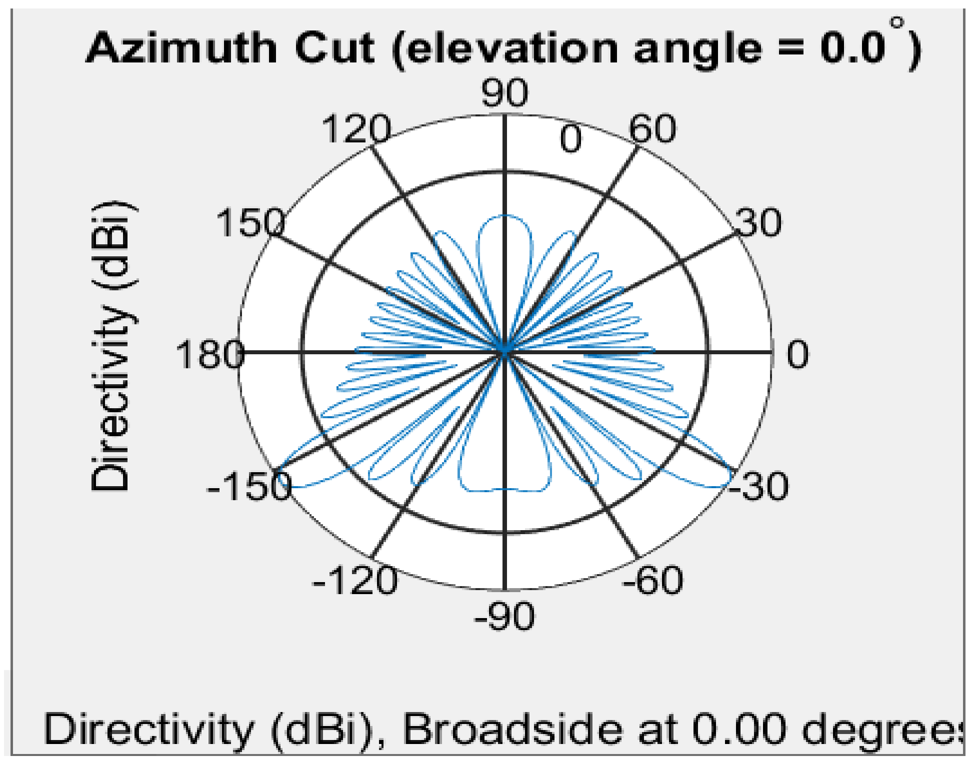

Figure 4.8 Received array azimuth pattern

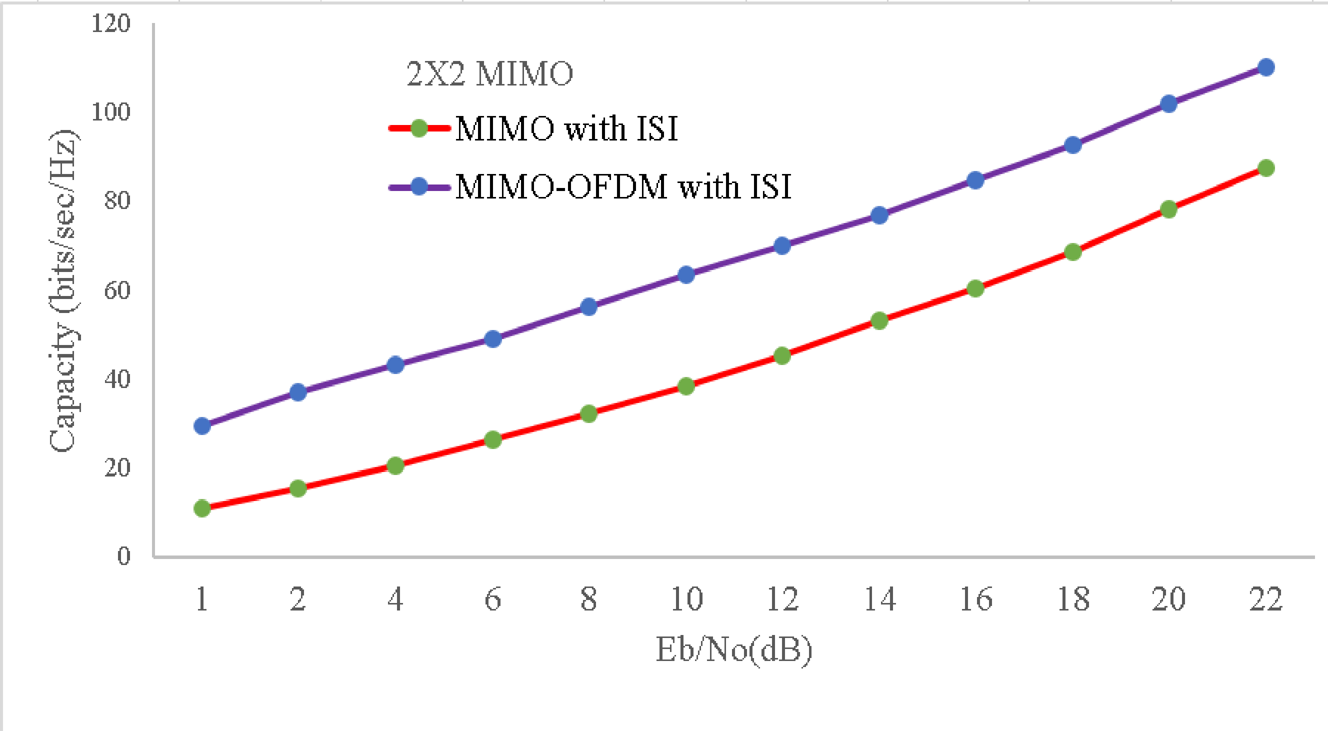

Figure 4.9 Capacity v/s Eb/No for 2x2 Antenna Configuration.

