

PERFORMANCE ANALYSIS OF ATMOSPHERIC TURBULENCE MITIGATION TECHNIQUES FOR FREE SPACE OPTICAL COMMUNICATION

*A Thesis
submitted in fulfilment of the requirement for the award of the degree
of*

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Submitted by

AJAY SHARMA
Registration No. 950806008

Under the guidance of

Dr. R.S. Kaler
Senior Professor



Department of Electronics & Communication Engineering
Thapar University,
Patiala-147004, Punjab, India

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Declaration

I, Ajay Sharma hereby declare that the work which is being presented in this thesis entitled **“Performance Analysis of Atmospheric Turbulence Mitigation Techniques for Free Space Optical Communication”** is an authentic record of my own work carried out towards the partial fulfilment for the award of degree of Doctor of Philosophy in Electronics and Communication Engineering Department, Thapar University, Patiala, under the guidance of Dr. R.S Kaler.

The matter presented in this thesis has not been submitted in any other University or Institute for the award of any degree.


(Ajay Sharma)

Signature of student

Dated: 19/01/2017

This is certified that the above statement made by the candidate is correct to the best of my knowledge and belief.


(Dr. R.S. Kaler)

Senior Professor, ECED

Dated: 19/01/2017

Abstract

The gigabit rate operated free space optical (FSO) link has been designed for inter-building or campus connectivity. The atmospheric losses have the major drawback in FSO, mainly because of fog scintillation and precipitation. The impact of fog, rain and snow on FSO has been investigated and analyze their performances for optical wireless system. Hybrid FSO/RF system with 1550 nm/2.4 GHz link has also been studied to provide uninterrupted communication in any atmospheric condition of heavy fog and rain.

The model of FSO system has been studied with the help of MATLAB simulator using simulink where channel considered as free space. In this model, Additive White Gaussian Noise (AWGN) channel has considered to analyses bit error rate (BER) and power of FSO signal. The consequence of atmospheric turbulence of free space on transmitted signal has examined. The BER as well as signal power has extremely ruined on rigorous atmospheric unstable condition even for a short distance in optical wireless channel. The bit error rate of less than 10^{-3} has been achieved for free space optical communication system which has been considered being excellent. The propagation of Gaussian beam in turbulent atmosphere for free space optical communication has been studied. The intensity on axis of Gaussian beam wave, beam radius and radius of curvature at the receiver has been evaluated and discussed. The effect of aperture averaging on Gaussian beam wave for different turbulence strength of atmosphere has been studied. The aperture averaging factor decreases under high atmospheric strength and averaging ability of the receiving system increases by increasing receiving aperture diameter. Additionally an improved expression of scintillation loss has been evaluated using threshold power approach. This expression takes into account the loss due to scintillation when Gaussian wave propagates through atmospheric turbulence condition. Results show that probability of fading and losses due to scintillation are considerably lower when threshold power level has been set low.

The varying weather conditions have a major influence on the performance of FSO transmission. This is investigation based on the effects of different weather circumstances on data rate, received signal and S/N ratio at 1550 nm/ 1300 nm/ 850 nm wavelength for a free space optical communication. The system performance improved in different weather condition by Fresnel lens techniques such as data rate, received power and S/N ratio. By using this technique, non coherent light source such as LED has been used instead of LASER in free space optical

communication. The potential of LEDs to be modulated at high speeds offers the possibility of using LED as sources for communication instead of LASER. Simulation results shows that heavy fog attenuates more optical signal then other atmospheric condition and in all weather conditions.

List of Publications

1. Ajay Sharma and R.S Kaler, “Designing of high speed inter-building connectivity by free space optical link with radio frequency backup”, IET Communications journal, Vol.6, Issue 16, pp. 2568-2574, June 2012. (SCI indexed, IF=0.742)
2. Ajay Sharma and R.S Kaler,” Performance analysis of optical wireless link under various atmospheric conditions using Fresnel lens technique”, Journal of Optoelectronics and Advanced Material, Vol.17, No.3-4, pp. 296-301, April 2015. (SCI indexed, IF=0.563)
3. Ajay Sharma and R.S Kaler,” Performance investigation of free space optical communication system using Gaussian beam wave”, Journal of Optoelectronics and Advanced Material, Vol.17, No.3-4, pp. 302-306, April 2015. (SCI indexed, IF=0.563)
4. Ajay Sharma and R.S Kaler,”Simulation Modeling of Optical Wireless Communication System”, Journal of Circuits, Systems, and Computers (JCSC), world scientific, under review. (SCI indexed, IF=0.481)
5. Ajay Sharma and R.S Kaler,” SNR Performance of Hybrid FSO/RF Availabilities in Optical Wireless Communication System”, Journal of Communications Technology and Electronics, Springer, Communicated. (SCI indexed, IF=0.331)

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List of Acronyms

FSO	Free Space Optics
RF	Radio Frequency
LAN	Local Area Networks
MAN	Metropolitan Area Networks
FCC	Federal Communications Commission
APD	Avalanche Photodiode
EMI	Electromagnetic Interference
LOS	Line of Sight
OOK	On Off Keying
PAT	Pointing Acquisition and Tracking
IRT	Index of Refractive Turbulence
BER	Bit Error Rate
PSK	Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
MCRT	Monte Carlo Ray Tracing
NRZ	Non Return to Zero
RZ	Return to Zero
BPSK	Binary Phase Shift Keying
DPSK	Differential Phase Shift Keying
LED	Light Emitting Diode
LASER	Light Amplification by Stimulated Emission of Radiation
WDM	Wavelength Division Multiplexing
VCSED	Vertical Cavity Surface Emitting Diode
APD	Avalanche Photodiode
AFGL	Air Force Geophysical Laboratory
RVR	Runway Visibility Range (RVR)
MTTF	Mean Time to Failure
FIT	Failure in Time

PECL	Positive Emitter Coupled Logic
GBIC	Gigabit Interface Converter
FCAL	Fibre Channel Arbitrated Loop
RLC	Redundant Link Controller
CRC	Cyclic Redundancy Check
MMW	Mille Meter Wave
QOS	Quality of Service
PSD	Power Spectral Density
PDF	Probability Density Function
CDF	Cumulative Distribution Function
IR	Infra Red
VCSEL	Vertical Cavity Surface Emitting Laser
EDFA	Erbium Doped Fiber Amplifier
ANSI	American National Standard Institution
MPE	Maximum Permissible Exposure
SNR	Signal to Noise Ratio
ATM	Transmitter Optical Efficiency
PC	personal Computer
DWDM	Dense Wave Division Multiplexing
PC	Personal Computer
AWGN	Additive White Gaussian Noise
OW	Optical Wireless
HD	High Definition
ISL	Inter Satellite Link
PLL	Phase Locked Loop
PPM	Parts Per Million
PIN	P Intrinsic N

Chapter 1

Introduction

1.1 Introduction and Overview

Optical wireless has been considered to be one of the vital key advances for acknowledging fast (Gb/s) and high bandwidth communication. FSO utilizes lasers as signal carriers and gives high capacity link within a limited distance.

Deployment of the Internet and multimedia formed congestion in the telecommunications networks. The FSO lasercom can be implemented; especially in regional local area networks (LANs) and metropolitan area networks (MANs) around urban communities where deployment of fiber optic links has been costly. At the point when the World Trade Center broken down on September 11, 2001, so fall down of the companies situated inside the structures. Countless dollars were lost because of the down-time that these organizations experienced. With the assistance of a couple of remote broadband suppliers utilizing FSO innovation, these corporations have been ready to get networks up and within a limited period of time notably minimum expenditure then to reinstall their lines wire or fiber or cable network.

Optical wireless offers generous preferences over customary RF communication because of better rate of information, intercept chances are low, minimum specifications of power required and small packaging area. It could be a practicable replacement to systems using fiber optics for number of applications, because this technology provides 99.999% availability that would be the requirement of many communication systems.

1.2 FSO Brief History

Communications by means of optical system is not a latest technology. Past Roman reports signify that metal plates with polished surface were utilized as mirrors to reflect back sunlight for signaling in high range. In early 1800's, this sunlight technology with mirrors had been used to transfer telegraph information from one mountain top to other. Also squinting lights have been utilized for many centuries to

send information from one ship to other. Alexander Graham Bell utilized photo phone as a trial where he utilized vibrating mirror with reflected daylight and a selenium photograph cell to drive message alerts at a limit of 600 ft. The historical past of optics with and without fiber could be study in the literature [1-2].

In 1895, Sir J.C. Bose utilizing electromagnetic waves to ring a bell placed at some distance in open exhibition on radio based systems [3-5]. According to Daily Chronicle of England reported, “J.C. Bose has broadcast signals within a mile distance”. Invited with the aid of Lord Rayleigh, he mentioned his experiments on millimeter wave in Royal school and other parts in U.K [6]. Marconi’s proposals were not accepted till 1897, so the innovator of wireless Communication was Sir J.C. Bose rather than Marconi. Additional work on Radio communication by Bose found in the paper [7]. After the primary demonstration on laser in 1960 at the Hughes research Laboratories, California, the first progress of optical communication referred as "Light phone". NASA also contributes various innovative improvements. During the development of optical system, civilian based optical system were undeveloped, however military based optical communication research were going on. For last four decades, incredible progress has been done in the field of optoelectronics, usually for defense applications. Systems developed for ground, airplane and satellite, including submarine applications.

1.3 FSO Applications

Free space optical communication has wide application in unmanned ground vehicles. These vehicles utilizes in commercial and military fields [8].

Few distinctive applications of FSO communication are:-

- a. LAN based links at Fast or Gigabit Ethernet Speeds.
- b. Delivery of high capacity of data.
- c. Installation of provisional network due to urgency.
- d. Re-establishment of high speed link connection in short time.
- e. For communications link among ground, spacecraft as well as satellite constellation.

- f. Ocean ship to ship communication link through high data rates providing full security.

1.4 FSO Challenges and Advantages

- a. Data Rates are high.
- b. High security for transmission.
- c. No frequency allotment compulsory required.
- d. Lower power consumption, light weight, small volume.
- e. Rapid deployment and Portability.
- f. Transmit information with improved security regarding financial and military services.

1.5 FSO Limitations

The regular existence of optical turbulence within the free space as channel due to different atmospheric conditions, limit the efficiency of FSO [9]. The two phenomenons named absorption and scattering of laser beam in atmosphere can have a great impact in execution and performance in FSO. A further difficulty faced by FSO communication has the condition of line of sight path among transmitter to receiver link, due to the fact that light cannot go through through buildings, obstacles, trees, mountains etc. One other challenge has the location of sun with respect to transmitter and receiver as receiver should be protected to come across the way. Atmosphere is major concern of FSO because FSO communication performs differently in weak and strong turbulence conditions in terms of their bit error rate [9, 10].

1.6 FSO Operation

In this communication system, the information transmitted and received by transmitter and receiver respectively through free space channel by a tolerable rate of error, at the same time providing high consistency. The transmitter section includes mainly a modulator, laser with driver circuit and a telescope. The working of modulator has to change data into electrical signal and modulates the light of

laser beam to produce modulated optical signal. The optical beam has further expanded by telescope to minimize diffraction [11].

The FSO signal propagates in the course of environmental channel. The information reached to receiver through telescope where detector convert optical signal back to electrical signal. The telescope gathers light signal and concentrate it to the receiver mount. In any communication system, multiple access schemes like FDMA, TDMA and CDMA are commonly used to increase the capacity but in FSO, OFDM is more favorable as far as performance is concerned [11, 12].

1.7 Background of Optical Wireless System

More research going on the field of Free Space Optical system to benefits it's over wired networks like quality and suppleness. The demand for information rate on wireless communication systems these days has increasing in exponential rate. In sight of this, many wireless networks are developed to handle the demand for top data carrying capability [13].

The amount of information transmitted in any communication system has directly associated with the data rate of the carrier that is directly associated with the carrier frequency. Optical signals use frequencies vary of 20 THz – 375 THz and guaranteed terribly high information rates. Optical communication systems therefore promise the best potential data carrying capability [14].

Now a days requirement of low range high bandwidth with speed are in demand for indoor wireless system. FSO accomplish this trustworthy wireless communication between any points in short distance [15].

FSO communication is like a viable tool for next generation communication, owing to its wide selection of applications [13, 14]. A number of its applications area unit involving satellites (inter-satellite communication), Pilotless Aerial Vehicles (UAVs), High Altitude Platforms (HAPs), terrestrial communications, ship-to-ship communication and craft. FSO has an alternative to give high information rates in areas wherever it's troublesome or where it's not possible to get glass fiber cables. Again, it is utilized in each military and civilian application. Its uses include temporal links within the event of disaster [16].

FSO has additional benefits over different ancient wireless technologies (i.e. Microwave systems). First, FSO offers higher information rates (several gigabytes of data) than that

provided by microwave systems. Secondly, it doesn't need licensing for its operation. This can be a significant value advantage over microwave links. Again, FSO channels are extremely proof against magnetic force interference (EMI) and extremely protected by low likelihood of detection and low likelihood of interception (LPD/LPI) properties [17].

On the other hand, FSO has some disadvantages that have hampered its wide deployment. It's low accessibility likelihood as a result of different climatic conditions [18]. The functional probability of a communication system is that the proportion of time through which the communication link is operational and for wireless communication systems, this should be 99.9% [19].

The primary atmospheric processes that have an effect on optical signal propagation area unit are region absorption, region scattering and index-of-refractive turbulence (Scintillation). For an optical radiation that traversing the atmosphere, absorption happens once a number of the photons area unit destroyed by molecular constituents of the atmosphere and their energy reborn into energy resulting in loss of optical power. Once more optical radiation through the atmosphere is attenuated by scattering caused by gas molecules and aerosols like fog/haze, rainfall, snow etc. Scattering causes changes within the direction of propagation of the optical wave. The beam widen out whereas forces the region path inflicting the dimensions of the acknowledged beam to become wider than recipient aperture. This results in important loss of optical power. Fog causes the foremost damaging effects with attenuation measurements of 480dB/km [20]. The concentration and distribution of molecular constituents of the atmosphere and aerosols rely on the region and also the season. The productive implementation of FSO communication thus depends on the weather patterns of the world. Careful data of amount of attenuation introduced by the native weather is thus needed before installation. Long lasercom links in the course of atmosphere experience degrades because of atmospheric turbulence (scintillation) [21]. The temperature variations in the atmosphere originate subsequent changes within the refraction index of the atmosphere [22]. Consequently, the optical wave moves on the turbulent atmosphere with dynamical index of refraction experiences quick fluctuations in its intensity and section. The transmitted optical power is reduced on the propagation path. The necessary margin to complete such loss is thus required [23].

Again, FSO Communication needs terribly correct inform, Pointing Acquisition and Tracking (PAT) techniques. This is often owing to its slender unguided beam propagation through free area. It needs tightly clear line-of-sight (LOS) transmission.

1.8 Comparison of Radio frequency and Free Space Optical technologies

Traditionally, wireless technology has nearly continually related to radio broadcasting, through carrier transmission. Apart from RF wave, Optical waves have many advantages and applications. The main advantage of FSO technology has its extremely large bandwidth accessibility that may offer wireless broadband service to end-users. It might modify the vision of net browsing without buffering, access audio/video, video conferencing, health reports transmit, and information records access that may need the maximum speed such as hundred Mbps speed on a continued basis [20].

Additionally, FSO allow the employment of thin directional optical beams that if deployed correctly; provide primarily protected channels through low chance of detection or interception (LPD/LPI). Thin Laser beams even enclose extensive obscuration, penetrates high. So, laser beam penetration in dense fog, for more than a hundred meters distances is possible at Gigabits per second data rates through zero micro-radian beam divergence [20].

Though, still FSO has several drawbacks. Ever since a LOS has needed along modulator and demodulator. Signal attenuation in atmospheric turbulence conditions such as fog, clouds, snow and rain inflicting FSO performance degradation and attainable connectivity failure [21, 22]. Furthermore, FSO links have comparatively short distance.

Table 1.1: Summarizes the Properties of FSO and RF Systems

	FSO Links	RF Links
Usual data rate	100 Mbps to nearly Gbps	not as much of 100 Mbps
Data Security	Very high	Low
Networking architecture	Scalable	Non-scalable
Used element dimension	Small	Large
Signal degradation sources	Turbulence in atmosphere mainly due to fog	Multipath fading, user interference and due to rain

Clearly, FSO system cannot substitute RF system. Relatively both continue to co-exist. Hybrid networks like FSO/RF combine the benefits of each other and keep away the disadvantages of

FSO and RF only. Although FSO availability can't be sustained every time, the connectivity of hybrid FSO/RF combination has noticeably larger than if RF links alone used. Hybrid FSO/RF wireless systems can offer high capability and availability.

1.9 Research Motivation

The continually growing bandwidth demand at low price communication systems in India has the main motive behind this analysis. Ancient microwave communication systems will not support this high bandwidth demand. Telecommunications firms within the country thus invest vast sums of cash in giving birth underground fiber cables for its backbone network. The more challenges these firms face in laying glass fiber cables within the major cities. These cities have already developed infrastructure (i.e. buildings and roads). Thus creating by removal and laying cables are terribly tough. In such areas, the businesses are forced to rely upon microwave links. Again, as a result of lack of previously developed network infrastructure system within the country, underground fiber cables are destroyed throughout road constructions. An alternate to fiber cables in inaccessible areas can be the utilization of FSO installation. FSO is used to offer backup links within the event of fiber cable destruction or as a backbone network.

1.10 Problem Statement

Optical wireless communication has the prospective to produce high data rates, secured and license-free transmission however it's extremely prone to region conditions. This thesis seeks to research the results of the atmospheric channel on FSO Systems to work out its practicableness.

1.11 General Objective

The major purpose of this thesis has to determine the atmospheric turbulence mitigation techniques for free space optical communication.

1.11.1 Specific Objectives

The precise objectives of research are:

1. To investigate the potential of FSO, as a mean of combating atmospheric turbulence induced scintillation (fading) phenomenon which significantly depreciate the performance of FSO system.

2. To Study the performance and the applicability of FSO & hybrid RF/FSO scheme to combat atmospheric turbulence in FSO system.
3. To estimate atmospheric-fading loss by threshold approach based on lognormal statistics of the received power of on-off keying modulated link.
4. To study the influence of scintillation caused by turbulence by using Rytov scintillation theory.

1.12 Organization of Thesis

Based on the proposed objectives, the main aim of this thesis is to investigate the atmospheric turbulence mitigation techniques for communication through free space. The thesis is well organized into six chapters. The content of each chapter is briefly described below.

The introduction to free space optical communication and its comparison with RF are covered in chapter 1. The motivation and problem formulation are also presented. The objectives of the thesis are crystallized in this chapter. The organization of the thesis is presented. Chapter 2 presents a review of existing literature on Free Space Optical Communication. Chapter 3 deals with the first two objectives of the thesis which is to investigate the potential of FSO, as a mean of combating atmospheric turbulence induced scintillation (fading) phenomenon which significantly deteriorate the functioning of FSO technology and to Study the performance and applicability in FSO and hybrid RF/FSO scheme to combat atmospheric turbulence in FSO system. Simulation model has been developed in Matlab for performance analysis of optical wireless system. Chapter 4 deals with the third & fourth objective of the thesis which is to estimate atmospheric-fading loss by threshold approach of the received power of on-off keying modulated link and to study the influence of scintillation caused by turbulence by using Rytov scintillation theory. Chapter 5 deals with the extension of first objective focus on the impact on the performance of FSO communication in different weather conditions. Thesis is then concluded in chapter 6 and the scope of future work has been presented.

1.13 Summary

In this section, a general starting discourse has been sketched out to help the readers for comprehend the general ideas and the goals for FSO Communication. This foundation material can be helpful in making smooth associations among every chapter in the thesis.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents an outline of FSO communication and a review of connected work did in the world of FSO communication. The challenges FSO communication faces are mentioned. Key options wherever FSO finds application are presented. This section ends by a conclusion and discussion on the essential design of Free Space Optical communication.

Transmission of information/data in optical wireless communication over long distances using modulated laser signals is through unguided media like free space. The unguided medium can be water, free air or a combination of these two. Since the research is regarding transmissions in free space, the medium of interest is the atmospheric conditions. The data, which has to be transmitted, should be modulated by varying the characteristics of the light signal. An optical link has a line of sight technology. It therefore requires the transmitter and the receiver to point directly to each other without any form of obstruction lying on the path. A usual execution of FSO has a communication between two points by means of two similar transceivers at both end of the linkage as shown in fig 2.1. This arrangement allows data to be transmitted simultaneously between the transmitter and receiver.

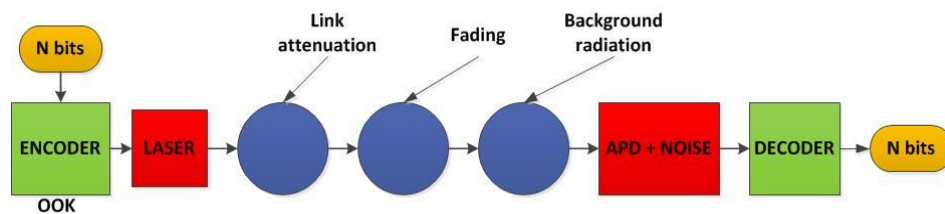


Figure 2.1: Data Transmission between Transmitter and Receiver

2.2 Review of Existing Related Work

In the view of all the challenges facing FSO Communication, many ways are planned to mitigate the results of atmospheric conditions like diversity techniques [27-30], hybrid FSO/RF techniques [31-33], error-control cryptography [34] and autonomous mechanisms [35, 36]. During this section, we are going to review some existing connected research works.

Fang Liu [17] investigates economical calculations to assemble early related optical wireless network within the physical layer. The network has preoccupied by a graph, where every joints or node corresponds to a base-station and moreover each edge related a link between the base-stations. Every node transmits and receives signal beacons among the given distance having a line of sight.

Xiaoming Zhu and J.M. Kahn [29] introduced each spatial-domain and temporal-domain techniques to mitigate the result of turbulence-induced attenuation.

Navidpour [30] used spacial diversity technique to mitigate the result of turbulence induced attenuation to improve the error rate performance of free space optical transmission. For this multiple receivers /transmitters has been employed through the optical link. A bit error rate of 10^{-7} has been attained. The disadvantage of this technique is that the received signal loss is severe if the correlation among multiple transmitters/receivers will increase. The system so needs enough separation between transmitters/receivers apertures.

Abdul Hussein *et al* [33] propose the implementation of FSO/RF hybrid systems. The significant hypothetical capability limits for FSO/RF hybrid communication has been established. A simulation results for communication link with raptor codes has been shown. The simulation results show accomplished transmission rates near the established hypothetical limits of hybrid FSO/RF systems. The planned system totally utilizes the FSO and RF channel resources in spite of the FSO/RF channel environment variations. The disadvantage of the planned system is that the parallel transmission of information on each the RF and FSO channels that compromises the protection advantages of FSO transmission [33]

X. Zhu and J.M. Kahn [30] showed that error control codes could mitigate turbulence-induced fade and so enhance system performance. The drawback of this work has that the assumption of weak turbulence. The pair wise error likely-hood is invalid below high turbulence.

Belmonte [37] derived a BER of M-ary PSK in taking into account both phase and amplitude fluctuations. Phase fluctuation is characterized by Gaussian distribution and the amplitude fluctuation is characterized by lognormal distribution. The signal phase is recovered at the receiver. Two dissimilar conditions of turbulence depending on receiver aperture's diameter are taken into account. Here authors deal particularly through QPSK by means of heterodyne or

synchronous detection. The quantity of modes required for compensation at the recipient is derived. If normalized aperture diameter has small value, the influence of phase noise will be low and intensity fluctuations will become dominant. System performance has therefore greatly hampered. If normalized aperture radius has high value, then the phase noise will be considerably high. Therefore a high order mode in favor of compensation required.

Aniceto Belmonte and J.M. Kahn [38] considered a coherent fiber array with heavily packed multiple sub-apertures into a hexagonal display. Each sub-aperture is line up to a single mode fiber cable for signal fading improvement. The Gaussian phase fluctuations, lognormal amplitude fluctuations and local oscillator shot noise are considered. The authors have analyzed the consequences of fluctuations in amplitude and wave front phase distortion on optical system efficiency and include acknowledged diverse conditions of turbulence rely on the receiver aperture radius size. Once the normalized aperture has large value, fluctuations in amplitude turn into very low or insignificant as well as phase fluctuations become leading part. It is shown numerically that such a coherent system using field conjugation adaptive arrays with multiple sub-apertures outperforms other coherent receivers employing single monolithic-aperture receivers. The drawback of this work is that the phase fluctuations become leading when the normalized aperture increases but in coherent systems the signal phase is also desired for information decoding.

Eric Wainright *et al* [39] investigated diversity technique of wavelength in order to nullify the effects due to two fog environment (radiation and advection fog) using MODTRAN simulation software. Information transmitted and encoded lying on three carriers of different wavelength having 850 nm, 1550 nm and 10000 nm wavelengths. The several carriers have collective plus processed by means of Equal Gain Combining Technique and Diversity Selective Technique. Simulation results showed major increase in the received power when Equal Gain Combining technique used. Although wavelengths, 850nm and 1550nm showed similar effect when propagating through the same fog situation. Therefore it reflects the system redundant when Selective diversity technique has been used. Moreover, 10000 nm wavelength laser equipments are not easily available for FSO system design.

E. Korevaar, I. Kim and B. McArthur [40] discuss the disconnection between opinion and reality of FSO in both the market place and technical community. The authors develop a simple model used to estimate availability probability of FSO system. Visibility data from 10 cities in the US

and 3 cities in the UK are used. Based on this model, the performance of four different FSO systems has compared. The model is as stated below [40]

$$\text{Availability} = 0.22 \times \alpha^{-1.18} - \times 100^{-(\alpha/265)^{10}} \quad (1)$$

Where α is the specific attenuation. The authors also extend a simple formula to predict the necessary link margin to give out scintillation fading. The method is as stated below [36]

$$\text{Margin (dB)} = 2 + \left(\frac{12}{N}\right) \times \left(\frac{100\text{mm}}{D}\right)^2 \times \left(\frac{R}{1000\text{m}}\right) \quad (2)$$

Where N is the number of transmitters, D represent diameter of the recipient telescope, R represent the propagation length. System availability has shown to decrease with increase in the link range. It is further revealed that the extra performance to be enhanced by adaptive optical technology can not generally justify the cost. The weakness of this work has that the outage/availability model does not consider the wavelength dependence of the attenuation even in high visibility conditions.

In [41], the experiment has been conducted. An FSO link operated at 830 nm wavelength lying on a 100 meter lengthy path and located at a height of 26 meters above ground level has implemented in Prague, Czech Republic. The authors express a good relationship between received power levels and visibility. The power levels fall as the visibility goes down and rises when visibility goes up. The shifted power law model and inhomogeneous model has been shown to perform superior for low and medium visibilities.

V. Sharma and G. Kaur [42] review interior and exterior parameters that decrease the performance of FSO links. Techniques to improve some of these challenges are also recommended. The authors reveal some of the degrading parameters as scintillation, absorption and scattering from fog, haze, rain drops and atmospheric molecules. The received power level and the amount of attenuation are shown to be dependent on the atmospheric visibility, operating wavelength, link length and the transmitted power. It is recommended here that spatial diversity techniques employing multiple transmitters and receivers may help mitigate degrading effects of scintillation. Hybrid RF/FSO techniques can also mitigate signal degradation due to fog and rain drops. The negative aspect of this work is that, the authors did not explain how the optional approaches can certainly mitigate the degrading parameters.

R. N. Mahalati and J.M. Kahn [43] discuss the propagation of light through fog with an atmospheric transmission model stand on the equation of radioactive transfer function. Here, the light source is considered to have an isotropic radiation pattern. The authors demonstrate that for thin fog, image flourishing loss has more leading than loss in term of attenuation and therefore image blooming loss needs to be considered when designing FSO systems. The main drawback of this work is the consideration of isotropic radiation pattern of the light source as transmitter used in FSO systems does not have isotropic radiation patterns. FSO systems typically deploy highly directional laser sources which require firm alignment; therefore the model will be unacceptable when applied to such systems [44].

Z. Hajjarian [45] examined the option of easier the MCRT (Monte Carlo Ray Tracing) algorithm during investigate channel behavior of wireless optical communication systems. Here straight pull out of the state conversion matrices related by means of standard Markov Chain model has been used. It has been shown by draw round a photon's path curve in space through a Markov Chain model, an angular distribution of the photon may be evaluated by an easy matrix multiplication. The computational complexity of this Markov Chain model has shown to be far less than the MCRT algorithm though it performs similar to the MCRT algorithm. The computational time for the Markov Chain model remains constant with increase in the optical thickness but the MCRT algorithm's computational time increases as the optical thickness increases. However, this model is still numerically intensive and more computationally complex. It should however be pointed out that more effective strategies to deal with atmospheric attenuations and PAT problems are still actively under research. Much work has been done as far as atmospheric turbulence is concerned. Effective PAT techniques still continues to be a major challenge. Attenuation due to fog still needs further investigation due to the complexity and persistence of fog in the atmosphere depending on the geographical location. FSO system design and implementation therefore requires careful study of the local atmospheric conditions of the area of installation.

2.3 Developments in FSO

The major developments in the field of optical wireless communication are presented in tabular form.

Table 2.1: Progress/Developments of FSO

FSO	Work Done	Authors, Year
Wavelengths used in practical FSO communication systems	830 nm:- Semi-conductor Inter-satellite Link Experiment (SILEX) in Inter-satellite communication	G. D. Fletcher <i>et al.</i> [46], 2002
	830 nm:- Ground/Orbiter Lasercomm Demonstration (GOLD) in Ground-to-satellite link	K. E. Wilson [47], 1996
	1064 nm:- RF/Optical hybrid System for Aurora (ROSA) in Deep space missions	T. Dreischer <i>et al.</i> [48], 2009
	1064 nm:- Short Range Optical Inter-satellite Link (SROIL) in Inter-satellite link	Z. Sodnik <i>et al.</i> [49], 2010
	1550 nm: Altair UAV-to-ground Lasercomm Demonstration in UAV-to-ground link	G. G. Ortiz <i>et al.</i> [50], 2003
Turbulence Profile Models in FSO	PAMELA Model:- Strong model for different terrains and weather conditions type, very sensitive to speed of wind, Does not execute well over marine/overseas atmosphere	E. Oh <i>et al.</i> [51], 2004
	NSLOT Model:- Execute well over marine/overseas atmosphere, Temperature inversion is problematic	S. Doss-Hammel <i>et al.</i> [52], 2004
	Fried Model: - Support weak, strong and moderate turbulence.	S. Karp <i>et al.</i> [53], 1988
	Gurvich Model: - Support all turbulence system from weak, moderate to strong.	A. S. Gurvich <i>et al.</i> [54], 1976
	Von Karman-Tatarski Model: - Used to calculate internal and external level of turbulence, responsive to vary in temperature.	M. R. Chatterjee and F. H. A. Mohamed [55], 2014
	Greenwood Model:- Applicable for turbulence profile in night time for sky-high imaging from high top sites.	A. Majumdar and J. Ricklin [56], 2008
	Submarine Laser Communication (SLC) Model:- Applicable for turbulence profile in day time at interior sites.	H. Hemmati [57], 2009
FSO coding/modulation schemes	Convolutional/ OOK:- Gamma-Gamma Direct Detection.	L. Yang, J. Cheng, and J. F. Holzman [58]. 2013
	OOK with Trellis code:- Negative exponential and K Direct Detection.	G. Z. Antonio <i>et al.</i> [59], 2010
	Bit-interleaved coded modulation (BICM) and Multilevel coding (MLC):- ppm/poisson Direct Detection.	T. T. Nguyen and L. Lampe [60], 2009
	LDPC coded OFDM/ OOK, QAM, QPSK, BPSK :- Gamma-Gamma Direct Detection.	I. B. Djordjevic <i>et al.</i> [61], 2007
	Convolutional code/ PPM:- Gamma-Gamma Iterative Detection.	F. Xu <i>et al.</i> [62], 2009

	Hybrid channel (Non-uniform and rate-compatible LDPC codes) & Adaptive Codes/ BPSK: - Kim model and Gamma-Gamma (Hybrid RF/FSO) ML Detection.	E. Ali <i>et al.</i> [63], 2010
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Many simulation models are developed including carrier sense multiple access/collision detection (CSMA/CD) analytic model to analyze the parameter including mean transfer time and mean queuing time [64]. Breakthroughs come in the year 1993, when Laser diode fabricated and provided multiple beam output. This P-N junction Laser was designed in edge emitting mode as well as surface emitting [65]. In free space optics, when the light propagates through conducting surfaces, then diffraction phenomenon and its effects come into picture which can be analyzed by different models [66].

2.4 Challenges of FSO

Free Space Optical (FSO) communication promises a very bright future in terms of its high data rate, immunity to electromagnetic interference (EMI) and security issues. In any communication system, network's cost and reliability is an essential foot step to accomplish efficient and smart optical backbone networks [67]. Apart from these advantages, some challenges have subdued its widespread deployment. In this section, the challenges faced by FSO communication are mentioned.

2.4.1 Atmospheric effects on FSO

Every channel of communication technology has some effects during signal propagation. Atmosphere of air is used as a propagation channel in FSO and the optical link reliability usually reliant on local climate patterns. Optical absorption, scattering and Index-of-Refractive-Turbulence (IRT) are the main atmospheric processes that influence FSO propagation. The main confront of free space optics in the atmosphere are optical power attenuation during propagation in addition to fluctuations optical signals at the receiver [16]. Our vision of distant objects are affected by surrounding conditions such as clouds, haze, fog, snow, rain along with dirt particles. Laser beam propagation in the course of atmosphere has affected through all these same climatic conditions. FSO signals are exposed by attenuation through absorption, scattering as well as refraction of wave optics by aerosols and gas molecules such as haze, fog, rain and snowfall. Fog is the main adverse attenuating factor with 480dB/km attenuation during dense fog [20].

Successful execution of Free Space Optical communication therefore requires detailed knowledge of the weather patterns in installation region. The region of FSO set up should be studied to ascertain the level of signal decay caused by local atmosphere patterns. Modulated light signals are still attenuated underneath clear weather environment by fluctuations in the index of refraction through propagation medium. Previous mentioned factors grant fast fluctuations in the signal at the recipient end. The necessary margin should therefore be incorporated in the budget of optical link to compensate signal power drop.

2.4.2 PAT Schemes

Pointing, Acquisition and Tracking, shortly known as PAT schemes have been serious challenge in front of FSO. Usual FSO communication requires uninterrupted line of sight (LOS) connecting transmission section and reception section. Modulators of transmitters send out laser beams with fine beam thickness with divergence of few mrad and demodulators of receivers have small aperture of view. This property associated with FSO has made optical links protected to electromagnetic-interference (EMI) and safe with small possibility of interference/low probability of detection (LPD) property [17]. These same properties on the other hand have made it very difficult to establish connection between two transceivers. To maintain connectivity between two transceivers, both must point at each other directly with very accurate LOS direction during transmission.

The pointing mechanism begins with finding out where potential nodes exist for establishing a link in free space and then proceeds to the connection procedure [18]. Since there may be many connection options available when multiple nodes are within range of each other, FSO nodes need to coordinate themselves. It is non-trivial to establish an initial connection between two transceivers even used for fixed nodes due to the thin beam size.

The acquisition method involves signal detection and modulation technique. The recipient aperture can capture many potential FSO beams and has to decide which individual is required as well as decode it accordingly. Again, in the aspect of physical aperture, the aperture diameter needs to be adjusted accordingly in the direction of laser beam emitted divergence along with distance so that it increases the efficiency of the power link budget [18].

Tracking mechanism must also be considered even for stationary links. This is also induced by the narrow beam width. Since FSO is a clear LOS technology and requires a very high pointing accuracy so signal tracking must be considered even in stationary transceivers and remains a

challenging factor. Transceivers can be blown out of alignment by strong winds. Nonalignment result may decrease the capability and enhance the outage probability of optical link, hence the linkage required to be tracked to sustain perfectly alignment.

Unlike in fiber optic communication, there is no possibility of non-linear cross-talk phenomenon by the signal carriers of different wavelength in free space optical communication [68].

In spite of all these challenges, recent research is shown that FSO has feasible when the weather conditions are favorable. Researchers have focused on the physical layer to fully take advantage of the potential of FSO. Several strategies have been proposed to deal with the low availability issues associated with FSO communication such as hybrid FSO/RF [31, 32], diversity techniques [19, 31, 32], autonomous mechanisms [17, 39, 40] etc.

2.5 FSO Characteristic

The fundamental characteristics of optical wireless technology stated here

- a. **High Data Rates (Bandwidth):** The amount of data that can be transmitted in any communication system is depending on the bandwidth of the modulated carrier which is directly related to the carrier frequency. The permissible signal bandwidth may be at the most 20% of the carrier signal frequency. FSO signals use 20THz - 375THz frequency range and could therefore guarantee very high data rates. For the reason that in electromagnetic spectrum, the optical wave carrier frequency consists of ultraviolet, visible along with infrared light are far higher than the radio frequency [14].
- b. **Narrow Beam width:** The beam width of optical signals is very narrow. Typical laser beams have diffraction divergence angle in between 0.01 – 0.10 mrad [19]. It means that optical influence is rigorous inside a thin area and therefore requires a line of sight connecting receiver and transmitter. Optical signals are immune to electromagnetic interference and provide opportunity for unlimited frequency reuse because of this property [19].
- c. **Highly Secured:** Optical signals are highly secured by low probability of detection or probability of interception properties (LPI/LPD) [30]. FSO systems produce laser beams which are very thin and not visible. This makes beams difficult for capture and

moreover difficult to decode. Optical beams cannot detect with RF meters or spectrum analyzers [69].

- d. **Weather dependency:** FSO implementation highly depends on the weather patterns of the area of installation because atmospheric conditions like rainfall, fog, temperature, atmospheric turbulence, dust particles and smoke directly affect the availability and reliability of the FSO link [29].
- e. **Unlicensed Spectrum:** RF signals face a major problem of interference as a result of congestion of the RF spectrum. Local regulatory authorities like Office of Communication and Federal Communication Commission in the United Kingdom and United States respectively, regulate the use of the RF spectrum in their respective countries. To use any RF, requires license from the local authorities which cost a lot of money. The use of the electromagnetic spectrum for FSO does not require any form of licensing from local authorities and therefore is a major cost advantage over the use of RF.
- f. **Ease of Deployment:** The installation time taken by FSO link to ready for operational condition is relatively short. The major requirement is to ensure clear LOS without any form of obstruction between the transmitter and receiver.

2.6 FSO Applications

The characteristic aspects of FSO discussed previously make it extremely attractive for various application scenarios. Again, FSO communication linkages may be employed in civilian as well as in military applications [25]. Below are some of the application scenarios of FSO:

- a. **Deep Space Investigation:** In deep space search, the power, mass and volume of carried apparatus is strictly not allowed and therefore the diameter of antenna and transmitted power are relatively bound. According to [70], lasercom workstations for space search have lesser mass than RF structure. If a huge aperture optical stage exists in a space location or in satellite system then a small user terminal would be operated in space survey. This type of place could comprise an efficient backbone for communication unaltered by visibility circumstances of the earth stations [18].
- b. **Satellite Communication:** Optical wireless links may be used in communications involved satellite to establish a worldwide backbone network. This is because

satellites may support every globally locality despite of any topographical restrictions whenever a line of sight (LOS) space path exists. Therefore FSO links connecting satellites may put forward high quality service (Gigabits data) even to remote areas such as a rural region, an island or an inaccessible country. Optical Links connecting satellites includes Inter Satellite Links (ISL), Satellite to Ground and Satellite to Air. ISL are designed for routing data traffic hop-by-hop through satellites toward a final end satellite that has down link and up link between earth stations or aircrafts. Normally, these linkages have very high data rates of greater than or equals to 10 Gbps. So ISL can provide worldwide communication link [14].

- c. **Terrestrial Networks:** FSO may be used in earthly networks to set up a FSO connection between two transceivers through the atmosphere. The distance of light propagation through atmospheric space can be from hundreds of meters to a few tens of kilometers due to the LOS property. Some applications that can be associated with optical global networks are [18].
- **Last Mile Solution:** Optical wireless can be utilized to link the bandwidth space that present among end users and backbone of fiber optic.
 - **Optical Fiber Back-up Link:** Optical wireless may be employed as a backup for the fiber optics in opposition to information failure or in the occasion of optical cable failure /demolition.
 - **Backhaul for Mobile Network:** FSO may provide a backhaul for communication between main switching stations to base stations in the 3G/4G generation system. FSO can be used as backbone connection in unreachable region where optical cables cannot be established subversive.
 - **Temporary Establishment:** FSO can be used to set up a provisional link in the event of failure or disintegrate of present network due to its ease of installation.

2.7 FSO System

FSO structure, like any other communication technology, is essentially composed of three major arrangements that is, transmitter, channel and receiver. The illustration of a usual FSO network is revealed in figure 2.2

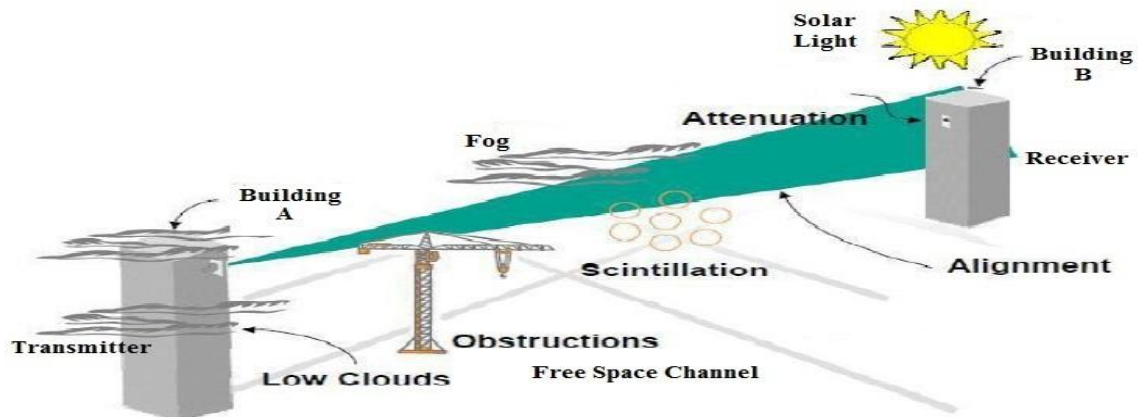


Figure 2.2: FSO architecture

2.7.1 Transmitter Section

The transmitter has main task of modulating the message signal into optical signal for propagation in the course of surrounding environment to the recipient end of communication channel. The transmitter section includes an optical source, modulator, transmitter telescope and the driver circuit. Modulator has accountable for modulating the message signal into the optical signal. On-Off Keying (OOK) modulation scheme has most commonly used in FSO communications. The message signal is modulated into the light intensity of the optical source. It is attained through changing the input current of the optical source accordingly with the data which is to be transmitted. Thus a logic “one” is transmitted by turning ON the optical source whilst logic “zero” is transmitted by turning OFF the optical source. This is called Non-Return-to-Zero (NRZ) coding in its simplest form. Return-to-Zero (RZ) coding, a variant of NRZ, also exists. From [71, 72], the RZ has more advantages over NRZ because in RZ, the clock signal lies within the modulation spectrum and has a higher sensitivity. 8B/0B-NRZ coding which is normally employed in optical fiber communications can also be employed in FSO communication systems. According to [16], 8B/10B-NRZ coding requires 25% more bandwidth than NRZ. 8B/0B-NRZ code scheme implements rapid level alteration irrespective of data flow input. Thus if there is transmission of long series of “0”s or “1”s, the clock signal can never be lost.

On-Off-Keying modulation is very sensitive to distortions in signal amplitude. Atmospheric conditions such as clouds and fog can significantly affect its performance by attenuating the

received signal. The exact wavelength and the phase of the optical carrier are however irrelevant for the demodulation of the received signal.

The optical signal can also be phase or frequency modulated. For example, coherent modulation format like Differential Phase Shift Keying (DPSK) and Binary Phase Shift Keying (BPSK) can be used in FSO systems. In BPSK modulation, the optical signal is shifted between two different states to transmit either a logic “zero” or logic “one”. In Coherent receiver systems, the receiver relies over superposition of the optical signal acknowledged with local oscillator output light. Phase locked loop (PLL) in optical system is employed by using BPSK coding. This permits the local oscillator to be exactly tuned to the phase and frequency of the optical signal received. Coherent modulation schemes are more sensitive than OOK. The disadvantages of coherent modulation schemes are higher system complexity and the fact that they are susceptible to distortions of the atmosphere. The modulated optical wave from the laser are utilized to transmit speech signals, these speech signals contain both voiced/non voiced (V/NV) regions [73].

Generally, intensity modulation schemes are more robust than coherent modulation schemes when considering atmospheric distortions. This is because in intensity modulation schemes, the information encoding is done only with the intensity of the signal whereas in coherent modulation schemes, both the signal intensity and the phase are used. It should be noted that distortions of atmosphere affect both phase of the optical signal and the intensity [72, 74].

Telescope of transmitter collects, directs and collimates the optical signal from the optical modulator to the receiver. The light source employed in FSO arrangement may be LASER or LED. For low data rates (up to 10Mbps) and shorter distances, LED can be used but for longer distances and high data rates (Gb/s of data), LASER is the preferred choice. Table 2.2 lists some optical sources and associated wavelengths used in optical organization.