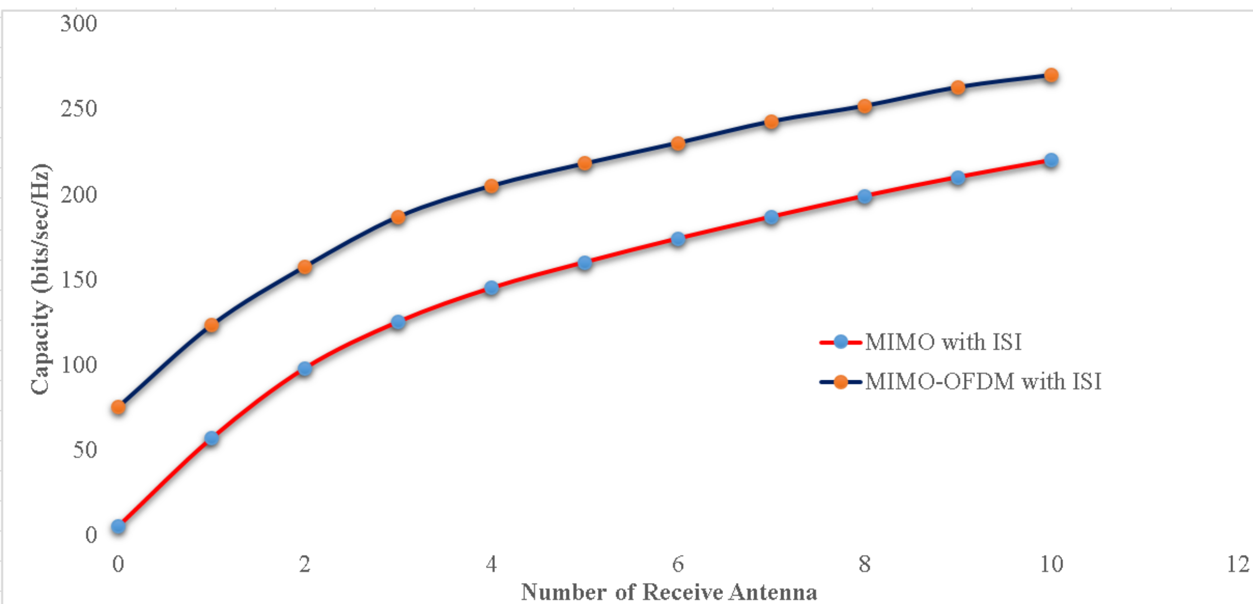

Figure 4.10 Capacity v/s Number of Receiver Antenna

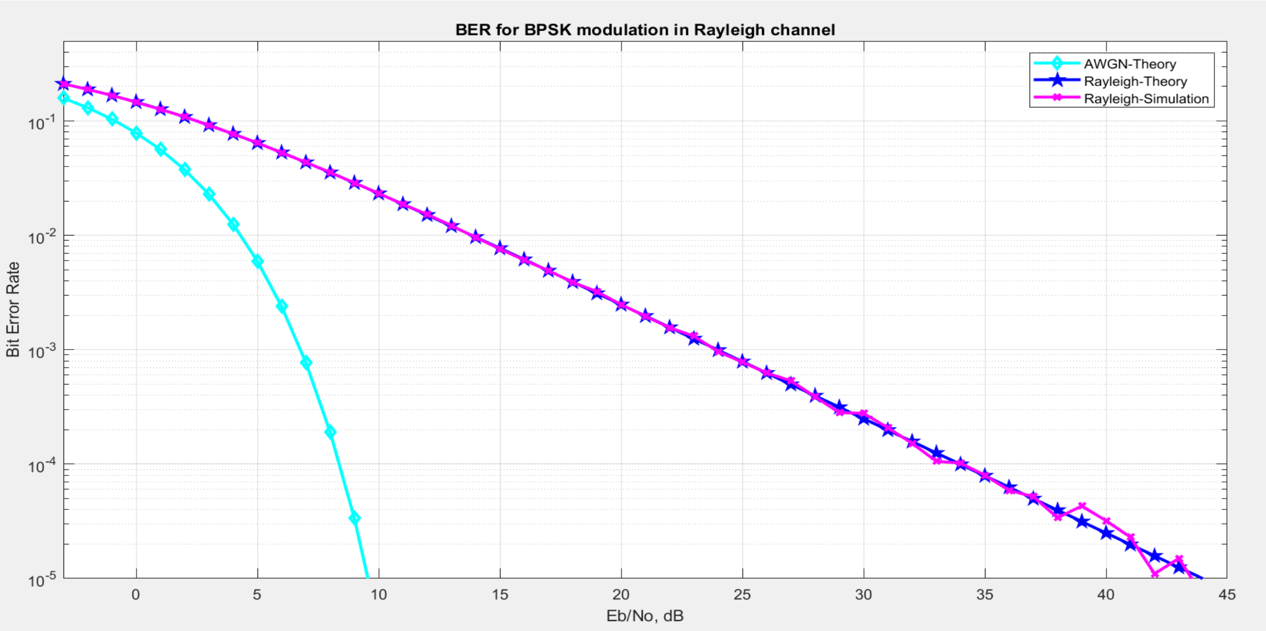

Figure 4.11 BER for modulation in Rayleigh channel

In this simulation diagram, we drive brief comparison using mat-lab between the responses of BPSK over different types of channels.

i. The first one is when transmitting signal affected by AWGN channel.

ii. The second one is when the channel is Rayleigh flat fading and

iii.The third one is when the BPSK simulated over rician fading channel. This simulation is used to determine the bit error rate, which is the number of bit error divided, by the total number of transmitted bits over a channel. The result shows a good agreement between the simulated and theoretical plots for BPSK modulation that there is no different between the BER performances of BPSK over AWGN channel and the theoretical energy per bit to noise power Eb/No this is due to the 180o phase shift between the two bits or symbol.