Table 2.2: Sources of optical signal [74]

Wavelength range (nm)	Laser Category	Remarks
780- 850	1) Vertical Cavity Surface Emitting Diode (VCSED)	1) Inexpensive CD laser and readily available components. 2) High performance and reliable. 3) Short life span. 4) Sensitive receivers. 5) Beam finding by the employ of night vision scope.

1300 - 1550	1) Distributed Feedback Lasers 2) Fabry Perot lasers	1) Longer life span. 2) Compatibility with wavelength division multiplexing (WDM). 3) Compatible with erbium-doped fiber amplifier technology (>500mW power). 4) More expensive components. 5) Less sensitive receivers.
~10000	1) Quantum Cascade Laser	1) Relatively new. 2) Better thin fog performance. 3) Cannot penetrate glass. 4) Components are not readily available.
Near infrared	1) LED	1) Cheaper. 2) Non coherent. 3) Simpler driver circuit. 4) Lower data rates.

This is essential to make a note that even though the atmosphere is assumed to be extremely clear in the near infrared and visible wavelength bands; definite wavelength bands may experience rigorous absorption. Inside near infrared band, absorption takes place mainly in reaction to water particles those are intrinsic components of the atmosphere still in clear atmosphere. There are numerous communication windows that are almost transparent (i.e. comprise attenuation of less than 2 dB/km [28]) inside the (700 – 10000) nm band. Mainstream FSO structures are intended to work in the (780 – 850) nm and (1520 – 1600) nm wavelength bands. The (780-850) nm is mainly used because apparatus are easily accessible as well as less expensive. Wavelength of 1550 nm is moreover best choice for a many reasons. It is allowed to transmit more power than its 850 nm counterpart for eye safety cause (i.e. additional power may be transmitted to conquer reduction of power by aerosols), compatibility with wavelength division multiplexing (WDM) and reduced background solar radiation and scattering in fog or haze [19]. However its disadvantages include reduced receiver sensitivity and higher component cost.

2.7.2 The Atmosphere

Atmosphere is the transmission channel for FSO. The transmission of FSO signals through free space is influenced by three main course of action namely Index of Refractive Turbulence (IRT), absorption and scattering. The transmittance of light optics radiation that travels at a distance L can be modeled through the B. Lambert’s law [16].

$$T = \frac{P_r}{P_t} e^{(-\alpha)} \quad L/\text{km} \quad (3)$$

Where P_r is the optical power received; P_t is the optical power transmitted; α represents extinction coefficient (km^{-1}) and L is the range of propagation (km). The extinction coefficient describes the extinction level of the medium. The extinction coefficient has two components namely absorption and scattering.

The optical radiations pass through the atmosphere, and then absorption occurs when several photons are turning off by molecular ingredients of the atmosphere and their energy converted into heat energy. Table 2.3 lists the molecular ingredients in atmosphere.

Table 2.3: Molecular ingredients in atmosphere [16]

Molecular ingredient in atmosphere	Percentage in atmosphere	Part per million in atmosphere
Carbon dioxide (CO ₂)	0.03	
Argon (Ar)	0.93	
Oxygen (O ₂)	20.95	
Nitrogen (N ₂)	78.09	
Xenon (Xe)		0.09
Ozone (O ₃)		0.05
Carbon monoxide (CO)		0.2
Nitrous Oxide (N ₂ O)		0.6
Hydrogen (H ₂)		1
Krypton (Kr)		1.1
Methane (CH ₄)		1.5
Helium (He)		5.2
Neon (Ne)		20
Water vapor (H ₂ O)		40 – 40000

Again optical emission through the environment is attenuated by scattering source by gas aerosols and molecules like fog/haze, rainfall, snow etc. This can be modeled by the Rayleigh or Mie scattering coefficient. In general, attenuation due to scattering reduces with wavelength and altitude [16]. Scattering causes changes in the path of propagation of the light wave. The optical beam broadens out while pass through the channel because the size of the received beam to be wider than the aperture of receiver. The concentration and amounts of the aerosols relies on the geographical place and the time of year. Therefore installation in FSO systems requires a detailed investigation to ascertain the level of attenuation caused by the local weather patterns of the area of installation.

Atmospheric turbulence is another feature that must be considered. Even under clear weather conditions, optical wave propagation is attenuated by atmospheric turbulence. When the earth is hit by the sun's radiation, the earth surface absorbs some of the radiation. This results in the heating up of the earth's surface air mass which rises up and mixes turbulently with the cooler surrounding air mass. The mixing up of warm and cool air accumulation causes small and temporary fluctuation in temperature of atmosphere [22]. The temperature non uniformity of the environment causes subsequent alteration in the atmospheric refractive index which results in the formation of chamber or packets of air called eddy with unstable dimensions range from 0.1cm to 10cm. These eddies look similar to refractive prisms with changeable refractive indices. Therefore the transmitted light wave has completely or moderately diverged from its original trajectory. The deviation depends on the relative beam size and the amount of temperature non uniformity down the pathway [22]. As a result, the FSO wave travelling along the turbulent atmospheric conditions shows fast fluctuations in phase and intensity. This phenomenon introduces losses in the transmitted optical source. The necessary margin is therefore required to compensate for such losses in the optical link budget [22]. Apart from FSO, the lightening condition of atmosphere also provides a hurdle in traffic monitoring and objects tracking dielectric techniques [75].

2.7.3 Receiver Section

The responsibility of the optoelectronics receiver has to pick up the transmitted data from the coming optical wave. Optical based receiver basically consists of photo detector, optical filter, post detection processor and receiver telescope.

The received optical signal has accumulated by the telescope and concentrated into the optical detector. Aperture averaging can be employed to reduce attenuations experienced as a result of beam spreading. In aperture averaging, the receiver telescope is made relatively larger so that it can collect multiple uncorrelated optical radiations, average them and focus their average onto the photodiode. This would however be note down that a wide receiver aperture also increases the background radiation or noise as it collects other light sources of light like the solar radiation. The optical filter is responsible for filtering the transmitted optical radiation from other sources of light like the sun impinging on the receiver aperture. This helps reduce the amount of background radiation [74].

The optical photodiode received the incident optical signal from the telescope and change light signal back in its electrical form. The Avalanche Photodiode (APD) or P-I-N diode has employed for the conversion process. The table 2.4 below lists the commonly used photodiodes in laser communication and their characteristics [74].

Table 2.4: Types of photodiodes [74]

Material & structure	Wavelength (nm)	Responsivity	Gain	Sensitivity
InGaAs APD	1000 to 1700	0.9	10	-33dBm @ 1.25Gbps
InGaAs P-I-N	1000 to 1700	0.9	1	-46dBm @ 155Mbps
Si P-I-N	300 to 1100	0.5	1	-34dBm @ 155Mbps

To assure an extremely reliable data resurgence, the post detection processor or decision circuitry workout the process of filtering, amplification, and signal processing. The recipient detection procedure can be categorized in two; namely, coherent detection receiver and direct detection receiver. The direct detection receiver detects the instantaneous optical power impose on the photo detector. Therefore the output of photo detector is comparative to the incident optical wave. The coherent detection based receiver employ on photo-combination phenomenon. The received optical signal is mixed with output optical signal of local oscillator on top surface of the photo detector. The coherent detection based receiver may ahead segregate into heterodyne and homodyne receivers. In heterodyne detection process the received emission and the local radiation wavelengths are dissimilar while in homodyne detection process the output signal wavelength of the local (optical) oscillator is just equal to the received emission.

2.8 Summary

Inside this chapter, the concept of FSO has been described. We reviewed some existing related work done. Features, application scenarios and challenges of FSO technology have been discussed. The atmosphere poses serious challenges in FSO and therefore imperative to study its effect on the system. This thesis seeks to investigate the effects of the atmospheric mitigation techniques on FSO communication systems. Again, the margin to compensate for losses due to scintillation effects will also be investigated. Implementation of FSO/RF communication systems has also been determined.

Chapter 3

Designing of Free Space Optical Link with RF Backup

3.1 Introduction

Optical Wireless offers an alluring option for exchanging high-transmission capacity information when installation of fibre optic has not been possible, propose a smart replacement for transmit high bandwidth information. Nevertheless, several adverse facets of the atmospheric channel that might guide to severe signal fading and yet the total lack of signal, for example, animals, insects, tree, or other reasons be capable of all time obstruct the laser viewable pathway. Platform/constructing movement because of airstream, discrepancy heating and cooling or else floor movement are able to bring about genuine disarrangement of altered location laser link. But significantly in all, the phenomenon of scattering and absorption as a result of particulate topic within the surroundings may enormously reduce the optical wave signal, even as haphazard atmospheric alteration has rigorously degraded the optical signal, because of that faded signal reached at receiver side [76].

Rain, fog, snow, smoke and different aerosol particles essentially weaken the laser beam signal. Absorption due to molecules has also reduces by proper choice of the wavelength of optical wave. The random instability within the atmosphere's index of refraction that drive optical turbulence continually result in extended optical BER. Turbulence in optics prompted signal degradation which increments further when as transmitter to recipient separation has expanded. There is no wavelength "window" where these impacts are stayed away (despite the fact that longer wavelengths are better). For some instances of realistic curiosity, the consistent existence of turbulence optics in the climatic path has the restricting aspect in risk less wi-fi optical wireless hyperlink performance. Optical wireless continue as solitary less distance covered broadband technology by knowing the fact that its enormous prospective in determining the "end mile" concern because of FSO ability of accomplishing close optimum capacity equivalent to optical fibre line along with a low cost and instant arrangement [76].

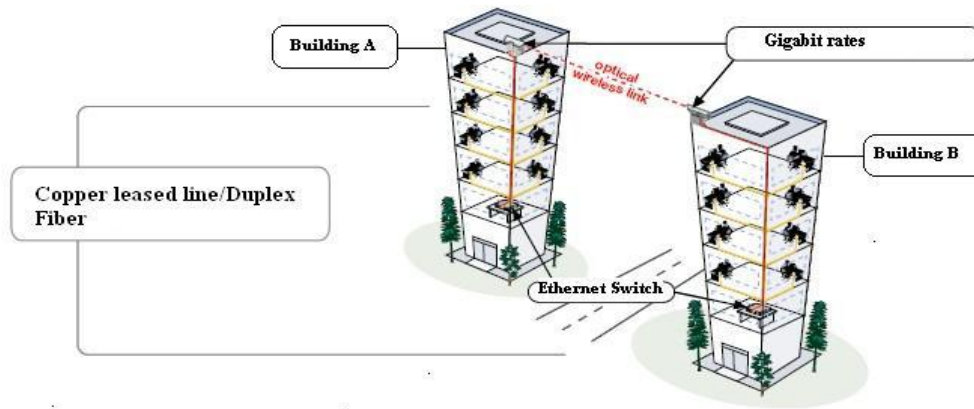


Figure 3.1: Wireless/ FSO link connecting two buildings

Optical wireless and RF technology may be the other option toward uninterrupted connectivity throughout the time as both supplementing each other's shortcomings, due to the fact that rain and fog definitely influence the RF and FSO interfaces separately, however the chances for both occur simultaneously is negligible.

Korevaar and Kim [77] stated that the atmosphere constriction of optical signal energy is an irregular function of the climatic conditions and this power fluctuates in range of 0.2 dB/km in especially plain climate (i.e., 50 km of visibility) to 350 dB/km in extremely thick haze/fog (i.e., 50 meter of visibility) and assessed the undignified influences lying on the hyperlink during link budget investigation and authentic climate information. Subsequently, this has persuaded various countless research efforts endeavors especially in the latest decade to plan and actualize a more predominant hybrid FSO/RF system, which exploits the media diversity technology through coordinating a lower information rate RF together with the FSO channel. Through the improved duality function to change among the two technological innovation choices, FSO/RF technique possibly combats the deterioration of signal high-quality and hyperlink outages, via sustaining minimal information transformation via the complementary RF link, for the interval when the principal FSO hyperlink has out of reach because of undesirable atmospheric circumstances [31, 78-81].

3.2 Laser Beam Destruction Due to Aerosols and Molecules in Atmosphere

Destruction/Extinction has characterized by a diminishment within the strength of an optical signal. Around two procedures available to facilitate about extinction are absorption and

scattering. These two phenomenons take away power from the transmitted beam path. Scattering and absorption approaches may also additional and be sub partitioned into two dimension areas: a molecular establishment and an establishment of bigger particles (aerosols).

3.2.1 Extinction

Extinction causes decay in power of an optical signal because signal travel throughout a space containing particles, molecules and other constituent part of medium. Goody and Yung II characterize basic law of elimination which expresses that the extinction progression is linear in strength of radiation and quantity of matter inside shows its physical state (i.e., pressure, composition, temperature) is alleged steady [82].

When monochromatic transmitting beam of laser contact through non vacuous space in excess of additional path extent ds , then alteration in intensity has specified as [82]

$$dI_v = - I_v \beta_{ext,v} ds \quad (1)$$

Here I_v be amount of intensity, $\beta_{ext,v}$ is an destruction/extinction coefficient, together at the frequency v . As the extinction process is linear, then extinction coefficient can be given as [82]

$$\beta_{ext,v} = \beta_{sca,v} + \beta_{abs,v} \quad (2)$$

i.e., the overall extinction consists of the linear sum of extinction coefficients because of absorption and scattering.

The optical width of a medium connecting two end h_1 and h_2 is expressed as [82]

$$\tau_v(h_1, h_2) = \int_{h_1}^{h_2} \beta_{ext,v}(s) ds \quad (3)$$

Through the information of the wave width τ_v , and preliminary intensity I_0 , the resulting drop in intensity subsequent to transmission between the two end h_1 and h_2 is given by [82]

$$I_v = I_0 e^{-\tau_v} \quad (4)$$

3.2.2 Molecular Extinction

Extinction is a predominant aspect in beam loss. Optical wavelengths higher than 1 pico-meter, molecules are not combined powerfully through the electromagnetic field. Moreover, molecular

extinction has mainly as a result of absorption of occurrence radiation by most effective small scattering contributions [83].

Atoms take up power in separate quanta, these results in altering the vibrational and rotational condition of the atoms. So atoms's spectrum thus contains a sequence of discrete absorption strains. The assimilation range of atoms along these lines are from 10 cm wavelengths to a 100 pm, vibrational spectra are normally from one hundred to one pm. Electronic moves are within the ultraviolet and visible bands. The vibrational spectra are the best impact in the frequencies significant to free space laser signal [83].

3.2.3 Molecular Transmittance Codes

The Air Force Geophysical Laboratory (AFGL) has created three representations to portray losses due to transmittance because of molecular extinction: Modtran, Lowtran and Fascode [84, 85].

The Fascode which is also a “line by line model”, decides the optical strength which is a function of wavelength. This absorption stripe has three fundamental parameters: the middle location ν_0 , a line strength S , and the profile function f . The profile (or Lorentz profile), which represent line shape is specified by [85]

$$f(\nu - \nu_0) = \frac{\delta}{\pi[(\nu - \nu_0)^2 + \delta^2]} \quad (5)$$

Here δ thickness of line. This profile is mainly significant in the low atmospheric circumstances of comparatively high pressure.

This model processes the line designed for all and every absorbing gas, which essentially incorporates the division of lines at different distance from the monochromatic line of significance. The outcome from computation is depth of optical layer, or an optical thickness. The ratio of radiant flux transmission by the surface or region denoted by ϕ_e^t to radiant flux received by the surface or the region denoted by ϕ_e^r is known as the Transmittance T of a region or surface and the expression involving these two radiant flux is given as follows equation (6) [86]

$$T = \frac{\phi_e^t}{\phi_e^r} \quad (6)$$

3.3 The last mile access and applications of Optical Networks

Free Space Optical System (FSO) connections may be utilized to setup communication in addition to radio and optical fiber systems. As a consequence, it's the broadband wi-fi solution for the "last mile" availability space all through metropolitan systems. FSO system suitable in thick metropolitan zones. It set up small distance communication hyperlinks among structures on a campus or exclusive office blocks of an organization or medical institution, which can be built up with ease innovation.

However, current research has also been investigating the use of light generators like LEDs in FSO by means of a broad beam angle. Now the utilization of free space optical communication in support of last mile has been investigated and illustrate in further aspect.

3.3.1 Line of Sight

Optical transmission via the surroundings need a line of sight without interruption from the end of transmitting terminal to other end of receiving terminal, however the climate impact is a key component in optical wave propagation. Visibility data accrued over several years more thoroughly with a transmission meter instrument at meteorological location or at airports to estimate availability in optical communication planning. Transmission through atmosphere may be depicted through the Beer-Lambert regulation [87].

$$T = \frac{P_d}{P_0} = e^{-\gamma d} \quad (7)$$

At a particular wavelength, the transmission T depends on optical power P_d at a distance of d to the transmitted optical power P_0 . As per the Beer-Lambert law, transmission may be expressed with the aid of the extinction coefficient $-\gamma$ and the atmospheric path distance d. The extinction coefficient $-\gamma$ is constituted by means of procedures of absorption and scattering through particles in the atmosphere.

Visibility data are used for infrared wavelength broadcast. The opening relation based on empirical dimension data has been projected by Kruse [87]

$$\gamma(\lambda) \approx \beta_a(\lambda) \approx \frac{3.912}{V} \left(\frac{\lambda}{550 \text{ nm}} \right)^{-q} \quad (8)$$

In equation (8) the exponent q lying on the visibility range. For taking account of lower visibilities in intense fog, the preliminary Kruse equation has been modified by Kim given below [84, 87]

$$q = \begin{cases} 1.6 (V > 50 \text{ km}) \\ 1.3 (6 \text{ km} < V < 50 \text{ km}) & \leq V < 50 \\ (0.16.V + 0.34) \text{ if } 1 \text{ km} \leq V < 6 \text{ km} \\ (V - 0.5) \text{ if } 0.5 \text{ km} < V < 1 \text{ km} \\ 0 \text{ if } V < 0.5 \text{ km} \end{cases} \quad (9)$$

On the whole this is challenging to get a relation that permits the re-computation of visibility data in between 550 nm to longer wavelengths. Fog of different types can bring about various attenuation for higher wavelengths in a similar visibility range, really relying upon molecule magnitude measurement distribution and its density consistent with Mie scattering model. Measurement data gives that longer wavelengths are less attenuated in haze and light fog, whereas there's no wavelength dependence in thick fog. Novel theoretical computations by Alnaboulsi for advection and convection fog point out that small wavelength are minimum attenuated at less visibility, as it is the requirement of high accessible FSO [87].

3.3.2 Reliability and Availability

System reliability $R(T)$ is a likelihood that the optical structure works properly for duration of time T over defined atmospheric circumstances and system availability $A(t)$ is the chance that system works in time t effectively.

Since information transfer in FSO uses physical layer, the conditions for right operation of it are outlined by using a highest tolerable bit error rate (BER) for the distinct data rate (e.g., $BER = 10^{-9}$ for 100 Mbps). If an excessive amount or not enough optical power has arriving, then BER increases. When long distance considered in FSO using extra collimated and coherent light, oscillation within the acquired power are more significant. Because of that, it is difficult to set the precise sensitivity boundary and would additionally rationale efficiency degradation by means of burst errors, which may be refrained by implement coding of channel and correction in error procedures [88].

The accessibility of an introduced FSO link most often depends upon the budget analysis of power link and the nearby weather conditions, causing more attenuation over durations of time.

The model of an FSO system also be concise within the parameter system power P_{sys} (in dBm) to [88].

$$\begin{aligned} P_{\text{SYS}} &= P_{\text{TX}} + G_{\text{TX}} + A_{\text{RX}} - \sum (\alpha_{\text{TX}} + \alpha_{\text{RX}}) \\ &= P_{\text{TX}} + 10\log\left(\frac{4\pi}{2\pi(1 - \cos\alpha/2)}\right) + 20\log(R_A) - \sum (\alpha_{\text{TX}} + \alpha_{\text{RX}}) \end{aligned} \quad (10)$$

In Eq. (10) P_{TX} represents the transmitted optical power in decibels (dBm), G_{TX} represents transmitter gain in decibels (depending on the whole beam divergence angle α), the receiver gain because of its aperture radius R_A has represented as A_{RX} . Furthermore, transmitter and receiver signal losses are α_{TX} and α_{RX} in dB respectively. Then the power received P_{RX} in distance d represented by [88]

$$P_{\text{RX}} = P_{\text{sys}} - D_L = P_{\text{sys}} - 20\log\left(\frac{2d}{1 \text{ m}}\right) \quad (11)$$

Equation (11) showed the distance D_L in decibel. Then P_{RX} be the received signal strength without any effect of atmospheric conditions or pointing losses.

Reliability may be defined as Mean Time to Failure (MTTF) rate or the Failure in Time (FIT) rate virtually. FIT approach the probability of a component failure in 10⁹ hours of action. In optical wireless systems particularly the transmitting essentials have a limitation of lifetime, depends on the operation conditions. Generally, the energy outputs of components decrease slowly, and eventually the components stop to perform. LASER and LED usually have a life of 10⁵ to 10⁸ hours of function. Running the gadgets below the prescribed maximum output energy and avoid over heating due to high temperature can increase the life of components [76, 88].

3.3.3 Last Mile Solution

Optical communication without fiber is an outstanding wideband solution for linking consumer. FSO technique could be visible as enhancement to usual radio hyperlinks and communication through fiber. Low price and short distance FSO communication put this technique attractive for many customers.

In the meanwhile, the main focus are on increment in reliability and availability of FSO. Both these factors are especially depends on local climatic situations. Better reliability and availability

may accomplished by short distance communication, by doing link-budget analysis and using the highest quality FSO structure.

The meshed architecture is ideal for FSO designs. Meshed structure consolidates small distances with excessive speed. The additional reliability and availability of FSO can be increased by participating in outdoor tests concerning the neighbourhood condition of atmosphere.

Reliability and Availability can further be improved by the arrangement of FSO and microwave hyperlinks, as mainly FSO has influenced by fog and RF has generally effected by rainwater. From the research, FSO/RF hyperlink had been set up and the results confirm a 99.9991% reliability of this hyperlink [76, 88].

3.3.4 Experimental Setup

To set up an optical wireless link, the separation between two structures has been around 500 meters that permit excessive-speed networking link. The optical wavelength of 1550 nm has been used. The line of sight alignment has been done by using telescopes alignment process.

Practicability exhibited by means of free space optical hyperlink connecting the two computers which has demonstrated in Fig. 3.2. The gigabit Ethernet companionable sequence of pulses in form of data has been coming from PC. The set up comprises of a two transceiver which makes use of Positive Emitter Coupled Logic (LVPECL) signaling. The pc generated an information pulse that must be changed over to PECL signal. The established link is unidirectional. It may possibly be two way by replicating the entire link arrangement in reverse course.

The conversion of received electrical signal into optical signal takes place in transceiver. The optical signal is then converted into extremely thin beam by using an optical collimator. The signal in the form of beam is put on the air or open space and by using optical receptor it has acknowledged by receiver. The photodiode of receiver has then changed again into electrical signal. The LVPECL electrical signal has now transformed into the Gigabit Ethernet form of electrical signal by GBIC connector.

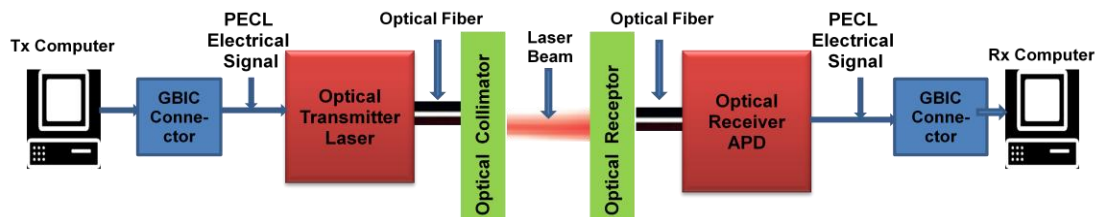


Figure.3.2: FSO link set-up

A gigabit interface converter (GBIC) most of the time utilizes Gigabit Ethernet and optical fiber. One gigabit port of this electrical interface can utilize by many physical media for example copper wire and optical fiber at some meter distance. Gigabit Interface Converter (GBIC) at the initially intended for Fiber Channel executions utilizing the Fiber Channel Arbitrated Loop (FC-AL), this is mainly used for Fiber Channel implementations including 1000 Mbit Ethernet [89,90]

The PECL drivers and receivers termination circuit in the host and the GBIC are shown in fig. 3.3 [89, 90].

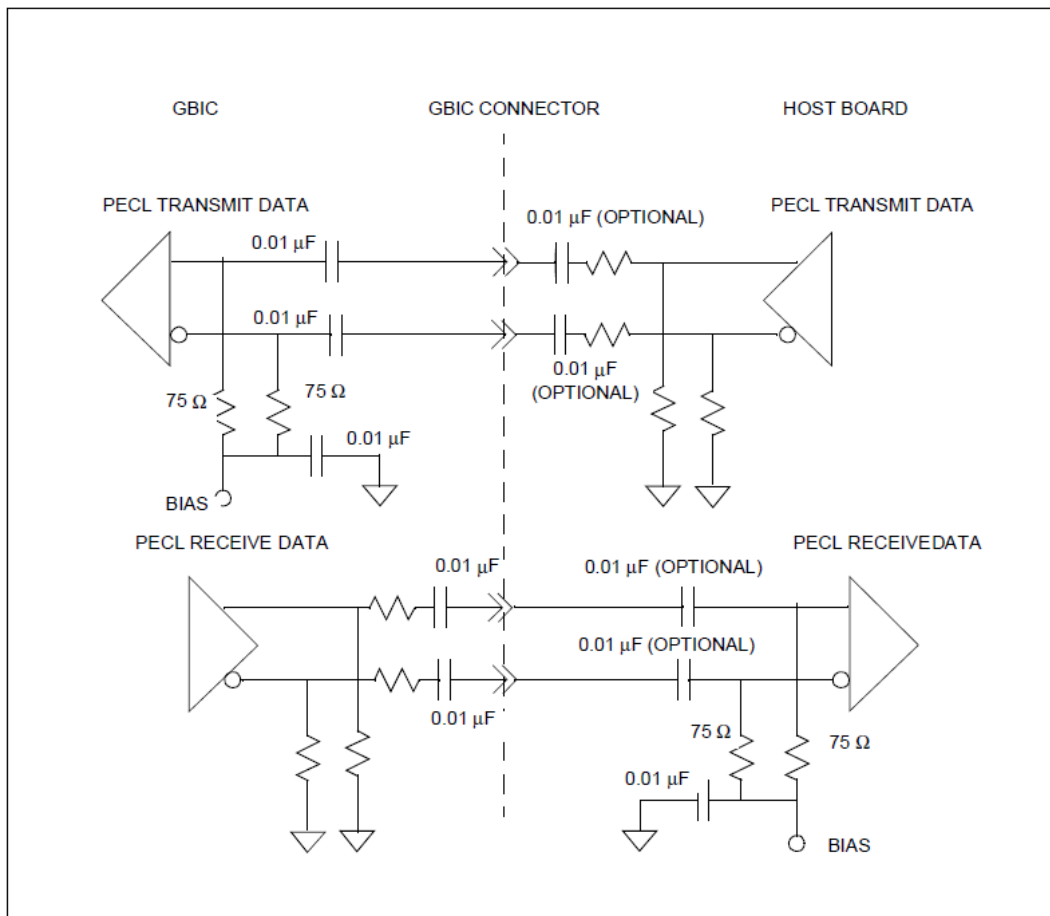


Figure.3.3: Termination circuit for the PECL transmitter and receiver and GBIC [89].

3.4 Optical System Design

For optical configuration, the optical wavelength of 1550 nm has been used and the separation connecting the two configurations is 500 meters. The 500 meter visibility and classification 3A eye-trustworthy power level has been viewed for the system design [91].

To measure environment condition which comprises of dust, mist, fog, other particles etc., Visibility has valuable parameter. Visibility decreases down to couple of meters due thick fog [92].

Signal attenuates and degrades in a FSO hyperlink by the effect different process of Scintillation, Scattering and Absorption. Dependency of all these effects depend on present local climate condition. By Beer's regulation, atmospheric attenuation is expressed as [93].

$$\tau = e^{-\alpha L} \quad (12)$$

Here, τ = atmospheric attenuation

L = distance in km

α = resultant coefficient of attenuation

Now,

$$\alpha = \alpha_{\text{abso}} + \alpha_{\text{scat}}$$

α_{abso} = molecular & aerosol absorption

α_{scat} = aerosol & molecular scattering

Absorption is due to the collision of optical beam's photons which collides with few finely dispersed liquid and strong molecules within the space comparable to vapors of water, snow, dust and organic particles. The absorption strains at visible and infrared wavelengths are narrow fine. For this reason, absorption may in general be negligible at wavelength of interest in optical wireless [93].

The attenuation due to scattering is shown by following expression [93].

$$\alpha_{\text{scat}} = \left(\frac{3.91}{V}\right) \left(\frac{550}{\lambda}\right)^{\delta(V)} \quad (13)$$

Here,

λ = wavelength in nm, V = visibility in km and $\delta(V)$ = scattered particle size which lies from 0.7 to 1.6 analogous to visibility situations [94]

Here, for

$\delta(V) = 1.6$ used for $V > 50$ km.

$\delta(V) = 1.3$ used for $6 \text{ km} \leq V \leq 50$ km.

$\delta(V) = 0.585 V^{1/3}$ used for $V < 6$ km. (14)

The attenuation due to Atmospheric condition for a different visibility within the limit of 1.5 km to 5 km has been shown in plot, which is shown in fig. 3.4.

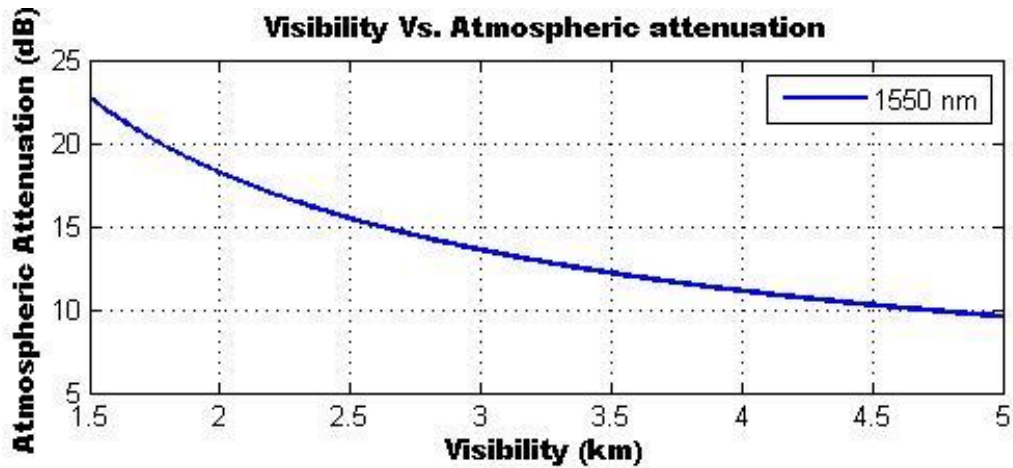


Figure.3.4: Visibility vs. Atmospheric conditions.

In FSO structure a slightly less diameter of transmitter aperture and a bigger diameter of receiver aperture are expected to build up high data rate FSO link. The transmitter aperture diameter is chosen to be a usual value of 3.5 cm and receptor diameter of 28 cm. The beam angle θ is considered to be a traditional value of 0.5 milli radian. Semiconductor based optical amplifier for 10 Gb/s non-return to zero configuration in single mode and dispersion connection are utilized [95].

3.4.1 Atmospheric Conditions based Attenuation Models

The instantaneous intensity of laser source changes by modulation process, and then modulated signal is transmitted. At the receiver, the signal has detected by photodiode of receiver. The optical signal propagates in free space where photons of optical signal are scattered and absorbed via the atmospheric constituent parts, like rain, snow and fog droplets. Usually, the radii of these droplets lies between 1 μm to 5000 μm , and quantity of droplets sharply decreases when drop size increases and various attenuation models relying on their density distribution [96].

For calculation of attenuation by rain, fog and snow, the two approaches empirical and theoretical are utilized. The empirical process may be exceptionally convenient and quick to

apply while; the theoretical method is quite complicated and takes long time. Kim's proposal has been used in foggy to clear condition to calculate the attenuation because of fog (α_{fog}) [97].

$$\alpha_{\text{fog}} = \frac{3.91}{V} \left(\frac{\lambda}{550} \right)^{-\delta(V)} \quad (15)$$

Here factor $\delta(V)$ associated to droplet size specified by [85]

$$\delta(V) = \begin{cases} 1.6 & (V > 50 \text{ km}) \\ 1.3 & (6 \text{ km} < V < 50 \text{ km}) \\ (0.16 \cdot V + 0.34) & \text{if } 1 \text{ km} \leq V < 6 \text{ km} \\ (V - 0.5) & \text{if } 0.5 \text{ km} < V < 1 \text{ km} \\ 0 & \text{if } V < 0.5 \text{ km} \end{cases} \quad (16)$$

For rain, the loss in optical energy is comparatively wavelength insensible and attenuation due to rain in terms of visibility is given by [98].

$$\alpha_{\text{rain}} = \frac{2.9}{V} \quad (17)$$

The attenuation of optical pulse due to fog in most cases due to Mie scattering consequence and the loss due to absorption may also be ignored. For this reason the evaluation of fog extinction coefficient is given by below equation [97].

$$\beta_{\text{fog}} = \int_{r_1}^{r_2} \pi r^2 Q_{\text{ext}} \left(m, \frac{r}{\lambda} \right) n(r) dr \quad \text{dB/km} \quad (18)$$

In equation (18) the representation for the refractive index and radius of the fog droplets are m and r correspondingly. The extinction efficiency and fog particle size gamma distribution by Q_{ext} and $n(r)$ correspondingly. The traditional equation for rain conditions is given by [98].

$$\beta_{\text{rain}} = 4.34 \int_{r_1}^{r_2} \alpha_{\text{scat}}(r) n(r) dr \quad \text{dB/km} \quad (19)$$

Here rain particle gamma distribution and radius of the rain drops represents by $n(r)$ and r , correspondingly. The rain rate R may be considered as [98],

$$R = 4.8 \int_0^{\infty} r^3 v(r) n(r) dr \quad \text{mm/hr} \quad (20)$$

$v(r)$ is the rain drop terminal velocity, which is specified as in equation (21) [98].

$$v(r) = 9.65 - 10.3e^{-1.2r} \text{ m/s} \quad (21)$$

Model of attenuation due to snow depends on the type of snow that is, dry or wet. The precise attenuation has been shown in equation (22) [99, 100].

$$\alpha_{\text{snow}} = a S^b \quad (22)$$

Here snow rate S is in mm/h

For dry snow at a particular wavelength λ , the values of a and b are [100]

$$a = 5.42 \times 10^{-5}\lambda + 5.4958776 \quad \text{and} \quad b = 1.38$$

For wet snow, the similar factors are [89]

$$a = 1.023 \times 10^{-4}\lambda + 3.7855466 \quad \text{and} \quad b = 0.72$$

Snow attenuation depends upon the type of snow as previously discussed. The relationship between snow attenuation and visibility range as follows [100, 101].

$$\alpha_{\text{snow}} = \frac{58}{V} \quad (23)$$

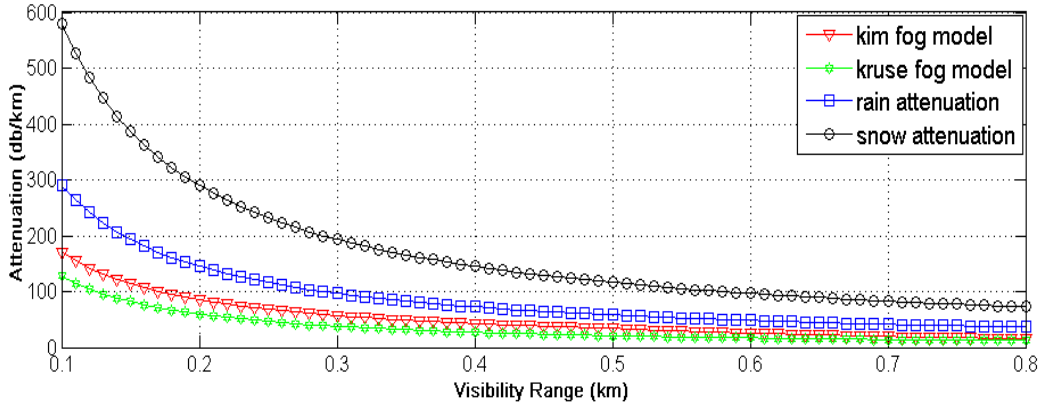


Figure 3.5: Plot of empirical model for fog, rain and snow conditions for FSO link at 1550 nm

Figure 3.5 demonstrates visibility against attenuation for rain, snow and fog. From this graphical result it has clear that losses due to fog, rain and snow results considerable to the optical signals transmission in open space. From the results, fog offers low visibility as compared to other atmospheric factors like rain and snow at the same amount of attenuation.

3.5 Optical/Microwave Hybrid Links

The accessibility of optical transmission is restricted via atmospheric condition like fog and intense snow down. While the communication link set up by microwave working at excessive frequencies of around 40 GHz delivered same data rates and served secondary path. Linkage accessibility for microwave system is confined by intense rain. Combination of both technology results in higher connection accessibility.

3.5.1 System Description

The free space optical communication is regularly restricted by extensive optical losses especially because of overwhelming fog. To build the system accessibility, an option has to utilize a Radio Frequency wave linkage alongside the Free Space Optical linkage [102].

The system execution in FSO has been mostly corrupted because of climatic condition change. In RF link, the execution is principally corrupted because of rain drops, as rain drops sizes are identical to wavelengths in RF range. Thus, RF may supplement FSO linkage and vice-versa. [103].

The availability in addition to range for simultaneous use of FSO and RF system may enhance considerably which revealed in figure 3.6. Hybrid FSO/RF linkages may offer a reasonable alternative for single or multichannel links along with higher data capability.

The Redundant Link Controller (RLC) method has been use for executing a FSO/RF framework. The RLC technique gives the FSO/RF communication by a hitless ability. This implies that no bit in frame is missing when FSO or RF starts to come below threshold power then alternate vice a versa starts to take control over the communication link, regardless the possibility of quickly switching because of altering atmospheric conditions. The frame by frame comparison on Cyclic Redundancy check (CRC) bit series need to determine whether an error or fault has came out. If the error has occurred in frame, then similar frame from alternate path has been used by RLC technique and ahead it to the end consumer [94].

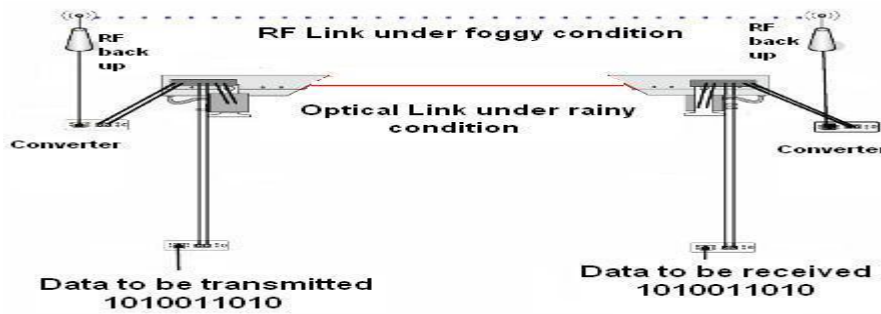


Figure 3.6: Set up of hybrid FSO/RF system in different atmospheric conditions.

Fig. 3.6 illustrates, optical link as a rule offer Gigabits/second information rate, while the Radio link has restricted to 100Meghabits/second. Additionally for further effective utilization of the hybrid hyperlink for all atmospheric conditions, the control unit ought to forward both the communication linkage. In terrible climate surroundings, the control unit ought to likewise consider different connection parameter issues, for example, received power for each system link and so on [94].

3.5.2 System Model

Figure 3.7 represents FSO cum RF link [104]

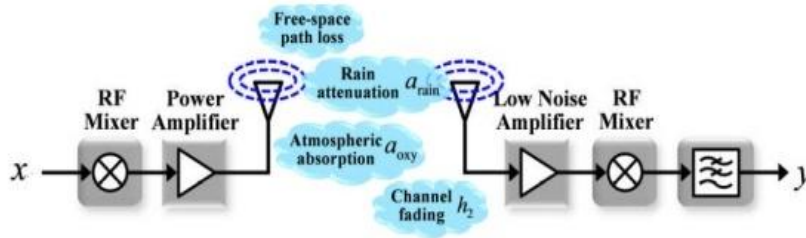


Figure 3.7: Arrangement of 60 GHz RF System

The substantial bandwidth accessibility of the 60 Giga Hertz millimeter wave unlicensed spectrum paying attention to various applications of wireless technology and services [104-107]. These comprise cellular broadband, mobile techniques, wireless backhaul networks and wi-fi. The millimeter wave has extremely vulnerable about attenuation due to atmosphere Moreover, millimeter wave experiences signal degradation due to absorption by rain drops and oxygen gives an extra 7-16 dB/km signal energy degradation. For a rainfall rate of around 50 mm/hour, the millimeter wave signal anticipates extra attenuation of 8-18 dB/km [104-107].

In the RF link as shown in figure 3.7, quadrature amplitude modulation system (QAM) has been used as a matching FSO hyperlink [107, 108].

The output signal through RF channel has been specified as [109]

$$y = \sqrt{P_{RF}}\sqrt{G_{RF}}h_2x + N_{0,RF} \quad (24)$$

Where P_{RF} is RF transmitted output, G_{RF} is the RF power gain in link, h_2 is fading gain of RF, x is RF signal in modulated form, and $N_{0,RF}$ be the complex AWGN along with variance.

3.5.3 Model of FSO and RF Channel

Atmospheric loss is mainly due to the factors like absorption, scattering and attenuation. Mathematically it may be represented by Lambert-Beers law [109].

$$\beta = e^{-\alpha L} \quad (25)$$

Where α and L denotes an attenuation coefficient which depend upon atmospheric condition and propagation distance L respectively. In adverse atmospheric surroundings, α may be evaluated by the visibility records by model of Kim [97].

$$\alpha = \frac{3.91}{V} \left(\frac{\lambda_1}{550} \right)^{-q} \quad (26)$$

Here V denotes visibility (km), λ_1 represents laser wavelength (nm), and q be particle dimension distribution. The scintillation because of atmospheric particles disturbance inside weak turbulence system, comes due to indiscriminate change in the index of refractive of free space. This scintillation comes from log-normal fading model. The PDF of the intensity (I) due to fluctuations in turbulent atmosphere is given by [110].

$$P(I) = \frac{1}{I\sigma_1(D)\sqrt{2\pi}} \exp \left\{ -\frac{\left[\ln \left(\frac{I}{\langle I \rangle} \right) + \frac{1}{2} \sigma_1^2(D) \right]^2}{2\sigma_1^2(D)} \right\}, \quad I > 0 \quad (27)$$

Where $\sigma_1^2(D)$ is the index of scintillation and $\langle I \rangle$ is mean intensity.

Scintillation index $\sigma_1^2(D)$ can be determined from the below equation [108]

$$\sigma_1^2(D) = \exp \left[\frac{0.49\chi^2}{(1+0.18d^2+0.56\chi^{12/5})^{7/6}} + \frac{0.51\chi^2(1+0.69\chi^{12/5})^{-5/6}}{1+0.90d^2+0.62d^2\chi^{12/5}} \right] - 1 \quad (28)$$

Here,

$$\chi^2 = 0.492 \left(\frac{2\pi}{\lambda_1} \right)^{7/6} C_n^2 L^{1/6} \quad \& \quad d = \sqrt{\frac{2\pi D^2}{4\lambda_1 L}}$$

Where χ^2 denotes Rytov variance for spherical Gaussian wave and D is receiver's aperture. C_n^2 denotes the structure parameter of refractive-index which represents the atmospheric turbulence strength. SNR be a fluctuating or instantaneous term, so implying that the average (mean) value

is required to provide a quantitative measure of the overall system performance. The mean signal to noise ratio (SNR_1) can be represented as [110]

$$\langle \text{SNR}_1 \rangle = \frac{\text{SNR}_0}{\sqrt{\frac{P_{SO}}{\langle P_S \rangle} + \sigma_1^2(D) \times \text{SNR}_0^2}} \quad (29)$$

Where SNR_0 represents SNR ratio in the non-turbulence condition, Signal power is denoted by P_{SO} in negligible atmospheric effects, $\langle P_S \rangle$ is the mean signal power at input and $\sigma_1^2(D)$ denotes scintillation index.

RF signal operational by means of amplitude shift keying (ASK) which is regarded like a subsidiary link along with FSO link [111]. The RF link overall gain G_{RF} may be modeled as [112]

$$G_{\text{RF}} [\text{dB}] = G_{\text{RX}} + G_{\text{TX}} - 20 \log_{10} \left(\frac{4\pi L}{\lambda_2} \right) - \alpha_{\text{oxy}} L - \alpha_{\text{rain}} L \quad (30)$$

Here G_{RX} and G_{TX} are the receiver & transmitter antenna gain correspondingly, λ_2 represent RF System wavelength, α_{rain} & α_{oxy} are attenuation because of rain and oxygen absorption in dB/km correspondingly.