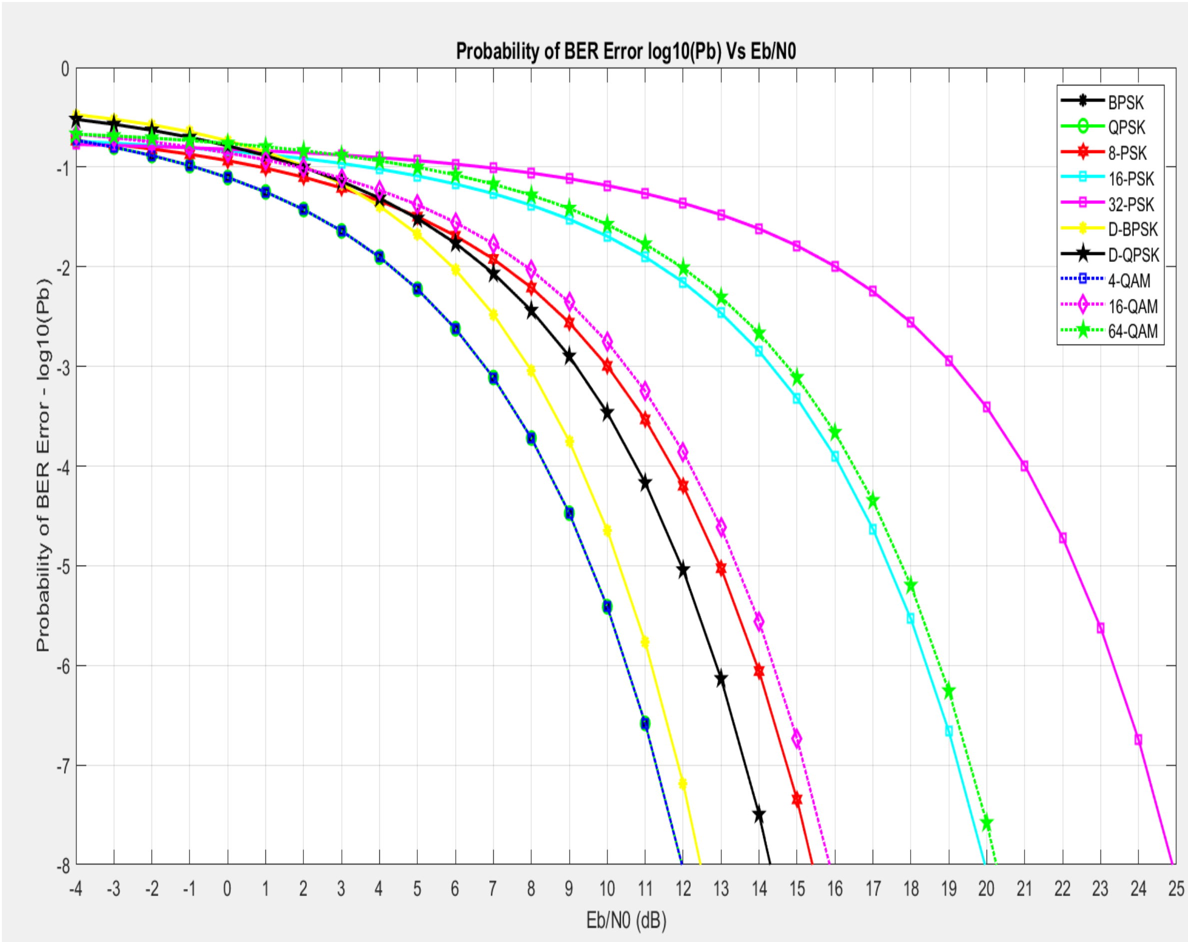

Figure 4.12 probability of BER VS Eb/No

The QPSK and BPSK modulators are used to change The amplitude, the frequency and the phase of carrier signal in order transmit information.

QPSK devices modulate input signals by 0°, 90°, 180°, and 270° phase shifts.

The bandwidth of BPSK can be set to about 12 kHz.

3.8. Performance system analysis of with and without filtering process

The following results show the comparative system performances of past and proposed model such that the variation of Q-factor, BER and link range with respect to the input laser power and data rate. From figures 4.14 - 4.17 shows the relation between maximum quality factors and optical range. It was, observed that with increasing optical range; the maximum quality factor was, decreased for both previous and modified model. Our modified model has achieved better results than the previous model.