RF's noise variance σ_{RF}^2 shown as [112]

$$\sigma_{\text{RF}}^2 (\text{dB}) = B N_0 + N_F \quad (31)$$

Here B is RF bandwidth, N_0 is power spectral density of noise, and N_F is noise figure at receiver, hence SNR of RF link may be calculated as follows [112]

$$\langle \text{SNR}_2 \rangle = \frac{P_{\text{RF}} G_{\text{RF}}}{\sigma_{\text{RF}}^2} \quad (32)$$

3.6 Simulation Modeling of Optical Wireless System

In existing RF communication, availability of limited bandwidth and required spectrum permission to achieve data rate is comparatively low. So, there should be a substitute technique. The solitary logical choice is optical wireless communication system [29].

Optical wireless communication establishes point to point communication in which optical signal transmits through atmosphere in free space. It requires line of sight communication without any

obstruction in between transmitter and receiver path. Features of FSO are interference immunity, large bandwidth, unlicensed spectrum and easy installation etc. Its major applications are in last mile connectivity and RF back up. But, the performance of free space optics has extremely exaggerated by fog and other climatic disorder. Bit error rate of the optical link increases due to atmospheric turbulence [113].

FSO proposes bandwidth of 10^5 times larger than the present RF based communication. It plays an important role in the development of high quality, high security, low cost, high data rate and high speed telecommunication systems [114].

In previous studies, optical wireless communication has been studied without taking into account all factors related to atmospheric circumstances and simulation parameter [115]. The proposed system BER performance has been evaluated by considering Gaussian channel and other simulation parameters.

3.6.1 Simulation Model

The simulated model has transmitter part, channel modeling and receiver part. The model has been designed in Simulink of Matlab program environment.

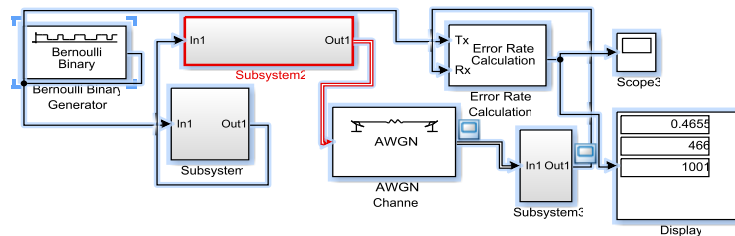


Figure 3.8: Simulation model of optical wireless system using simulink.

3.6.2 Random data sequence generation

In this model, the Bernoulli generator generates the random bit signal which has been coded by particular data coding system. The data series generated by user has been coded by code word and passed it through free space channel. The transmitted signal is received by receiver section but the intermittent path shows some dislocation and errors which further displayed by the display installed inside the system [116].

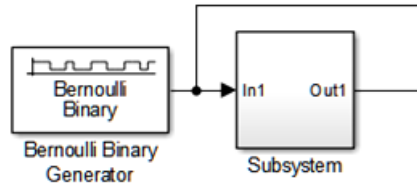


Figure 3.9: Random data sequence generation.

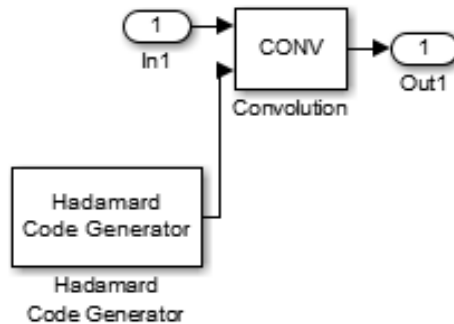


Figure 3.10: Signature code of coding data sequence.

3.6.3 Optical wireless Simulink model of free space channel

The data signal converted into frequency domain by taking its Fast Fourier Transform (FFT). Subsequently take the product of this FFT signal and constant as transfer function of free space. Lastly, to get the data in time domain by taking inverse Fast Fourier Transform (IFFT) as shown in fig. 3.11 [116].

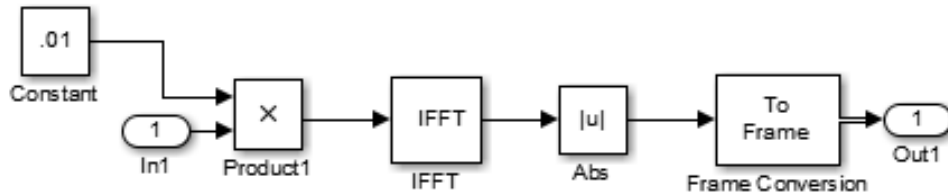


Figure 3.11: Optical wireless Simulink model of free space channel.

3.6.4 Receiver Model

There has to be a method for recovery of user data at receiver side in the model wireless structure. This has to be shown below in fig.3.12 [116].

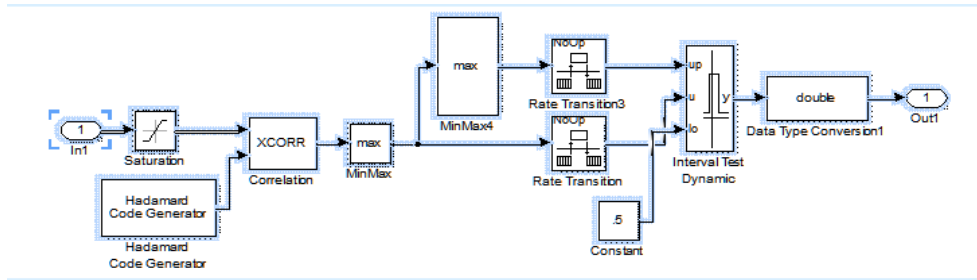


Figure 3.12: Receiver Model.

3.6.5 Simulation Results

The results achieved in the Simulink environment of MATLAB are shown in this section. The results are represented in terms of Bit Error Rate and signal power.

Table 3.1: Simulation Parameters.

Parameters	Values
No. of samples per second	5000
No. of Users	1
Coding	Hadamard
Code Length	32
SNR	0-10 dB
Noise Channel	AWGN

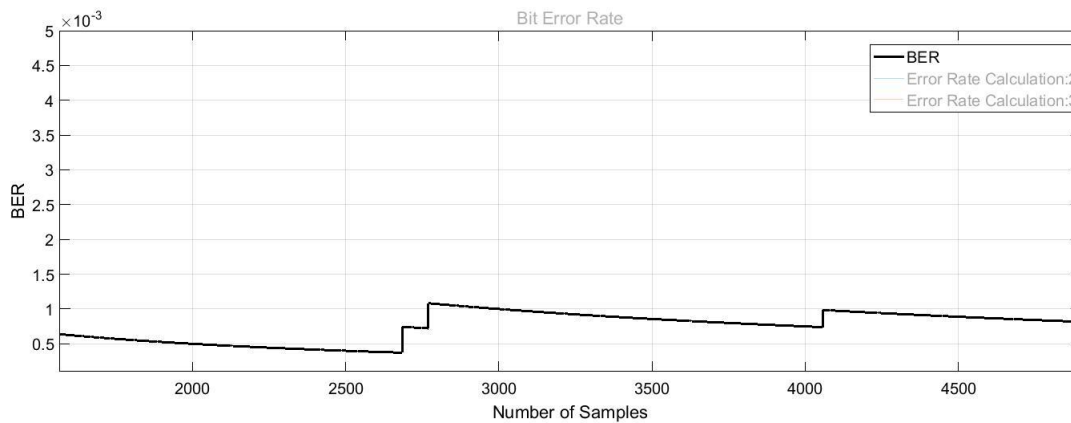


Figure 3.13: Bit error rate.

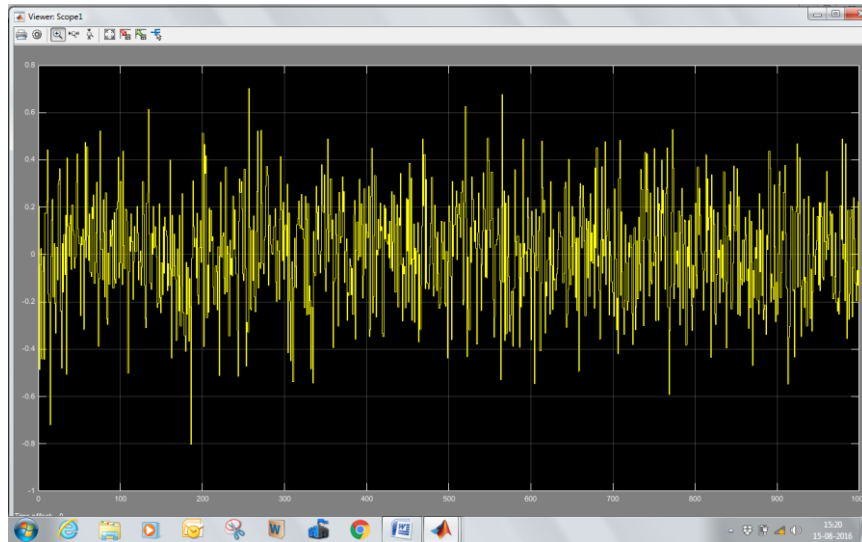


Figure 3.14: Transmitted Signal in frequency domain.

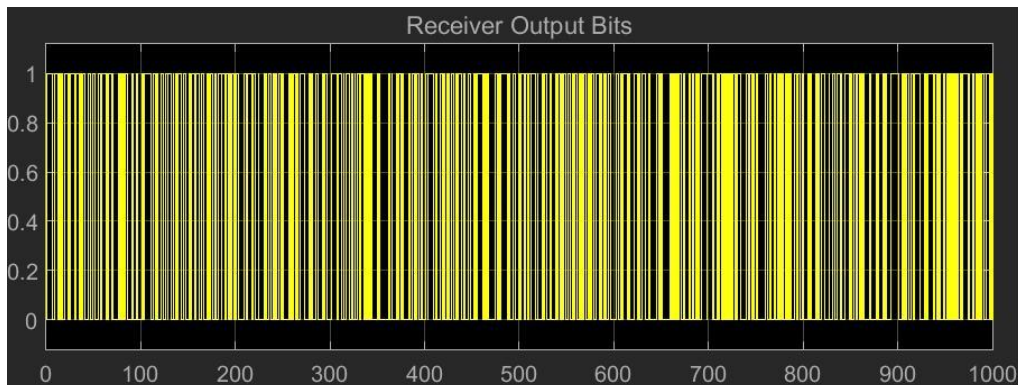


Figure 3.15: Received Bit Stream.

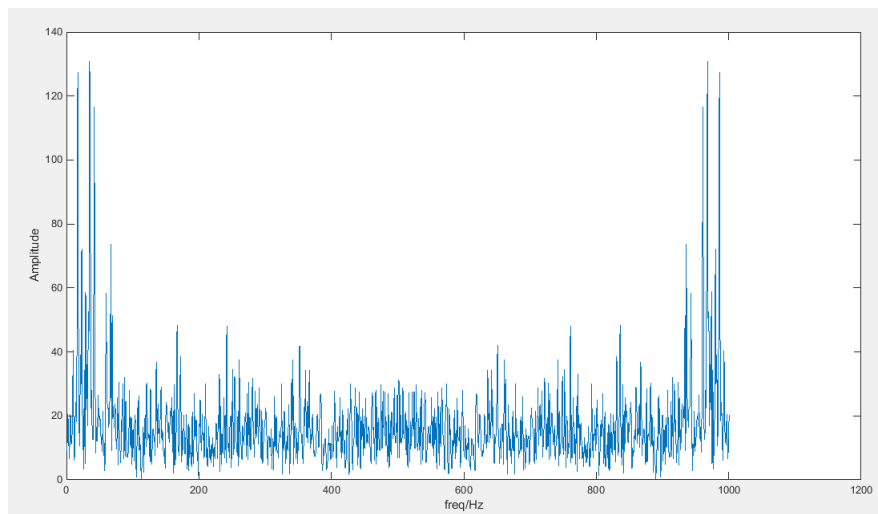


Figure 3.16: Transmitted Signal Power.

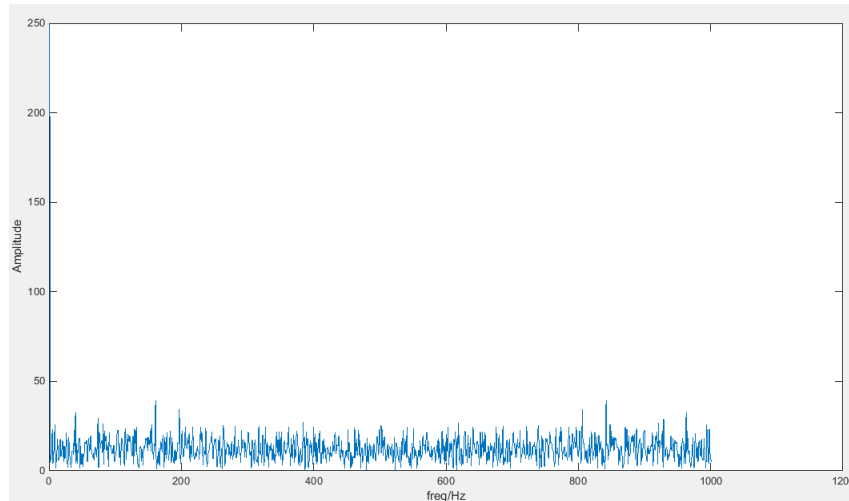


Figure 3.17: Received Signal Power.

3.7 Discussion and Impact

As this technology is in developing stage so this will provide more advancement in new economy within the world. For establishment high speed networking infrastructure among medical centers, colleges, schools, etc. for transfer of information, this purpose can be solved by this technology.

Through gamma model, additional progress in optical wireless system can be achieved in the form of fading channel modeling. Bit error rate, quantity of fading and signal outage may also be considered for additional analysis [117].

3.8 Conclusion

This work actualizes a basic and non costly fast optical wireless link connecting two structures/ campus. The wireless link using a laser beam has been designed. The GBIC Ethernet and LVPECL signaling are used in the system. The transmission and reception of text file among computers achieved across the hyperlink efficiently.

Free Space Optics can give a reasonable high transmission capacity within a kilometer limit. Hybrid link of FSO and RF has been inspected to give high transmission capacity and bandwidth for longer range.

For FSO communication, loss due to fog in the atmosphere has essentially the major element as comparison with the losses due to rain and snow. This information is extremely helpful in

estimation of specific fade margin, which has high importance on the optical hyperlinks availability.

Due to the accessibility of FSO/RF structure, a great extent metro area is now accessible for the users. Study shows the relationship between these technology options, whereby rain and fog drastically affect the RF and FSO links respectively and rarely occur concurrently. RF system may be utilized as a corresponding path for communication in high foggy conditions to attain high extension in the link range designed for a particular Signal to Noise Ratio. Therefore, FSO/RF hybrid system is a viable means to minimize performance degradation because of undesirable weather effects experienced by usual FSO systems.

The simulation model has been developed in Matlab for performance analysis of optical wireless system. Random data series has been generated from Bernoulli generator for a particular user, then data is encoded using Hadamard code for single user, and then the encoded data has been passed through free space channel with AWGN. Generated binary data has been transmitted at the rate of 5000 samples per second. Then data has received at receiver where it is decoded and user data has been retrieved. BER has been evaluated by using Gaussian channel. The choice of AWGN channel is best as it has BER lower as compared to other channels.

Then BER of less than 10^{-3} has been evaluated by this model for free space optical communication system, which is excellent for FSO. The received power has reduced to approximately half compared to transmitted power.

The study of this chapter provides opportunity for more research in the area of emerging technology.

Chapter 4

Performance Investigation of Free Space Optical Communication System using Gaussian Beam Wave

4.1 Introduction

Previous studies on optical wireless communication have been emphasized on the atmosphere that degrades an optical signal in free space optics [109].

When optical wave propagates through the turbulent atmospheric situation, it encounters an irregular irradiance variances, called scintillation. This is because of perturbations with the aid of refractive index fluctuations. Optical scintillation has been viewed to be main impact on FSO that attract much focus in applications, like tracking, ranging of laser programs and laser imaging programs [109, 118-122].

In the mid 1960s, Tatarskii and Cherenkov concentrated on Rytov estimation technique and assessed the index of scintillation expressions of spherical and unbounded plane wave however their outcomes has been restricted to weak turbulent only. After that plenty of theoretical and experimental work founded on irradiance fluctuation beneath strong turbulence regimes in system. A number of mathematical models of scintillation phenomenon has been later developed and modified via others [123-128].

Andrews *et al* gave a complete abstract of the research about plane wave, spherical wave, and Gaussian wave. Wu and Wei examined the Gaussian beam scintillation index by considering inner-scale and outer-scale on slant course. Previous work also focused on average power of coherent beam [109, 129-131].

Then Eyyuboglu and Baykal exhibited scintillation analysis in vulnerable atmospheric turbulent approach for quite coherent normal beams in light of the comprehensive Huygens- Fresnel principle [132, 133].

We overview the optical turbulence due to atmospheric phenomenology with discussion and evaluation in free space.

4.2 Channel Effects caused by Optical Turbulence

Optical turbulence due to randomly change in refractive index of atmosphere, are accountable for random fluctuations in the laser beam signal referred to as 'scintillations'. Turbulence precipitated results include beam spreading due to diffraction (which decreases spatial intensity incident on the receiver), and a continuous random movement of the beam centroid about the receiver ('beam wander'). These effects cause signal losses at the receiver, resulting in system bit error rate [118-121].

4.2.1 The Refractive Index Structure Parameter C_n^2

The presence of optical turbulence due to turbulent winds in the surroundings combined with temperature gradients due to warming of sun on earth, makes abnormalities within the atmosphere's refractive index called eddies or optical tubules. These optical tubules characterized by variety of optical tubule sizes bounded via the turbulent outer scale L_0 and the turbulent interior scale l_0 . The stochastic refractive index $n(\rho)$ at a vector location ρ in the turbulent surroundings has been characterized by a index structure parameter. Let $n(\rho_1)$ and $n(\rho_2)$ be values of the refractive index on the vector places ρ_1 and ρ_2 respectively. We are able to describe fluctuations in the refractive index utilizing the refractive index structure perform D_n outlined as [134-137].

$$D_n(\rho_1, \rho_2) = \langle |n(\rho_1) - n(\rho_2)|^2 \rangle \quad (1)$$

Here, $\langle \dots \dots \rangle$ denotes statistical averaging. The $D_n(\rho_1, \rho_2) = D_n(\rho)$ in the inertial sub range the refractive index structure function has been described via the Kolmogorov-Obukhov two thirds power law [122,138].

$$D_n(\rho) = C_n^2(h)\rho^{2/3}, \quad l_0 < \rho < L_0 \quad (2)$$

Here $C_n^2(h)$, is the refractive index structure parameter, depends on wavelength and surrounding temperature at the height h . The refractive index $n(\rho)$ may also be distinguished by spatial power spectral density function $\phi_n(k)$, which has been given as [138].

$$\phi_n(k) = 0.033C_n^2k^{-11/3}, \quad k_0 < k < k_1 \quad (3)$$

Here $K_1 = 2\pi/l_0$ and $K_0 = 2\pi/L_0$ are the spatial spectrum boundaries in the inertial sub range .The spectrum wave number has been defined as $K = 2\pi/l$, where l signify magnitude of turbulent eddy. Small turbulent eddies have large spectrum wave numbers, and large turbulent eddies have small spectrum wave numbers [138].

4.3 Gaussian Beam Propagation

Let us take the case of general optical Gaussian beam wave with parabolic profile that permits full characterization of a laser beam wave. The initially proposed beam wave model has been utilized and discussed in many reviews involving laser beam propagation by means of random media [123-126][139-141].

Now consider the transmitting aperture of the Gaussian beam which has been placed in the plane $Z = 0$ and the distribution of amplitude has a Gaussian function with effective radius of beam is W_0 and phase distribution is in parabolic shape along with radius of curvature F_0 . Optical field of the wave on this plane having amplitude A_0 at the axis is given below [109].

$$U_0(\mathbf{r}, 0) = A_0 \exp\left[-r^2/W_0^2 - ik r^2/2F_0\right] \quad (4)$$

Here r is perpendicular distance from center line of beam.

Introducing the complex parameter α_0 [127]

$$\alpha_0 = \frac{2}{kW_0^2} + i\frac{1}{F_0} \quad , \quad [m^{-1}] \quad (5)$$

Here W_0 is waist size, $K=2\pi/\lambda$ denote wave number and i represent imaginary unit. From (5), the Gaussian beam wave of equation (4) may be represented by [125].

$$U(r, L) = A_0 \exp\left(-\frac{1}{2}\alpha_0 kr^2\right) \quad (6)$$

The Gaussian-beam wave optical field of equation (6) at distance of $z = L$ along the positive z axis represented by the Huygens-Fresnel integral [125, 142].

$$U_0(r, L) = -2ik \int \int_{-\infty}^{\infty} G(s, r; L) U_0(s, 0) d^2 s \quad (7)$$

Here $U_0(s, 0)$ signify the wave field at the transmission section and $G(s, r; L)$ represent by green's function derived under the paraxial approximation by [142]

$$G(s, r; L) = \frac{1}{4\pi L} \exp \left[ikL + \frac{ik}{2L} |s - r| \right] \quad (8)$$

By inserting the Gaussian-beam formulation of equation (5) into equation (6) and evaluate the resulting integrals, resulting a Gaussian-beam wave similar to equation (6) but with complex amplitude $A_0/(1 + i\alpha_0 L)$ [135].

$$U_0(\mathbf{r}, L) = \frac{A_0}{1+i\alpha_0 L} \exp \left[ikL - \frac{1}{2} \left(\frac{\alpha_0 k r^2}{1+i\alpha_0 L} \right) \right] = \frac{A_0}{p(L)} \exp \left[ikL - \frac{1}{2} \left(\frac{\alpha_0 k r^2}{p(L)} \right) \right] \quad (9)$$

Where $p(L) = 1 + i\alpha_0 L$ called the propagation parameters [14].

The optical field $U_0(\mathbf{r}, 0)$ transmits through a aperture of radius r at perpendicular plane $Z=0$

$$U_0(\mathbf{r}, 0) = A_0 \exp \left[-\frac{1}{2} (\alpha_0 k r^2) \right] e^{i\omega t} \quad (10)$$

Where $e^{i\omega t}$ has time dependence parameter that may be ignored in the further equations.

The optical intensity associated with Gaussian beam at radial distance r from the axis [135].

$$I(r, L) = I_0 \frac{W_0^2}{W^2(L)} \exp \left[-\frac{2r^2}{W^2(L)} \right] \quad (11)$$

The corresponding time-averaged intensity or irradiance for the beam located in plane $Z=0$

$$I(r, 0) = \frac{|E(r,0)|^2}{2\eta} = I_0 \exp \left(\frac{2r^2}{W_0^2} \right) \quad (12)$$

Here $I_0 = I(0, 0)$ represent Gaussian beam intensity at the waist.

The incident power P on receiver aperture diameter D at a distance L is given as [142, 143]

$$P(D, L) = P_0 \left[1 - e^{\left(-\frac{D^2}{2W^2(L)} \right)} \right] \quad (13)$$

The power P passing through a aperture of diameter D at transverse plane $Z=0$

$$P(D, 0) = P_0 \left[1 - e^{-D^2/2W_0^2} \right] \quad (14)$$

Here, beam total power transmitted is $P_0 = \frac{1}{2} \pi I_0 W_0^2$.

Now consider a point receiver, a diameter D approach to zero, so the peak intensity on the axis of Gaussian beam has been calculated using L'Hospital rule.

$$I(0,0) = \lim_{D \rightarrow 0} \frac{P_0 [1 - e^{-D^2/2W_0^2}]}{\frac{\pi D^2}{4}} \quad (15)$$

$$I(0,0) = \frac{2P_0}{\pi W_0^2} \quad (16)$$

For physical interpretation it is needful to express beam wave equation in other form of phase front radius of curvature and beam radius at the receiver side. For this, introduce the following notation [14].

$$1 + i\alpha_0 L = \Theta_0 + i\Lambda_0, \quad (17)$$

Where Θ_0 and Λ_0 are non dimensional real parameters at transmitter is defined by [14]

$$\Theta_0 = \text{Re}(1 + i\alpha_0 L) = 1 - \frac{L}{F_0}, \quad (18)$$

$$\Lambda_0 = \text{Im}(1 + i\alpha_0 L) = \frac{2L}{kW_0^2} \quad (19)$$

Here F and W are phase front radius of curvature and beam radius at recipient respectively. The phase front radius of curvature of beam at the receiver side has been associated to the transmitter side beam parameters, given by [14]

$$F = F_0(\Theta_0^2 + \Lambda_0^2)(\Theta_0 - 1)/(\Theta_0^2 + \Lambda_0^2 - \Theta_0) \quad (20)$$

Due to atmospheric effects, these beam parameters associated with Gaussian wave in an indiscriminate medium, makes analysis more complicated. So it requires a characterization of related beam parameters of Gaussian beam at the plane of receiver side.

From conformal transformation, $1/(\Theta_0 + i\Lambda_0) = \Theta - i\Lambda$, where the real parameters (non dimensional) Θ and Λ are defined by [144, 145].

$$\Theta = \frac{\Theta_0}{\Theta_0^2 + \Lambda_0^2}, \quad \Lambda = \frac{\Lambda_0}{\Theta_0^2 + \Lambda_0^2} \quad (21)$$

$$\Theta = 1 + \frac{L}{F}, \quad \Lambda = \frac{2L}{kW^2} \quad (22)$$

By using above parameters, beam radius and radius of curvature of phase front at the recipient side may be represented in terms of beam parameters at transmission side, follows as

$$W = \left(\frac{2L(\Theta_0^2 + \Lambda_0^2)}{K\Lambda_0} \right)^{1/2} \quad (23)$$

$$F = \frac{L(\Theta_0^2 + \Lambda_0^2)}{\Theta_0^2 + \Lambda_0^2 + \Theta_0} \quad (24)$$

By introducing beam parameters without dimensions at both sides, beam radius and radius of curvature, as well as other beam parameters are determined from either set of beam parameters. We can use these beam parameters to find out the location and size of the geometric focus and the beam waist.

When the Gaussian beam wave reach at the receiver side, the consequence of scintillation can be minimized by aperture averaging technique that is discussed in coming section.

4.4 Performance Prediction and Analysis of Laser Communication under Scintillation Conditions

Laser radiation engendering via turbulence creates fluctuations in intensity, which is characterized as scintillation. Scintillation is a major issue for laser communications data information links, as it could actually generate massive transient dips within the signal. The signals fading at receiver below a given threshold quickly degrades hyperlink efficiency. Throughout the decades, numerous PDF models have been anticipated for each strong and weak turbulence circumstances.

We now talk about few PDF models for irradiance fluctuations as a way to be used for evaluating the efficiency of more than a few optical communication systems equivalent to physical (terrestrial) link.

In this section we can sum up few of the proposed models which are critical to optical communications. We will be able to overview the performance of free space optical systems that operates more than a few atmospheric conditions. Each turbulent regime might be expected homogeneous with refractive index structure parameter C_n^2 .

An electric field concern by travelling electromagnetic wave is resulting from the stochastic Helmholtz equation [109].

$$\nabla^2 E + k^2 n^2(\vec{r})E = 0 \quad (25)$$

Here the wave number $K = 2\pi/\lambda$, \vec{r} is any point in space and $n(\vec{r})$ is given as [109]

$$n(\vec{r}) = n_0 + n_1(\vec{r}) \quad (26)$$

Here n_0 represent the mean value of refraction index, $n_1(\vec{r})$ is zero mean of random variable, which represent change due to turbulence in atmosphere.

The scalar stochastic Helmholtz equation is given by [109]

$$\nabla^2 U + k^2 n^2(\vec{r})U = 0 \quad (27)$$

Rytov variance σ_R^2 is a primary parameter in the analysis of optical wave in turbulent and unpredicted medium also called as scintillation index used for a plane wave in the weak turbulence system. The Rytov variance may be able to expressed as [109]

$$\sigma_R^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \quad (28)$$

The Rytov approximation is suitable only in weak irradiance intensity fluctuations scenario that is why an expansion of the Rytov theory is desirable to analyze strong irradiance intensity fluctuations on optical propagating waves. When optical wave passes through the turbulent atmospheric conditions then, its amount of transverse spatial coherence tend to decreases, this lost coherence is measured by means of the spatial coherence radius, given by below equation [146]

$$\rho_{0=} \begin{cases} \left(\frac{3}{1+\Theta+\Theta^2+\Lambda^2} \right)^{1/2} (1.87 C_n^2 k^2 L l_0^{-1/3})^{-1/2}, & \rho_0 \ll l_0 \\ \left(\frac{8}{3(a+0.62\Lambda^{11/6})} \right)^{3/5} (1.46 C_n^2 k^2 L)^{-3/5}, & l_0 \ll \rho_0 \ll L_0 \end{cases} \quad (29)$$

Where $a = \text{constant}$, it is also be signified that Θ & Λ are dimensionless factors related with the Gaussian beam wave. In above expression for ρ_0 , ρ_0 is the restrictive case of a spherical wave ($\Lambda = 0, \Theta = 0$) and plane wave ($\Lambda = 1, \Theta = 0$) and may be evaluated form equation (29).

The concept behind using extended Rytov procedure is to separate the impact on the turbulence in two components, particularly, that brought about via small-scale eddies and, by the large-scale eddies. Numerically the irradiance has then composed as [147, 148]

$$\hat{I} = \frac{I}{\langle I \rangle} = XY \quad (30)$$

Here Y and X are independent variables represent small-scale and large-scale size of turbulence, respectively.

From Rytov theory extension, the refractive index $n_1(\vec{r})$ in previous equation (26) may be seen as the consequence of the influence of two in homogeneities that is, the large scale in homogeneities $n_x(\vec{r})$ and the small scale in homogeneities $n_y(\vec{r})$. So, as the refractive index straightly affect the turbulence power spectrum, an effective power spectral density (psd) for refractive index fluctuations may be expressed by [1]

$$\phi_{ne}(k) = \phi_n(k)G(k, l_0, L_0) = \phi_n(k)[G_X(k, l_0, L_0) + G_Y(k, l_0)] \quad (31)$$

Here G_Y and G_X are amplitude spatial filters of small scale and large scale perturbations, respectively and L_0 and l_0 and are outer scale of turbulence and inner scale of turbulence, respectively.

When optical beam travelling in the course of the atmosphere, then their propagation is changed by means of refractive index in-homogeneities. At the receiver side, a haphazard or random type nature of pattern is formed in domain of time & space. This irradiance fluctuation on the receiver side plane looks like the speckle incident. The factor that shows these coming irradiance fluctuations is known as scintillation index [146].

$$\sigma_I^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} = \frac{\langle I^2 \rangle}{\langle I \rangle^2} - 1 \quad (32)$$

Gaussian beam wave scintillation index lying on axis of for a negligible aperture sized point receiver has the following expression [148].

$$\sigma_I^2(0) = \exp\left(\sigma_{\ln X}^2(0) + \sigma_{\ln Y}^2(0)\right) = \exp\left\{\frac{0.49\sigma_B^2}{\left[1+0.56(1+\Theta)\sigma_B^{12/5}\right]^{7/6}} + \frac{0.51\sigma_B^2}{\left(1+0.69\sigma_B^{12/5}\right)^{5/6}}\right\} \quad (33)$$

Where σ_B^2 is the Rytov variance used for a Gaussian beam wave and it is specified by [148]

$$\sigma_B^2 = 3.86 \sigma_R^2 \left\{ 0.40[(1 + 2\Theta)^2 + 4\Lambda^2]^{5/12} \cos \left[\frac{5}{6} \tan^{-1} \left(\frac{1+2\Theta}{2\Lambda} \right) \right] - \frac{11}{16} \Lambda^{5/6} \right\} \quad (34)$$

Here Θ and Λ are distinct by Eq. (18) and Eq. (19), respectively.

Also, the mathematical term of the scintillation index of Gaussian beam for a receiver of predetermined aperture diameter D is specified by [145].

$$\begin{aligned} \sigma_I^2(D) = & \\ & 8\pi^2 k^2 L \int_0^1 \int_0^\infty k \phi_n(k) \exp \left(-\frac{Lk^2}{k(\Lambda + \Omega_G)} [(1 - \bar{\Theta})^2 + \Lambda \Omega_G \xi^2] \right) \times \left(1 - \cos \left[\frac{Lk^2}{k} \left(\frac{\Omega_G - \Lambda}{\Omega_G + \Lambda} \right) \xi (1 - \bar{\Theta} \xi) \right] \right) dk d\xi, \Omega_G \geq \Lambda \end{aligned} \quad (35)$$

Here $\Omega_G = 2L/kWG$ be a non dimensional factor which signifies the beam radius at receiver. A simplified expression for Eq. (35) has been derived, having large scale and small scale variances [148].

$$\sigma_I^2(D) = \exp \left(\sigma_{\ln X}^2(D) + \sigma_{\ln Y}^2(D) \right) - 1 \quad (36)$$

Where large scale and small scale size of turbulence are [148]

$$\sigma_{\ln X}^2(D) = \frac{0.49 \left(\frac{\Omega_G - \Lambda}{\Omega_G + \Lambda} \right)^2 \sigma_B^2}{\left[1 + \frac{0.4(2+\Theta)(\sigma_B/\sigma_R)^{12/7}}{(\Omega_G + \Lambda) \left(\frac{1}{3} - \frac{1}{2}\Theta + \frac{1}{5}\Theta^2 \right)^{6/7}} + 0.56(1+\Theta)\sigma_B^{12/5} \right]^{7/6}} \quad (37)$$

$$\sigma_{\ln Y}^2(D) = \frac{0.51 \sigma_B^2 (\Omega_G + \Lambda) (1 + 0.69 \sigma_B^{12/5})^{-5/6}}{\Omega_G + \Lambda + 1.20 (\sigma_R/\sigma_B)^{12/5} + 0.83 \sigma_R^{12/5}} \quad (38)$$

The mathematical term of the scintillation index of Gaussian beam for receiver of fixed aperture diameter D for the two cases when the Rytov variance is less than unity and greater than unity, shown below

$$\begin{aligned} \sigma_I^2(D) = & \\ & \exp \left[\frac{0.25(\Omega_G - \Lambda)^2 \sigma_B^2}{\Omega_G + \Lambda} \right] - \exp \left[\frac{1 + 1.6(\sigma_B/\sigma_R)^{12/7}}{\Omega_G + \Lambda} + 0.56\Theta \sigma_B^{12/5} \right] \left[(\Omega_G + \Lambda) + 1.20 \left(\frac{\sigma_R}{\sigma_B} \right)^{12/5} + \right. \\ & \left. 0.83 \sigma_R^{12/5} \right] \quad \text{for } \sigma_B^2 \ll 1 \end{aligned} \quad (39)$$

$$\sigma_I^2(D) = \exp\left[\frac{1}{4}(0.69)^{5/6}\frac{(\Omega_G - \Lambda)^2}{\Omega_G + \Lambda}\right] - \exp\left[\frac{1+1.6(\sigma_B/\sigma_R)^{12/7}}{\Omega_G + \Lambda} + 0.56\Theta\sigma_B^{12/5}\right] \left[(\Omega_G + \Lambda) + 1.20\left(\frac{\sigma_R}{\sigma_B}\right)^{12/5} + 0.83\sigma_R^{12/5} \right] \quad \text{for } \sigma_B^2 \gg 1 \quad (40)$$

The plane or spherical wave is forever an approximation to the practical conditions, the plane wave must gives stronger scintillation than spherical profile waves, while Gaussian wave be positioned someplace in between the two [149].

The amplitude of electrical signal $s(t)$ depends on the optical signal power $P_R(t)$ reached at receiver. The gain parameter at the receiver of aperture area A_R is time dependent integral of the optical intensity $I(x,y,t)$. Thus, we may use the received optical power P_R rather than electrical amplitude given as [150]

$$P_R(t) = \int \int_{A_R} I(x, y, t) dx dy \propto s(t) \quad (41)$$

As per Rytov conception, the intensity distribution pursues lognormal behavior, only in vulnerable to intermediate turbulence. Investigation and trial check demonstrates that lognormal behavior of the acquired energy also put into effect to a excellent approximation in the entire turbulence regime (weak, intermediate, robust, saturation) besides when severe quantities of aperture averaging take position [150-153].

The low order Gaussian beam wave model in all turbulence fluctuation circumstances is as follows [154].

$$\sigma_p^2 = 11.8\sigma_R^2\Lambda_e^{5/6} \int_0^1 \frac{C_n^2(\xi H)}{C_{no}^2} \xi^{5/3} d\xi \frac{r^2}{W_e^2} + \exp\left[\frac{0.49\sigma_I^2}{(1+0.56\sigma_e^{12/5})^{7/6}} + \frac{0.51\sigma_I^2}{(1+0.69\sigma_e^{12/5})^{5/6}}\right] - 1 \quad (42)$$

4.4.1 Effect of aperture averaging for different atmospheric turbulence conditions

In tremendous atmospheric turbulence, when light beam propagates adequately elongated course and as a result strengths of signal quality breakup into areas of excessive and low depth of intensity which leads to sufficient signal fades. In this situation, we can expand the span of receiver aperture comparative to the patches dimensions of low and high power and these fluctuations are averaged over the aperture dimension. It is then referred to as "aperture averaging" [141, 155].

According to Rytov hypothesis, the intensity distribution shows lognormal conduct only in weak to intermediate turbulence. Statistical analysis and experimental verification shows that lognormal action of the received intensity in addition implement good estimate in the entire turbulence regime (strong, intermediate, weak, saturation) except while extreme amounts of aperture averaging take position [148-150].

Aperture averaging factor is considered to measure the fading loss that decreases by aperture averaging process. An aperture averaging parameter is expressed below [109, 156].

$$A = \frac{\sigma_I^2(D)}{\sigma_I^2(0)} \quad (43)$$

Here, $\sigma_I^2(D)$ and $\sigma_I^2(0)$ denotes the index of scintillation of aperture diameter D at receiver and a point($D \approx 0$) receiver whose diameter is approximately equals to zero respectively.

The aperture factor A should have minimum probable value in order to beat fading because of instability in atmosphere [155].

The scintillation index obtained as follows [146, 157].

$$\sigma_I^2(D) = \exp \left[\frac{0.49\sigma_R^2}{(1+0.653d^2+1.11\sigma_R^{12/5})^{7/6}} + \frac{0.51\sigma_R^2(1+0.69\sigma_R^{12/5})^{-5/6}}{1+0.9d^2+0.621d^2\sigma_R^{12/5}} \right] - 1 \quad (44)$$

$$\sigma_I^2(0) = \exp \left\{ \frac{0.49\sigma_B^2}{[1+0.56(1+\theta)\sigma_B^{12/5}]^{7/6}} + \frac{0.51\sigma_B^2}{(1+0.69\sigma_B^{12/5})^{5/6}} \right\} - 1 \quad (45)$$

The aperture averaging factor can be approximated as [109]

$$A \approx \left[1 + 1.062 \left(\frac{D^2 k}{4 L} \right) \right]^{-7/6} \quad (46)$$

Also note that, above equation assumes $l_0 \ll \sqrt{L/k}$

According to Kolmogorov spectrum, the spectral density function for index of refraction ups down fluctuations under the internal range is characterize by [109]

$$\phi_n(K) = 0.033C_n^2 K^{-11/3} \quad 1/L_0 \ll K \ll 1/l_0 \quad (47)$$

The atmospheric turbulence strength factor can be obtained from equation (47) as follows

$$30.3\phi_n(K)K^{11/3} = C_n^2 \tag{48}$$

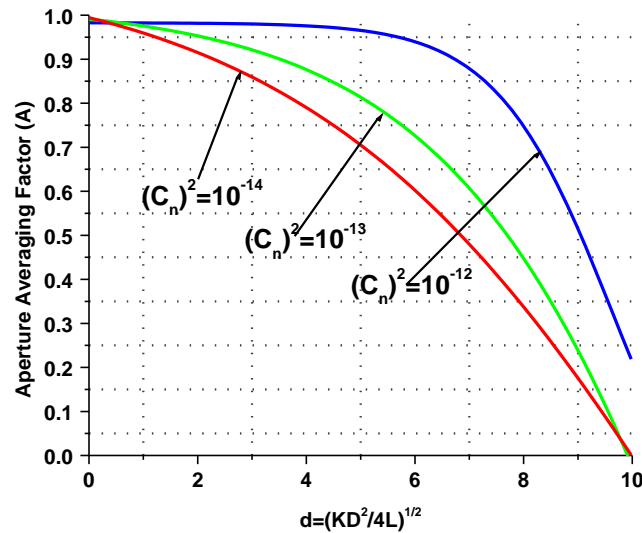


Figure 4.1: Aperture averaging parameter for different turbulence strength of atmosphere versus aperture circular radius d which depends on receiver aperture radius $D/2$ [109].

By considering three regime of turbulence for Gaussian beam wave, results in fig.4.1 [109] shows that the outcome of aperture averaging bound by diverse propagation scenarios. The aperture averaging parameter move downward very slowly under higher atmospheric turbulence strength. Moreover, from the results, the aperture averaging ability of receiving system goes high by increment in receiving aperture radius.

4.4.2 The Beam Wander

At the point when optical beam propagates by means of optical tubules, which might be minor than the radius of the beam, the superiority of the beam wave front is ruined leading scintillation. Nevertheless, optical tubules bigger than the beam diameter as an alternative have a tendency that the whole optical beam is repelled back, this referred to as "beam wander" [158].

4.4.3 Optical Turbulence Effects Reductions

There are various methods accessible to minimize the impacts of optical turbulence. For instance, increased sized receiver aperture recommends an easy way to scale back turbulence causing signal fading. An associated procedure has to utilize low priced beam expander, consequently reduction in signal fading and scintillations via "synthetic" effect of aperture

averaging [108]. These two methods shrink diameter of light beam as compared to the receiver aperture dimensions. A tremendous drop in BER can be seen by the scintillation minimization by "artificial" aperture averaging. The utilization of multiple transceiver apertures can be an extra associated method which has to decrease fluctuations in intensity [159]. At the same time these three approaches may also be beneficial in mitigating bit error rate in optical turbulence system. Here, we considered one type of optical wave for assessment optical performance, which is Gaussian beam wave [160-162].

4.5 Fade Probability of Optical Link

In communication system, the purpose of planning has to make sure to get continuous data interchanges among transmitter and receiver. As mentioned previously that in existence of unpredictable variation in atmospheric path, the fluctuated signal received at receiver which fall beneath a suitable detection degree. In optical communication, the fading probability could be resolved by knowing depth of fluctuations and index of scintillation. The consistency of successful communication without failure can be determined by fading probability of optical link. Let $I(t)$ be an irradiance instantaneous value then we are interested to know the portion of time $I(t) \geq I_{thr}$, where I_{thr} has threshold intensity level for a particular communication scheme. In case of an ergodic process for optical propagation, the time averages are equal to ensemble averages, so the portion of time the intensity is below threshold intensity that is $I \leq I_{thr}$ is given as [163]

$$\text{Fraction}(I \leq I_{thr}) = CP_1(I \leq I_{thr}) = \int_0^{I_{thr}} P_1(I) dI \quad (49)$$

Here CP_1 is the irradiance cumulative probability. The fade threshold factor F_{thr} of a signal (in decibels) may be characterized by [163]

$$F_{thr} = 10 \log_{10}(\langle I_r(0, L) \rangle / I_{thr}) \quad (50)$$

Where $I_r(0, L)$ is mean intensity on the on-axis at L distance, above equation (50) also be written as [163]

$$\ln \left[\frac{I_{thr}}{\langle I_r(0, L) \rangle} \right] = -0.23 F_{thr} \quad (51)$$

4.5.1 Scintillation loss evaluation by threshold approach

The probability of fading received in Gaussian wave signal is determined using threshold approach technique. This approach is based on the theory that due to fading and within a certain time interval, the received optical signal power or its intensity drops below the receiver sensitivity (threshold level).

The threshold approach reduces the complication in analysis of fading as it does not require a complete and in depth investigation of a particular receiver performance. The probability of fading can be evaluated by cumulative distribution function (CDF) [14].

$$P_r[I \leq I_t(0, L)] = \int_0^{I_r(0, L)} P(I) dI \quad (52)$$

Where $I_r(0, L)$ is intensity at receiver.

For Gaussian optical wave, the intensity of wave at the radial distance r commencing the axis can be given as [14].

$$I^0(r, L) = I_0 \left[\frac{w_0}{W(L)} \right]^2 \exp \left[-\frac{2r^2}{W^2(L)} \right] \quad (53)$$

Where I_0 is the output intensity of transmitter on the centre axis line.

Now the relation between Gaussian wave intensity and the total beam power at the center line of the beam can be given by [142].

$$I^0(0, L) = I_0 \left[-\frac{W_0^2}{W^2(L)} \right] = \frac{2P_0}{\pi W^2(L)} \quad (54)$$

Here P_0 is the power of beam at transmitter side.

When beam reached at the receiver side, the incident power P at a distance L on the receiver lens of aperture diameter D is [142].

$$P(D, L) = P_0 \left[1 - \exp \left(-\frac{D^2}{2W^2(L)} \right) \right] \quad (55)$$

Solving the equation (54) for P_0

$$P_0 = \frac{-\pi I_0 W_0^2}{2} \quad (56)$$

On substituting P_0 from equation (56) in equation (55) and assuming that the received power is approximately equals the receiver sensitivity that is $P(D,l) = P_r$ then intensity becomes threshold intensity that is $I_0 = I_{thr}$ then the threshold intensity represented as

$$I_{thr} = -\frac{2P_r}{\pi W_0^2} \left[1 - \exp\left(-\frac{D}{2w^2(D)}\right) \right]^{-1} \quad (57)$$

With this threshold approach, when received power P_r is below certain minimum power P_{min} during certain time, no data reception is possible.