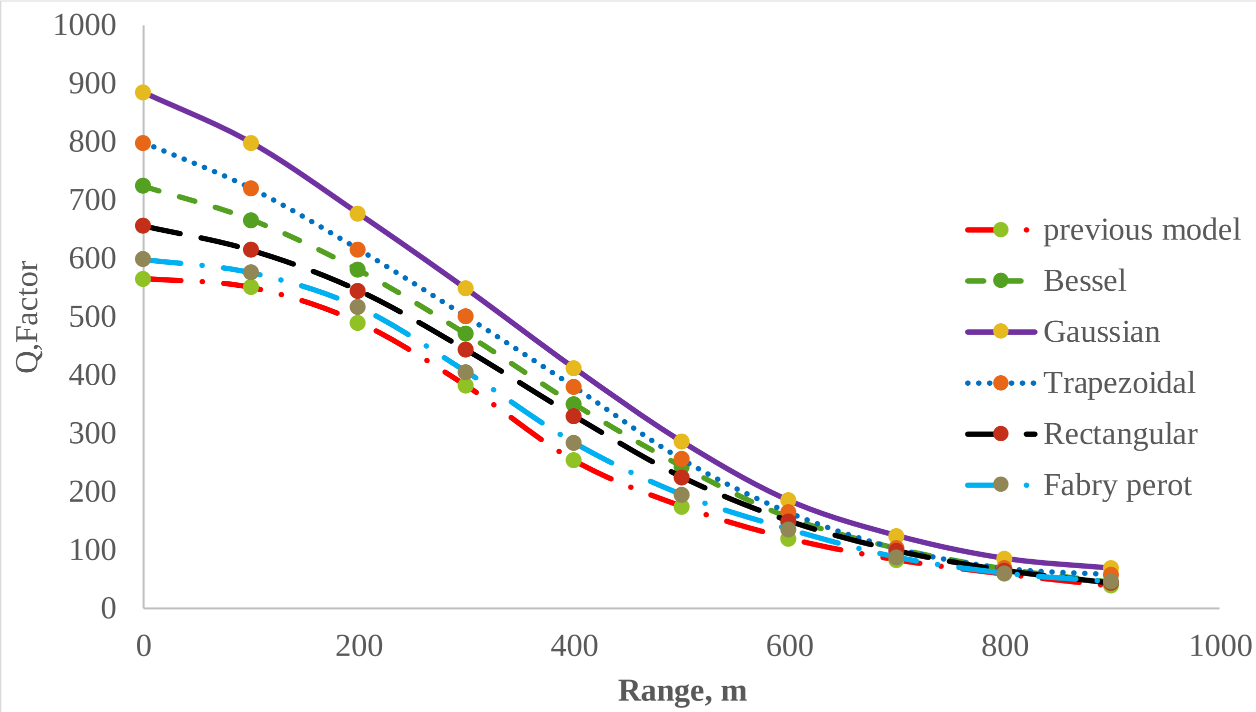

Figure 4.13 Q. factor vs. Range of pre-amplified optical filters

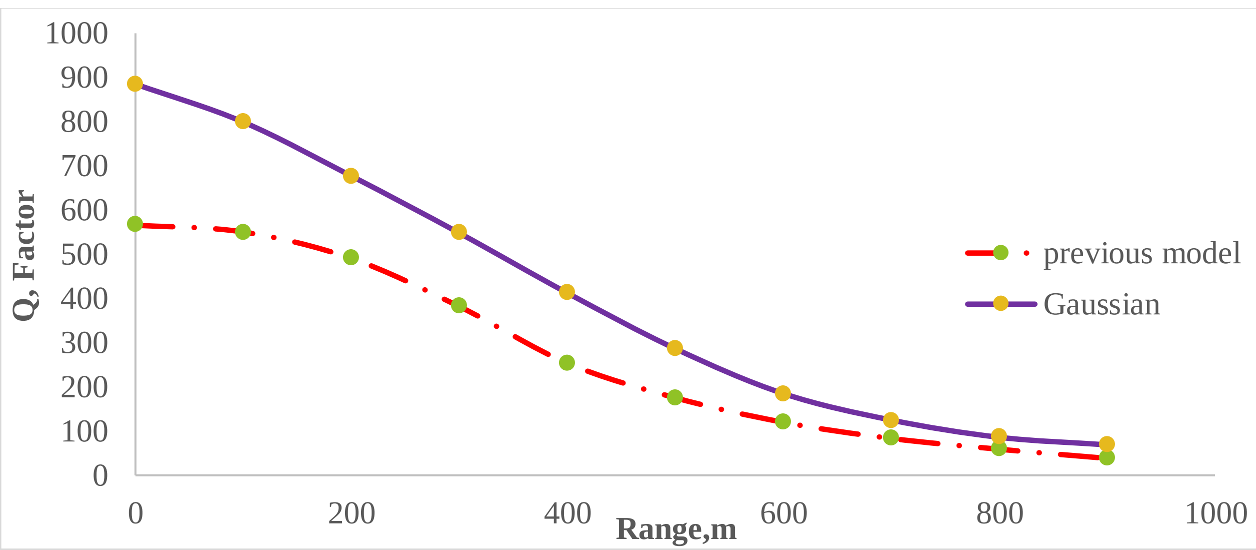

Figure 4.14 Max. Q. factor against short range applications with using Gaussian optical filter

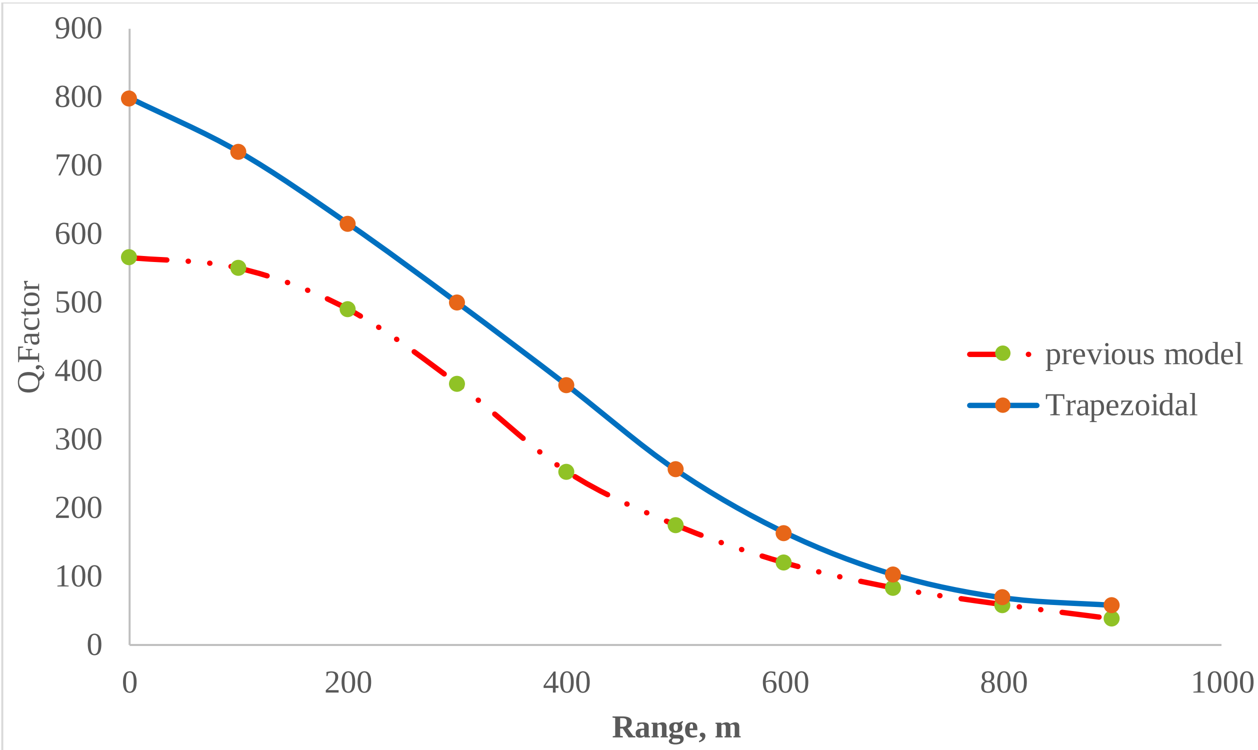

Figure 4.15 Max. Q. factor against short-range applications with using Trapezoidal optical filter