The time during which $P_r < P_{min}$, then power margin between the received power P_r and minimum power P_{min} or threshold power P_{thr} should be calculated the same as an extra loss in the linkage account computation. So the scintillation loss α_{sci} can be described by this additional loss of communication structure, which is calculated in dB (decibels) as follows.

$$\alpha_{sci} = 10 \log_{10} \left(\frac{P_{min} \text{ or } P_{thr}}{P_r} \right), \quad \alpha_{sci} < 0 \quad (58)$$

The value of threshold power P_{thr} for point receiver can be evaluated from the equation below [163]

$$P_{thr} = \frac{1}{2} \left(1 + \operatorname{erf} \left\{ \frac{\ln[\alpha_{sci} (\sigma_p^2 + 1)^{1/2}]}{[2 \ln(\sigma_p^2 + 1)]^{1/2}} \right\} \right) \quad (59)$$

Where σ_p^2 is power scintillation index.

Solving the equation (59) using Taylor series expansion, the new modified expression of scintillation loss α_{sci}

$$\alpha_{sci} = \frac{e^{\frac{\sqrt{\pi}(2P_{thr} - 1) \ln[(\sigma_p^2 + 1)]}{\sqrt{2}}}}{\sigma_p^2 + 1} \quad (60)$$

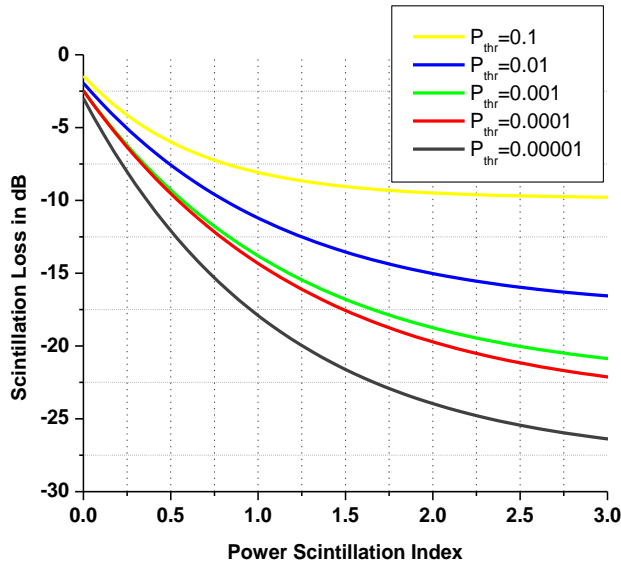


Figure 4.2: Power scintillation index versus Scintillation loss with threshold power as parameter [164]

Results show that losses due to scintillation and probability of fading are considerably low when threshold power level is low. The scintillation loss without difficulty exceeds 18 dB for minimum threshold power when power scintillation index is less than one, as compared to other threshold levels. When some portion of total data loss is considered then by threshold method, the losses due to scintillation can be evaluated according to newly evaluated equation (60). This approach is not restricted to Gaussian waves, spherical or plane waves but can be implemented to other beams whenever power scintillation index is known.

4.6 Results and Discussion

Representation of various parameters like field, intensity and power associated with Gaussian beam wave at the axis is by new expressions. By developing the Gaussian beam parameters for transmitter and receiver side in terms of their respective opposite side, spot radius of beam, radius of curvature and other parameters can be determined, so that we can identify the beam waist, location and focus size of Gaussian wave. At receiver side, effect of scintillation for Gaussian wave may be lowered down by aperture averaging technique. The averaging of aperture effect depends on receiving aperture diameter and it increases with it in different

propagation conditions defined by structure parameter C_n^2 . Results show that aperture averaging effect becomes lower for higher atmospheric turbulence strength.

The scintillation loss in received Gaussian wave signal is determined using threshold approach technique. Scintillation loss can also be evaluated from new derived mathematical expression. This new approach is not restricted to Gaussian beam wave profile only however it may be implemented to plane or spherical beam wave profile whenever power scintillation index is known.

4.7 Conclusion

We discussed the free space optical communication performance and executions by theoretical and analytical investigation required for optical wireless design. This section discusses theoretical analysis and essential factors for plane optical wireless system including the system that should work in different climatic circumstances.

Chapter 5

Performance Analysis of Optical Wireless Link under various Atmospheric Conditions

5.1 Introduction

Regardless the enormous specialized research of accessible devices, the real confinement of free space laser (laser com) execution is due to environment issues. The fact about FSO is that the atmospheric condition dependably incorporates turbulence and numerous scattering impacts. Beginning from a basic comprehension of the laser communication framework under assorted climate conditions, this chapter gives an exhaustive treatment of the assessment of parameters required for breaking down free space optical execution.

There has been large technical development of LASER/LED based transmitter and optical receiver with high sensitivity, support high bandwidth, efficient modulation techniques. The performance of an optical method is most often enumerated by the "link margin [165].

Free space optical communication systems have lots of advantages over radio frequency (RF) system in terms of better bandwidth, high gain and smaller antenna dimension [165]. The Free Space Optics is usually used in various areas, such as military application, space communications, ad-hoc network, satellite communications and of course within 1 km range communication [166–169].

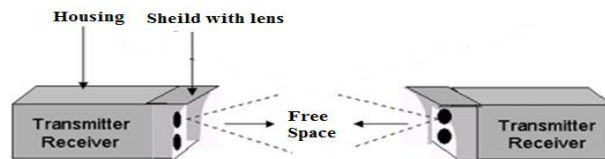


Figure 5.1: Free space optical communication link

Apart from this there are various challenges faced by optical wireless system. Due to turbulent environment, a beam of laser experiences indiscriminate refractive index fluctuations over its pathway. The indiscriminate fluctuations in refractive index gives random wave front deformation, beam broadening, and beam wander. These all propagating effects results in decay of received signal energy due to fluctuation in signal. These signal fluctuations are called fading

on the receiver side. Fading phenomenon causes decreased signal to noise ratio and data rate [170-174].

Previous studies on optical wireless technology have been emphasized on the effect of attenuation due to the atmosphere such as rain, haze and fog. Atmospheric effects are different for different system for example radio-relay system, microwave system, laser beam system etc. [175-179].

As far as free space optical communication has concern, fog is the key factor for degradation of optical signal, especially for visible and IR waves [180, 181].

So the performance of optical wireless has been considerably degraded and limited due to scattering and absorption phenomenon due to fog particles of the environment. Fog and snow are the most undesirable weather conditions for FSO as they imply a high reduction in optical wave. Numerous work and models on atmospheric availability, visibilities and connected optical degradation has been published previously [182-184].

Different approaches have been implemented to diminish the fading and power loss troubles like multiple aperture receiver and transmitter [185,186], adaptive optics technique in FSO [187, 188].

This investigation based on different atmosphere circumstances such as haze, clear, light fog, thin fog and heavy fog effects on data rate, signal to noise ratio and received signal at 850nm, 1300nm and 1550nm wavelength for a free space optical communication. It is possible to increase the procedure performance such as signal to noise ratio, received power and data rate in unique climate condition by the use of Fresnel lens technique. By using this technique, non coherent light source such as LED has been used instead of LASER in free space optical communication. Simulation results show that in all weather conditions, the performance of the system improved by using Fresnel lens technique and heavy fog attenuates more optical signal than other atmospheric condition.

5.2 Optical Wireless Link Analysis

5.2.1. Communication Channel

The essential components describing an environmental communication channel are the atmospheric attenuation and scintillation. The optical wave in atmosphere can be attenuated by many methods, including absorption of sun light, Rayleigh or Mie scattering with the aid of

gasoline molecules and aerosol particles present within the air [189]. Scattering due to particles, such as dirt, clouds, smoke and fog additionally make contributions to the beam attenuation.

Scintillation is the fluctuations in the optical signal due to refractive index change along the channel. With the aid of scintillation, the noise in the signal results in expanded BER and diminished efficiency. Scintillation induced fades can finally be the reason of signal loss altogether. The turbulence strength of the surroundings is traditionally taking in terms of a scintillation index, defined in previous chapter [97,190].

5.2.2 Receiver and Transmitter System

Mainly optical wireless systems are planned to function in the home windows of 780-850 and 1520-1600 nm. In the region of 800 nm, safe, low cost, excessive-efficiency transmitter and detector devices are effortlessly on demand. These are frequently utilized as a part of system and transmission gear. A silicon based avalanche photodiode (APD) and a sophisticated vertical-cavity floor-emitting laser (VCSEL) are accessible for operation at 850 nm. For the wavelength ranges from 1520 to 1600 nm, high performance transmitter and detector are likewise promptly accessible. For longer wavelength, InGaAs has mostly used detector material; it displays large data transfer capacity ability along with large bandwidth [109].

5.2.3 System link Analysis

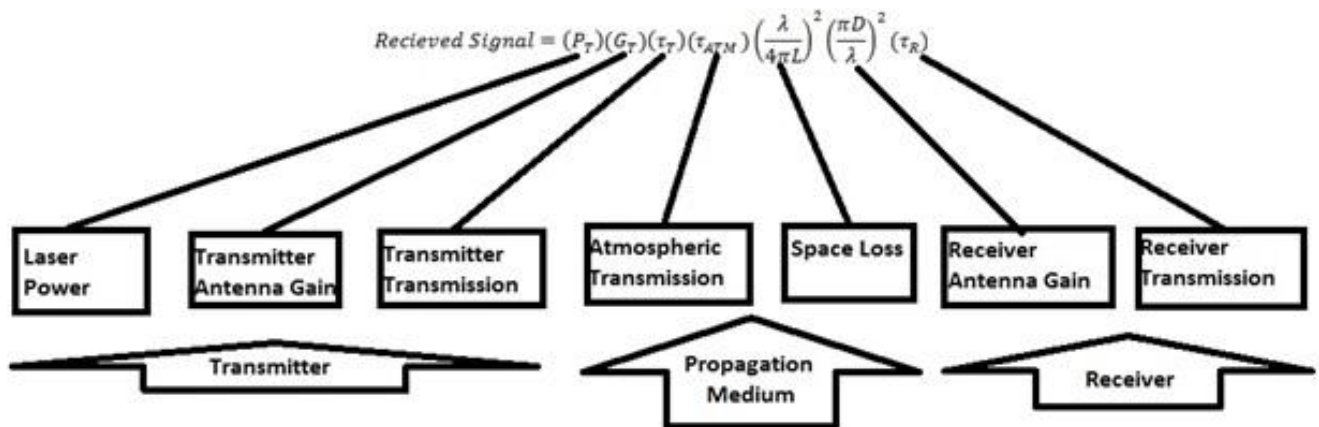


Figure 5.2 System link analysis.

The communication system general framework executed by the use of a hyperlink budget link analysis includes all attenuations and geometrical features to evaluate the signal power at receiver. Figure 5.2 shows the system link estimation. The amount of received signal required at receiver to get a desired sign-to-noise ratio (SNR) depends on receiver's sensitivity for a given anticipated optical communication performance.

By take into account of wave propagation in free space optical communication. Keep in mind a laser diode based transmitter having antenna of gain G_T , transmitted power P_T , transmitting wavelength λ , the received signal power can be obtained as [109].

$$\text{Recieved Signal Power} == P_T G_T \tau_T \tau_{ATM} S G_R \tau_R \quad (1)$$

Where, τ_T is transmitted optical efficiency, τ_{ATM} is atmospheric transmission efficiency at wavelength λ , free space loss is S , G_R is the receiver antenna gain and τ_R is optical efficiency of receiver. The transmitted antenna gain G_T and received antenna gain are given by $G_T = 16/\theta_T^2$ (where θ_T is the full transmitted divergence angle), $S = \left(\frac{\lambda}{4\pi L}\right)^2$ (where L is the link range), and $G_R = \left(\frac{\pi D}{\lambda}\right)^2$ (where D is diameter of receiver). τ_{ATM} can be written in terms of the atmospheric attenuation factor $\alpha = -10\log(\tau_{ATM})/L$. Then the expression for received signal as [109]

$$P_{REC} (\text{Recieved Power Signal}) = P_T G_T \tau_T \tau_{ATM} \left(\frac{\lambda}{4\pi L}\right)^2 \left(\frac{\pi D}{\lambda}\right)^2 \tau_R \quad (2)$$

Above equation (2) may be expressed as [109].

$$P_{REC} = P_T (D^2/\theta_T^2 L^2) \tau_T \tau_{ATM} \tau_R \quad (3)$$

If we express τ_{ATM} in terms of α (dB/km), atmospheric attenuation factor, at λ , wavelength, and then the Power received is [109].

$$P_{REC} = P_T (D^2/\theta_T^2 L^2) (\tau_T) 10^{(-\alpha L/10)} (\tau_R) \quad (4)$$

Usually an optical set up consists of two transceivers at each end. Transmission section optics (mirrors, lenses, and telescope) guide and focus the laser beam at the receiver section optics in order that the beam signal power received and concentrated on optical detector.

5.3 Fresnel lens for free space optical communication

Fresnel lens has low cost and light weight lens available in large sizes so that it provides an opportunity to use in free space optical communications. They are used for collimating beams of light and concentrate light from a far transmitting source into an optical receiver [191].

Fresnel lens are not perfectly adequate to attain the diffraction boundary, so it can't be utilized to properly collimate a stimulated light source like laser and hence attempt to continue this can cause in a considerable part of the light being lost by scattering. That is why non-coherent light source like LED can also be used instead of LASER in free space optical communication. In optics, Fresnel lenses are fabricated that have focal ratio number in between 0.5 to 1.5. This is also feasible to use this lens as a collimator in optical communication system to generate highly parallel beams similar to spotlight as seen in figure 5.3 [191].

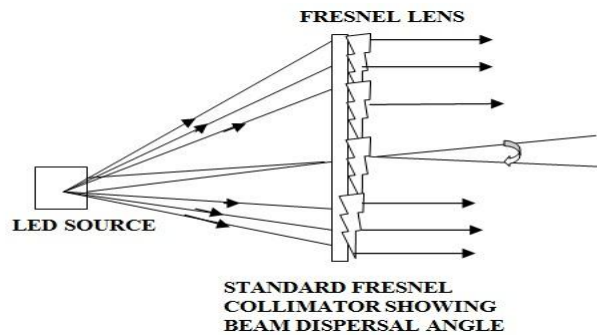


Figure 5.3: Fresnel lens collimate light from an LED source.

Sometimes, another second lens may be placed very near to the LED source to minimize the angle due to which the LED light has been transmit to allow a much large proportion of it to appear at the lens [191].

5.4 Receiver Technology

Together with photon and energy affectivity, the receiver performance mainly involves reliability of system within the atmospheric area, presence of background noise and other channel effects. The SNR of optical receiver is finally restricted with the aid of the number of photons/bit that are impartial to the received waveform shape. This causes the stiffness within the receiver to receive signal of any autonomous profile. Moreover, there may be plentiful bandwidth available which

reduce channel bandwidth barriers and allows extra bandwidth to increased sensitivity via modulation and coding.

5.4.1 Signal power at the receiver

Consider a super luminescent LED that transmits a power P_t at the 1550 nm wavelength. The detector received a power that has been evaluated as follows [192]

$$P_{r1} = P_t \frac{D^2}{\theta_{div}^2 L^2} 10^{-\gamma L/10} \tau_t \tau_r \quad (5)$$

Where, receiver aperture diameter represented by 'D', ' θ ' represents angle of divergence, ' γ ' is the parameter that represent attenuation factor (dB/m). The receiver and transmitter optical efficiency is represented by τ_r and τ_t , respectively.

By introducing the lens at the transmitter side, the total power becomes

$$P_{ttotal} = P_t + 10 \log_{10} N_t \quad (6)$$

Where N_t represents the number of transmitter lenses of a single FSO unit

At the detector of receiver, the new equation of power after the introduction of lens technique is as follows

$$P_{r2} = P_{ttotal} \frac{D^2}{\theta_{div}^2 L^2} 10^{-\gamma L/10} \tau_t \tau_r \quad (7)$$

The achievable data rate R_1 for transmitted power P_t with angle of divergence θ , aperture diameter receiver D, transmitter efficiency τ_t and receiver efficiency τ_r can be evaluated as [193]

$$R_1 = \frac{P_t \tau_t \tau_r 10^{-\gamma L/10} D^2}{\pi(\theta/2)^2 L^2 E_p N_b} \quad (8)$$

Here, $E_p = hC/\lambda$, has the energy of photon.

Now by introducing lens technique, the newly expression is represented as

$$R_2 = \frac{P_{ttotal} \tau_t \tau_r 10^{-\gamma L/10} D^2}{\pi(\theta/2)^2 L^2 E_p N_b} \quad (9)$$

5.4.2 Optical Link Margin

One more important parameter in optical communications hyperlink evaluation is "Link Margin", to accomplish a predetermined bit error rate (BER) at a given information rate. The necessary power P_{REC} (watts) at receiver section to attain a specified data rate R (bits/sec) and receiver sensitivity N_b (photons/bit) is given by a relation $P_{REC} = N_b R h \nu = N_b R h C / \lambda$, where ν is the frequency of laser at wavelength λ (C = velocity of light, h = Planck's constant). Finally, the link margin M is given as [193]

$$M = \text{Power Received} / \text{Power Required} \quad (10)$$

Then the expression of M becomes [193]

$$M = [P_T / N_b R h \nu] (D^2 / \theta_T^2 L^2) \tau_T 10^{(-\alpha L / 10)} \tau_R \quad (11)$$

5.4.3 Direct Detection PIN Photodiode

Probably the main usable receiver for excellent performance in optics is the PIN photodiode. It is quite simple, and design to accomplish high rate execution [194-196].

Now, analyzing the shot noise and thermal noise that make contributions to the SNR, given as [194]

$$\sigma_{th}^2 = (4 K_B T / R_L) F_{RF} B_e \quad (12)$$

$$\sigma_{sh}^2 = 2q(i_s + i_d) B_e \quad (13)$$

Where σ_{sh}^2 is shot noise comes due to dark current and randomness in signal and σ_{th}^2 is the thermal noise generate through load resistor R_L and F_{RF} amplifier noise figure [196-198].

In direct detection, using these noise sources, the SNR expresses as [198]

$$SNR_{PIN} = \frac{\langle i_s \rangle^2}{\sigma_{sh}^2 + \sigma_{th}^2} \quad (14)$$

5.4.4 Direct Detection Avalanche-Photodiode (APD)

The received optical signal has electrical power which is directly related to mean squared current of avalanche photodiode APD [199].

$$\langle i_{APD}^2 \rangle = (R_0 P_{r1} M)^2 \quad (15)$$

And,

$$R_0 = \frac{\eta q \lambda}{h c} \quad (16)$$

Where R_0 represent sensitivity, M represents gain, η denotes efficiency of APD and q denotes charge on the electron.

Shot noise has major concern as far as Signal to Noise ratio calculation is considered. Shot noise exists since phenomena corresponding to light comprise the movement of discrete 'packets', coming out of a laser at random times, this causes the relative fluctuations in number of photons, These fluctuations are shot noise.

If average current signal has much high, then dark current can be disregarded. If typical signal level present has greater value, then dark current can also be disregarded. This relates to high optical power signal and low dark current. If the shot-noise power is much high as the thermal-noise, then the thermal power may also be omitted.

The expression for shot noise [199]

$$\sigma_{\text{shot noise}}^2 = 2q(R_0 P_{r1}) M^{x+2} B \quad (17)$$

The expression for surface leakage current [199]

$$\sigma_{\text{surface}}^2 = 2q I_L B \quad (18)$$

The multiplied dark current noise [199]

$$\sigma_{\text{dark}}^2 = 2q(I_D) M^{x+2} B \quad (19)$$

The Johnson noise [71]

$$\sigma_{\text{Johnson}}^2 = \frac{4KT B F_T}{R_{eq}} \quad (20)$$

The excess noise factor [199]

$$F(M) = M^x (0 \leq x \leq 1) \quad (21)$$

Where I_D represents bulk dark current, I_L represent surface leakage current, k denotes constant (Boltzmann), B denotes bandwidth noise equivalent, R_{eq} represents circuit resistance equivalent, F_T represents noise figure of the electronic circuit, T represents temperature and x is a parameter whose value ranges from 0.3 to 0.5 in case of silicon APDs and 0.7 to 1 in case of germanium APDs.

SNR for the optical wireless system then evaluated as [199]

$$SNR_{APD} = \frac{(R_0 P_{r1} M)^2}{2q(R_0 P_{r1} + I_D) M^{x+2} B + 2q I_L B + 4kTB F_T / R_{eq}} \quad (22)$$

Now by introducing lens technique, the newly expression of SNR

$$SNR_{APD} = \frac{(R_0 P_{r2} M)^2}{2q(R_0 P_{r2} + I_D) M^{x+2} B + 2q I_L B + 4kTB F_T / R_{eq}} \quad (23)$$

5.5 Simulation Results

Following are the system parameters shown in table 5.1 [200].

Table 5.1: System parameters used in this simulation for 1550 nm.

Parameter	Value
Wavelength	1550 nm
Transmitter Optical Power (mw)	100
Transmitter Efficiency	0.5
Transmitter Divergence Angle (mrad)	$1 \leq \theta \leq 3$
Efficiency of Receiver	0.5
Sensitivity of Receiver (dBm)	-20
Diameter of Receiver (cm)	$1 \leq D \leq 10$
Range (meter)	$1 \leq L \leq 1000$
Dark Bulk Current (I_D)	0.05 nA
Gain of APD	100
Excess Noise Factor (x)	0.5
Bandwidth (B)	25 MHz
Surface Leakage Current (I_L)	0.001 A
System Temperature (T)	290 K
Noise Figure (F_T)	3 dB
Equivalent Noise Resistance (R_{equ})	50 k Ω

Table 5.2: Atmospheric attenuation in (dB/km) corresponds to visibilities for 1550 nm [193].

Climate	Visibility (km)	Attenuation (dB/km)
Clear	23	0.49

Haze	2	6.50
Thin Fog	1.5	8.98
Light Fog	1	13.95
Heavy Fog	0.5	34.70

By using equations models and system parameters, following are the results.