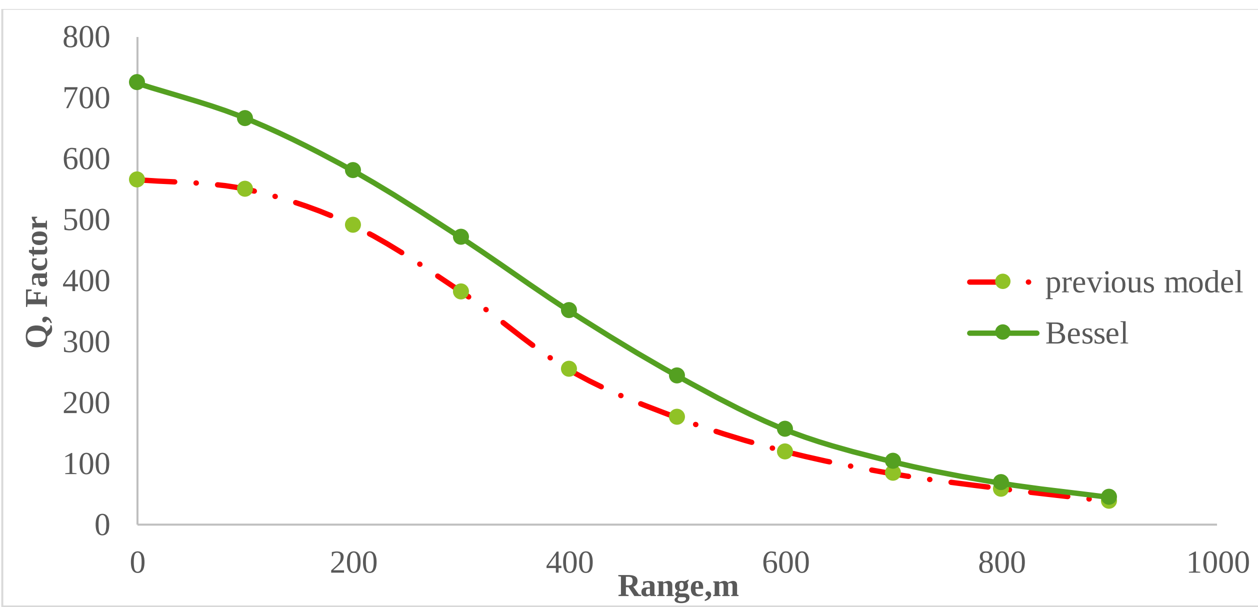

Figure 4.16 Max. Q. factor against short-range applications with using Bessel optical filter

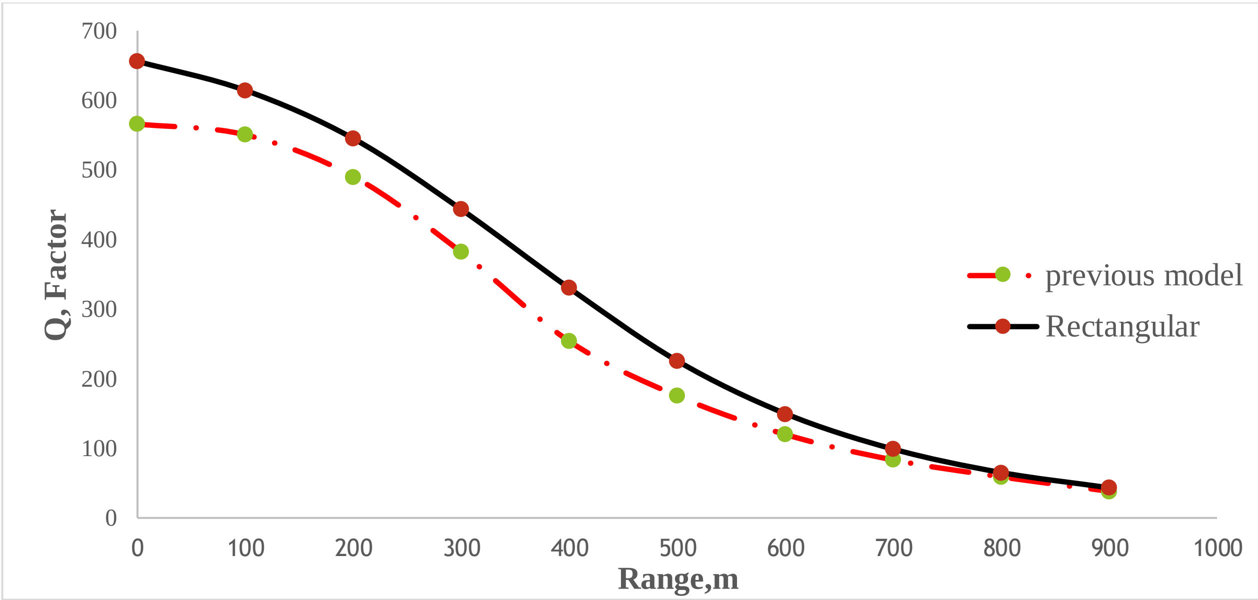

Figure 4.17 Max. Q. Factor against short-range applications with using Rectangular optical filter

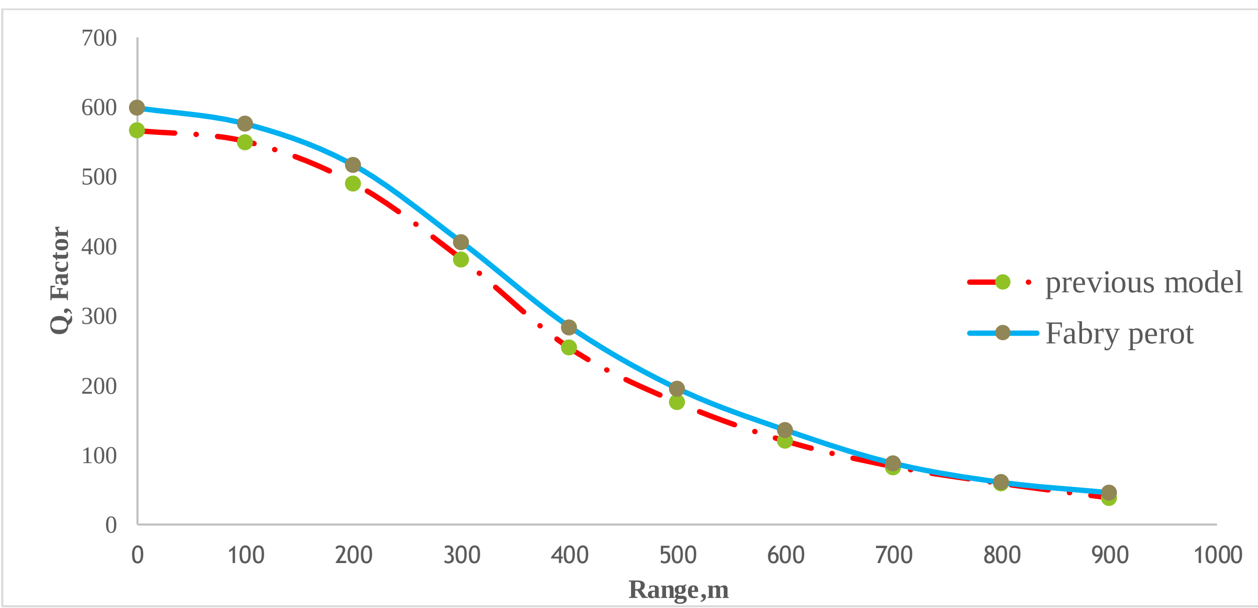

Figure 4.18 Max. Q. factor against short-range applications with using Fabry perot optical filter

The graphs shown in Figure 4.19 present the analysis between Q-factor vs. range for pre-amplified optical filters i.e. Bessel, Gaussian, Trapezoidal, Rectangular and Fabry perot optical filter. The Q-factor was maximum for range 100 m in case of Gaussian optical filter in comparison to both Bessel and Rectangle optical filter. The Q-factor starts deteriorating beyond the range of 1 km for Bessel, Gaussian, Trapezoidal, Fabry perot and Rectangular filters.

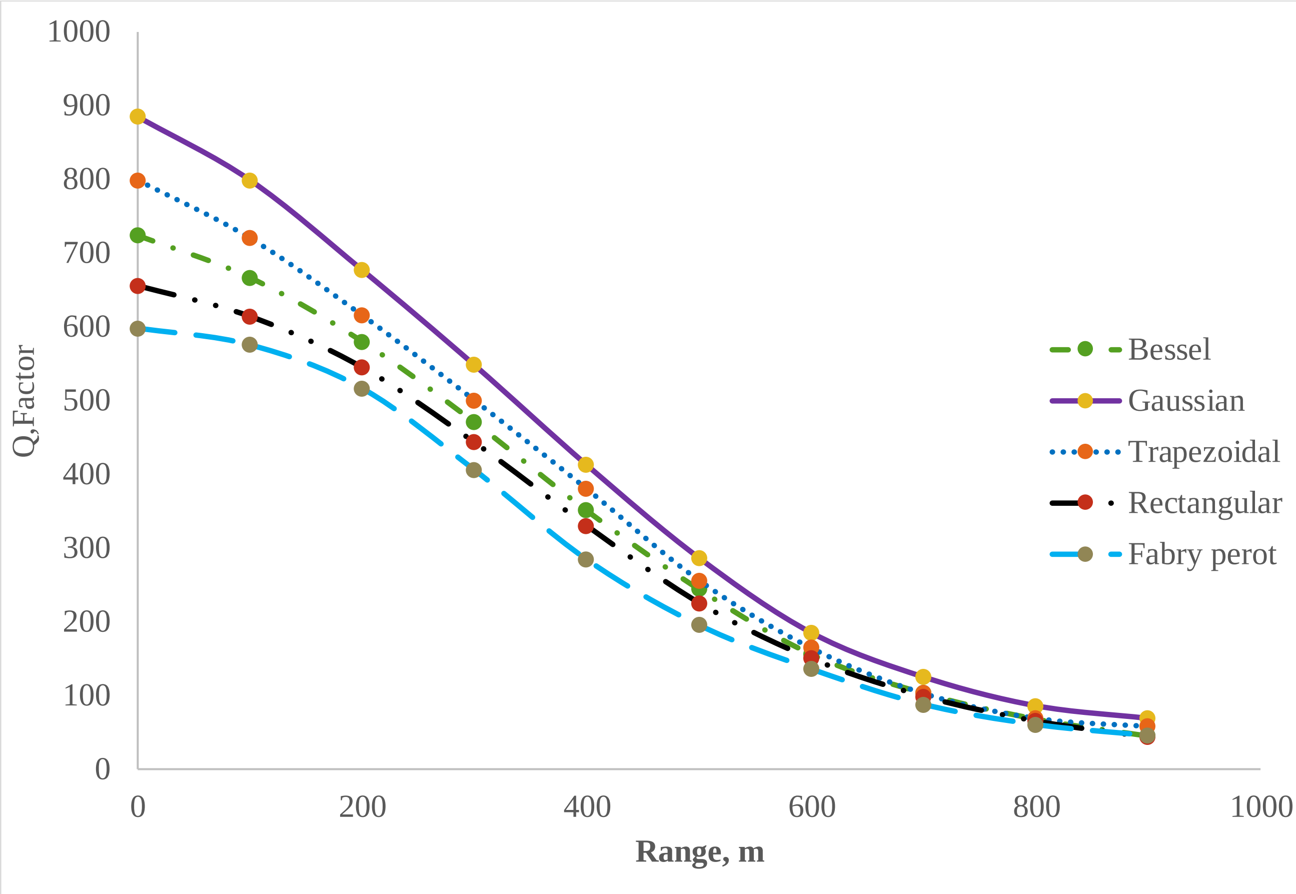

Figure 4.19 Max. Q. factor with short-range applications for different optical filters

3.9. Performance analysis of pre-post amplified optical filtering model

The final proposed 5G system having the amplified input optical signal before going to the various Filtering process was, analyzed numerically. The system stability with respect to the channel modeling such as link range, transmitter aperture size, receiver aperture size, and beam divergence has noticed. While the presence of the minimal effect in the wireless medium. Hence, the impact of Q-factor has been, plotted and studied with the function of all free space medium parameters by various filtering techniques. The filtering process includes Gaussian, Trapezoidal, Bessel, Rectangular and Fabry perot. Figure 4.19 & 4.20 present the relation between maximum quality factors, Transmitter, and Receiver aperture diameter. It has observed that with increasing Transmitter and receiver aperture diameter, these results in decreasing of the maximum quality factor for proposed model.

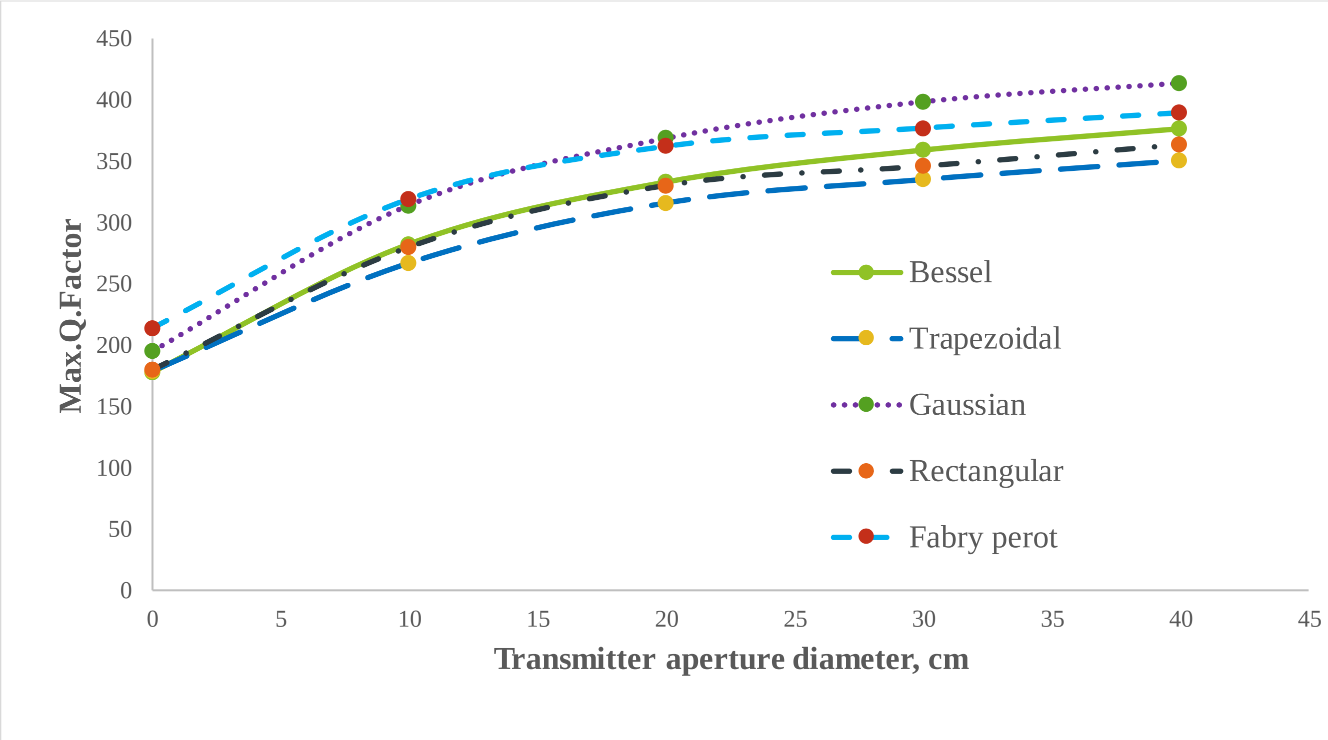

Figure 4.20 Max. Q. factor in relation to transmitter aperture diameter at short-range application

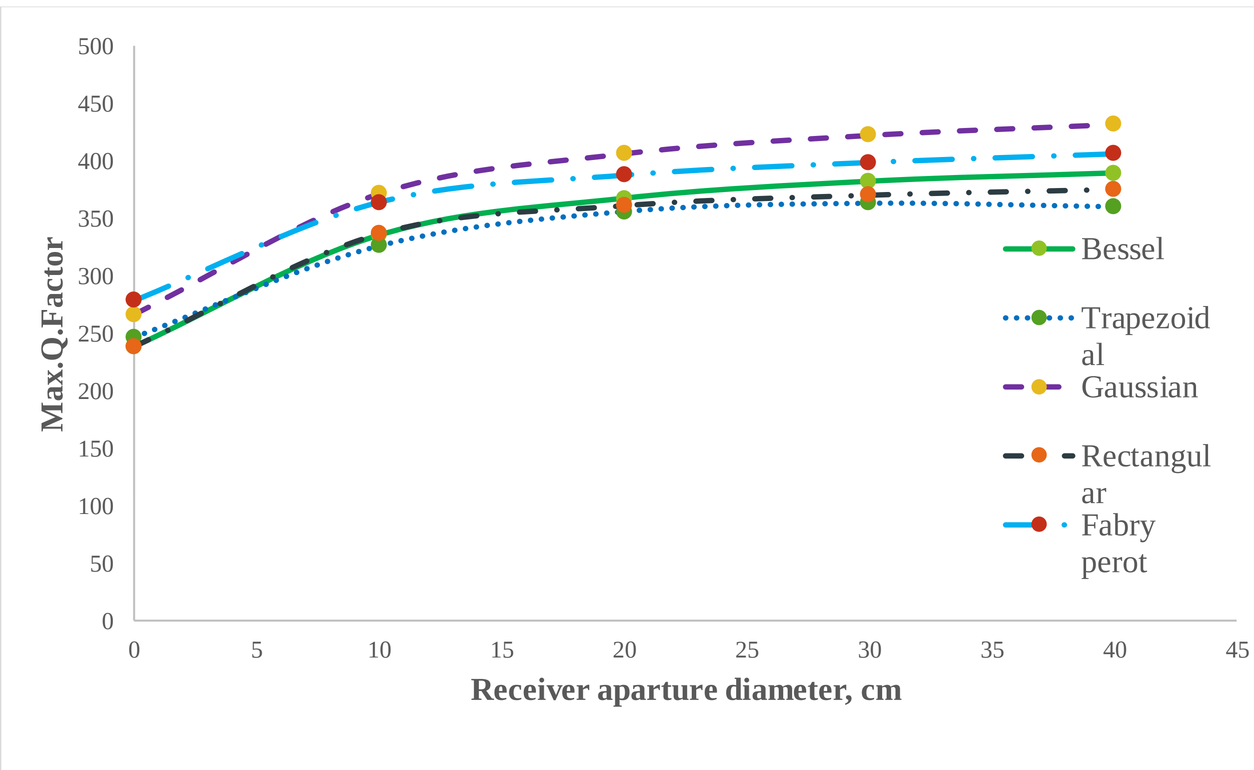

Figure 4.21 Max. Q. factor in relation to receiver aperture diameter at short-range application

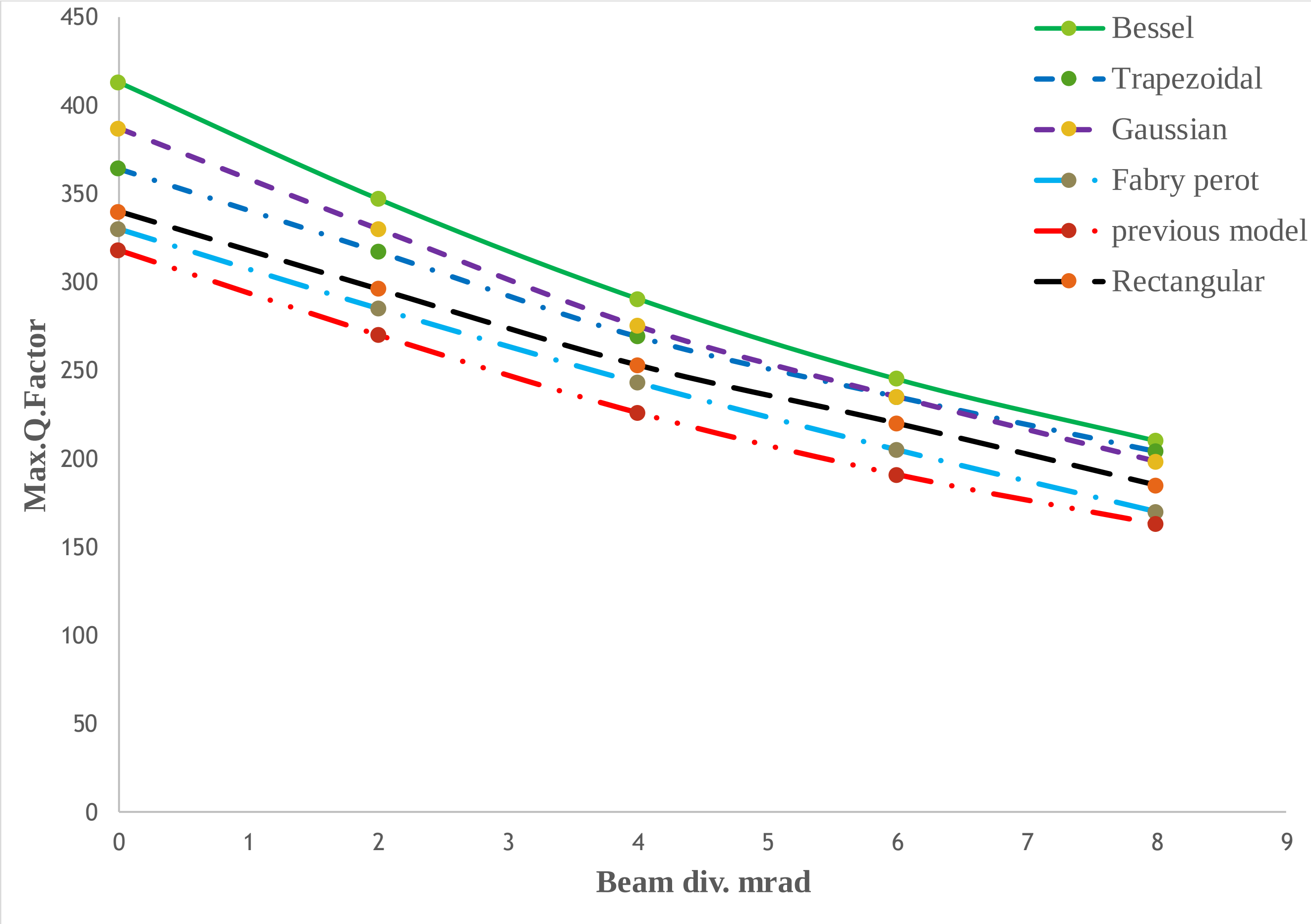

Figure 4.22 Max. Q. factor v/s beam div. for short-range applications with previous modified model.

From figure 4.22 shows that the relation between maximum quality factors and beam divergence. It has observed that with increasing beam divergence, this results in decreasing of a maximum quality factor for both previous and modified model. Our modified model has achieved better results than the previous model.

CHAPTER FIVE

5. Conclusion and Recommendation

5.1. Conclusion

The aim of this thesis is to decrease or minimize the most important phenomena that affect the performance of a FSO link are absorption, scattering, and atmospheric turbulence that are, occurred during signal transmission through FSO communication. To minimize this problem, the performance of FSO communication can be, improved by using MIMO, Massive MIMO and Massive MIMO-OFDM and optical filters are, employed. When MIMO systems are, used significant capacity gain can be, observed as it exploits spatial multiplexing by having several transmit and receive antennas. At high data rate, for dispersive channel, Inter Symbol Interference (ISI) plays a vital role. Due to the effect of ISI, the capacity of the MIMO system severely degrades. In OFDM, the original signal is, modulated by orthogonal tones. The entire stream is, divided into many parallel sub streams. Hence, the symbol duration is increased and the effect of Inter Symbol Interference (ISI) is, mitigated. OFDM has high spectral efficiency and simple frequency domain equalization. The implementation of OFDM can be, easily carried out by using IFFT at the transmitter and FFT at the receiver. Thus, it provides a cost effective solution to combat the fading caused by atmospheric turbulence in FSO transmission. The use of OFDM in conjunction with MIMO is an attractive technology to meet up the needs of future broadband wireless communication. MIMO-OFDM is the current technology used in the 5G wireless communication system The OFDM provides a solution to this problem. MIMO-OFDM is the current technology used in the 5G wireless communication system; hence, our approach to the evaluation of the capacity of the proposed FSO communication system with MIMO-OFDM will be very useful for providing a solution to the problem of the last mile bottleneck. Therefore, in this thesis, we modeled MIMO-OFDM detection with 4-QAM, 16-QAM, 32-QAM, and 64-QAM and 256-QAM. In this work, the performances, of BER and SNR with help of optical filter. Based on performance analysis it can be, concluded that the modified and proposed model is better than the previous model. The result of simulation graphs between Q-factor versus range and Q-factor versus beam divergence proves that modified model is better with Gaussian optical filter as compared to Bessel, Rectangular, Trapezoidal and Fabry perot optical filter. In proposed model, Q-factor achieved is maximum in case of Gaussian optical filter when transmitter aperture is minimum and receiver aperture is maximum. This Analysis shows that Q-factor depends upon beam divergence, link distance, and diameter of transmitter aperture and receiver aperture. The modified and proposed model Q-factor represents the improvement of the system. Different optical filters using pre post amplification provides high bandwidth for 5G application.

5.2. Recommendation for Feature work

In this thesis, the focus has been, made Design and Performance Analysis of Free Space Optical (FSO) Communication over Various Optical Filtering for Fifth Generation System. If the length of the transmission is, increased largely, the signal is, dispersed which can be explored as future work. The quality of the signal to noise ratio also decreases as the distances increases as well as BER increases as the transmission distances increases, so to minimize this the further work should be done by using higher order modulation techniques such as 1024-QAM and more to analyze the performance and to decrease BER as much as possible.

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