5.5.1 Simulation at 1550 nm

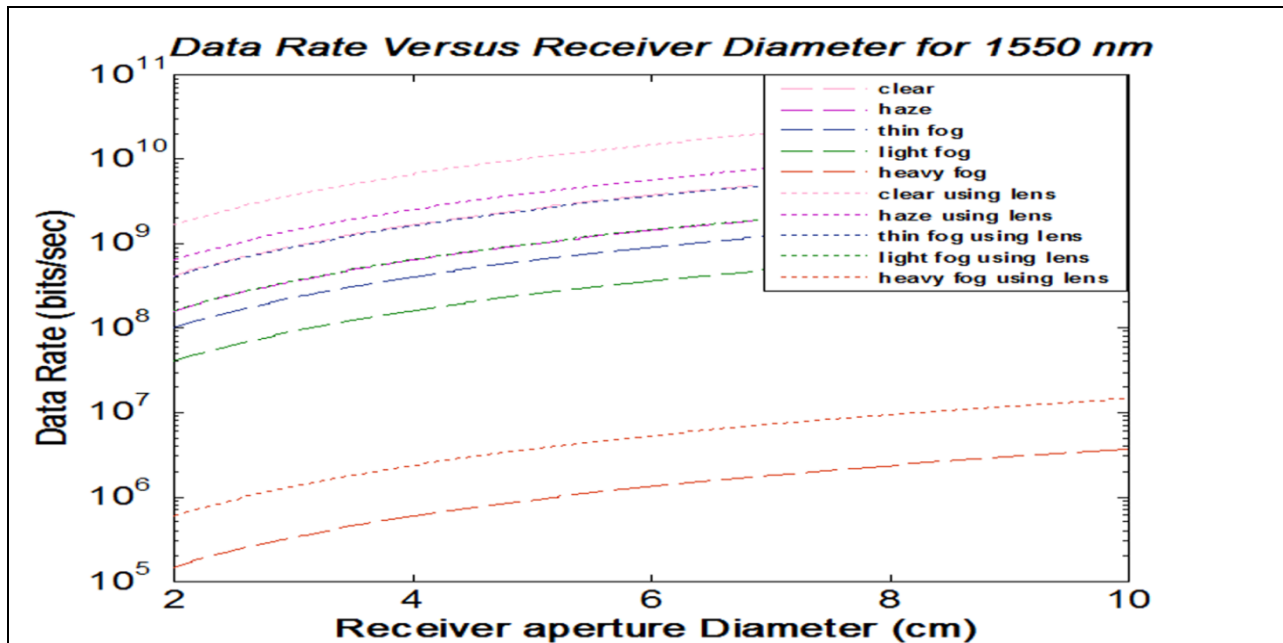


Figure 5.4: Data Rate Versus receiver diameter in different atmospheric conditions for 1550 nm.

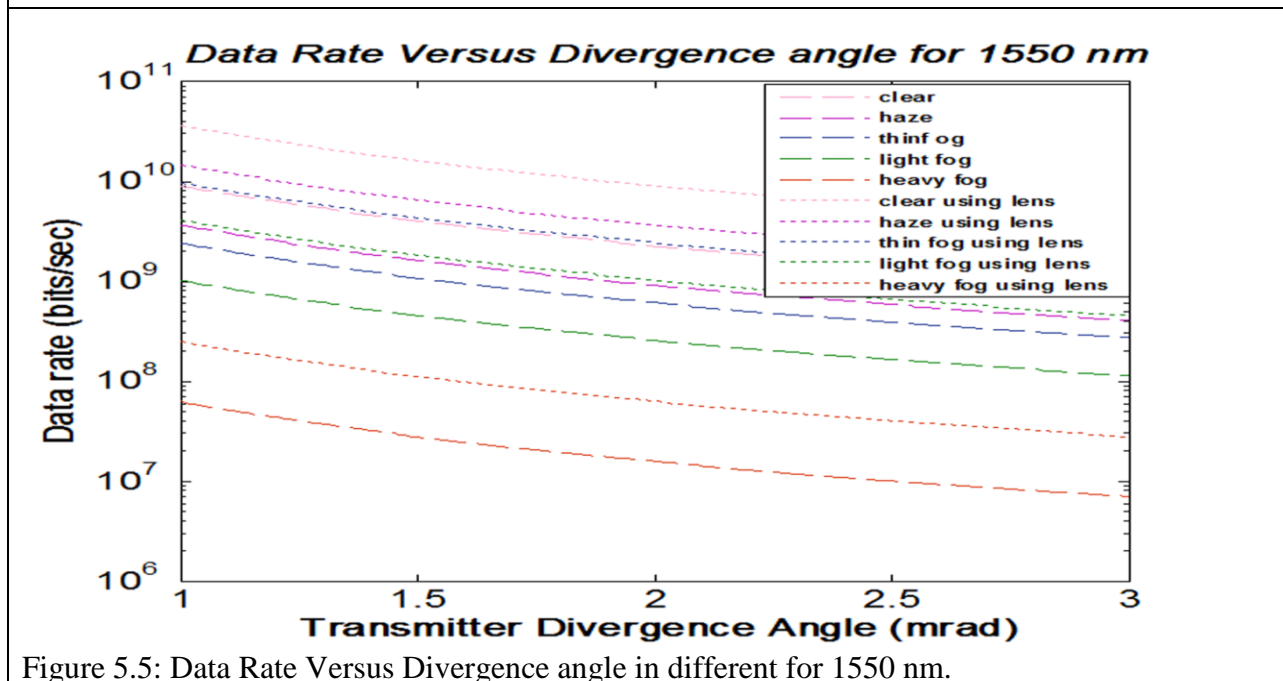


Figure 5.5: Data Rate Versus Divergence angle in different for 1550 nm.

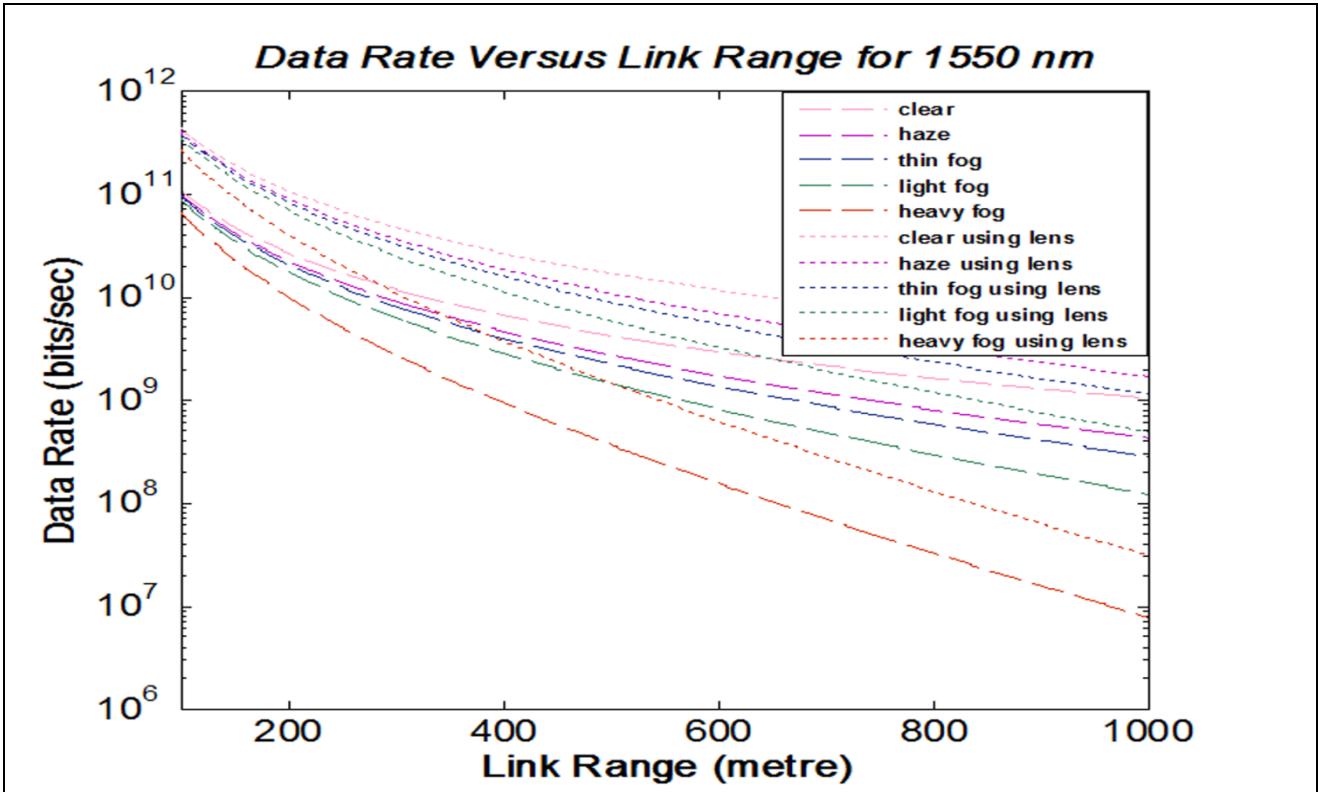


Figure 5.6: Data Rate Versus Link Range in different atmospheric conditions for 1550 nm.

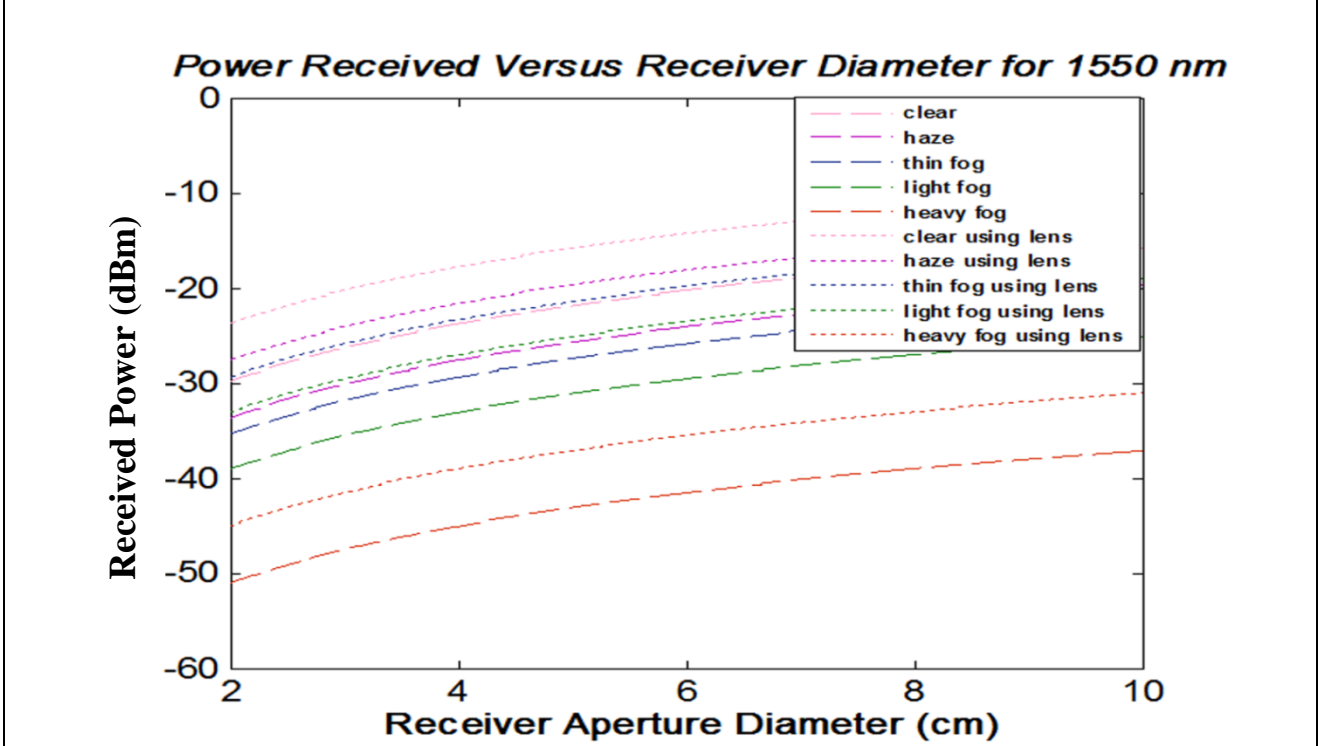


Figure 5.7: Power Received Versus Receiver Diameter in different atmospheric conditions for 1550 nm.

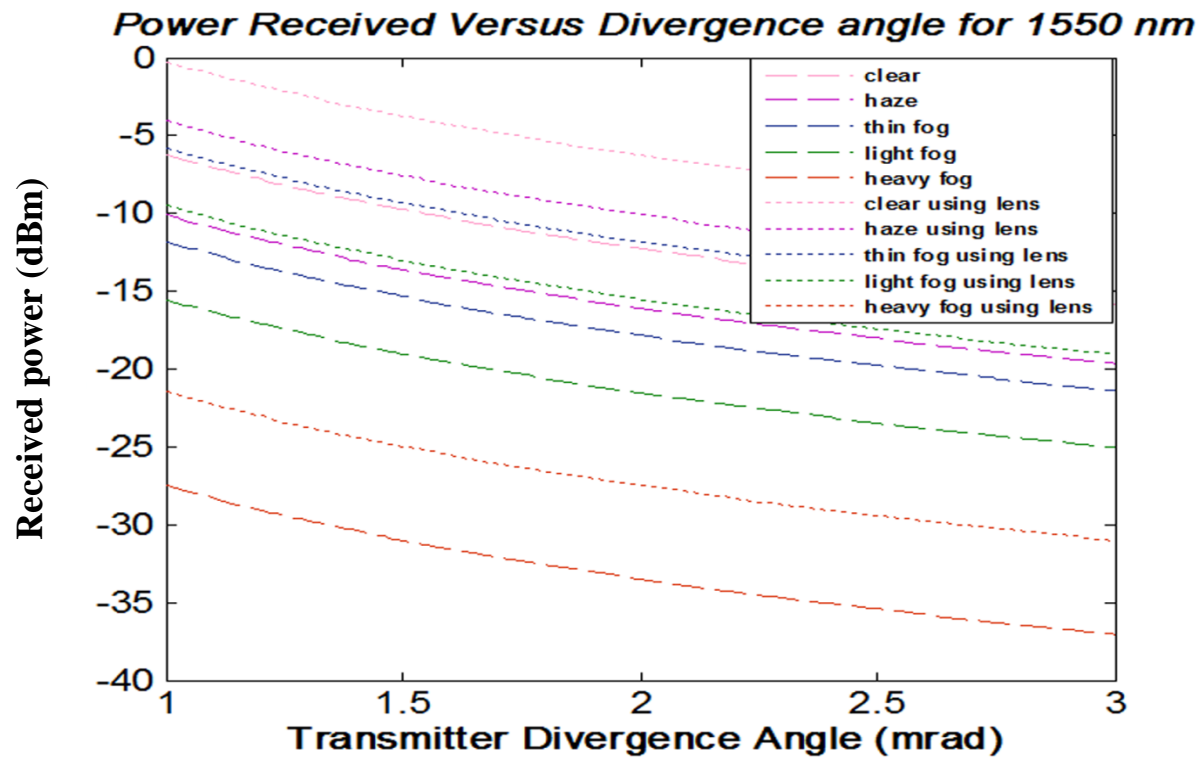


Figure 5.8: Power Received Versus Divergence angle in different atmospheric conditions for 1550 nm.

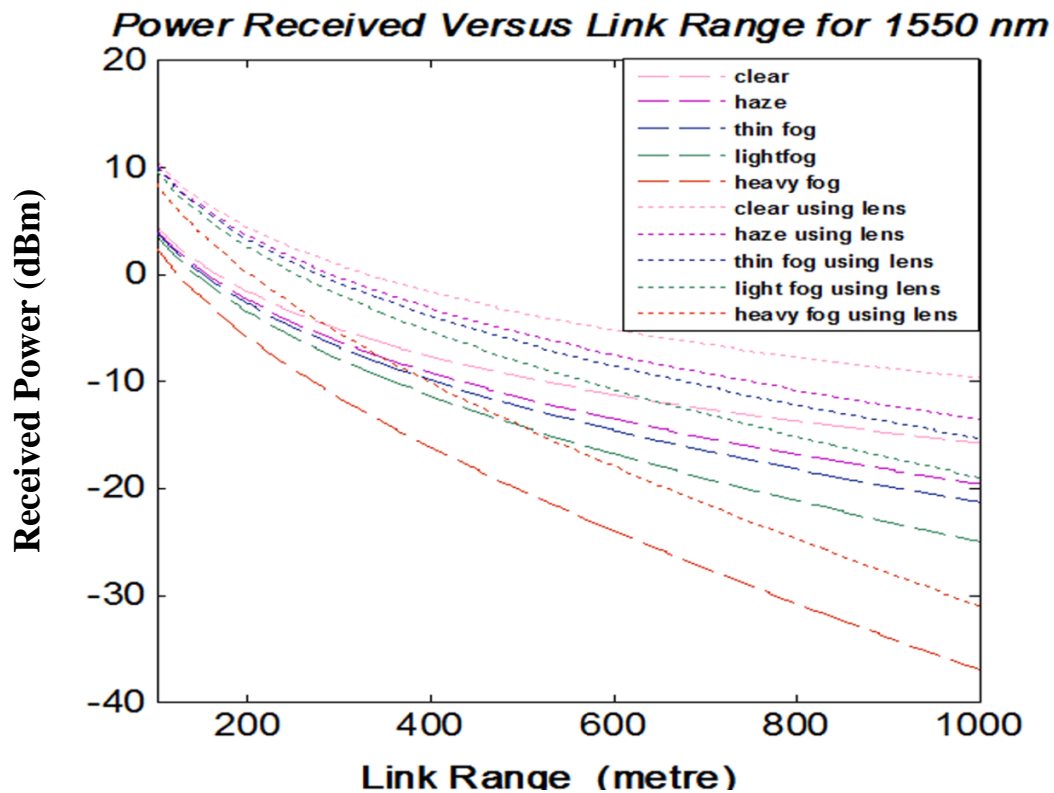


Figure 5.9: Power Received Versus Link Range in different atmospheric conditions for 1550 nm.

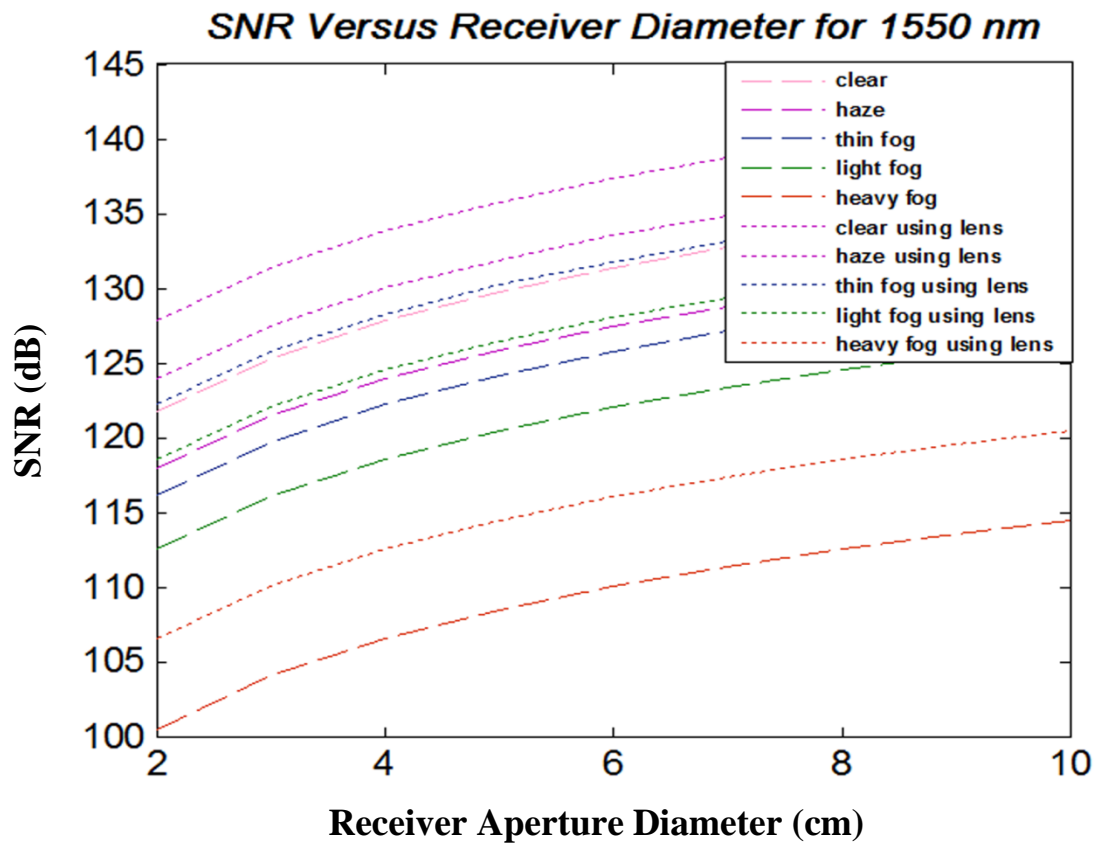


Figure 5.10: SNR Versus Receiver Diameter in different atmospheric conditions for 1550 nm.

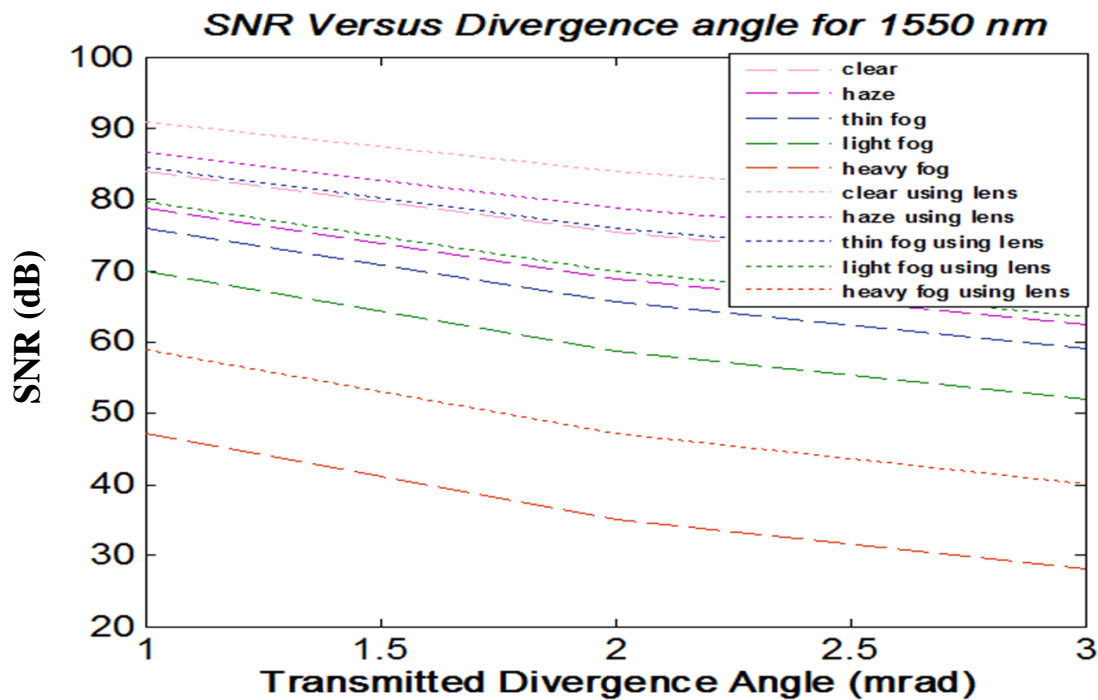


Figure 5.11: SNR Versus Divergence Angle in different atmospheric conditions for 1550 nm.

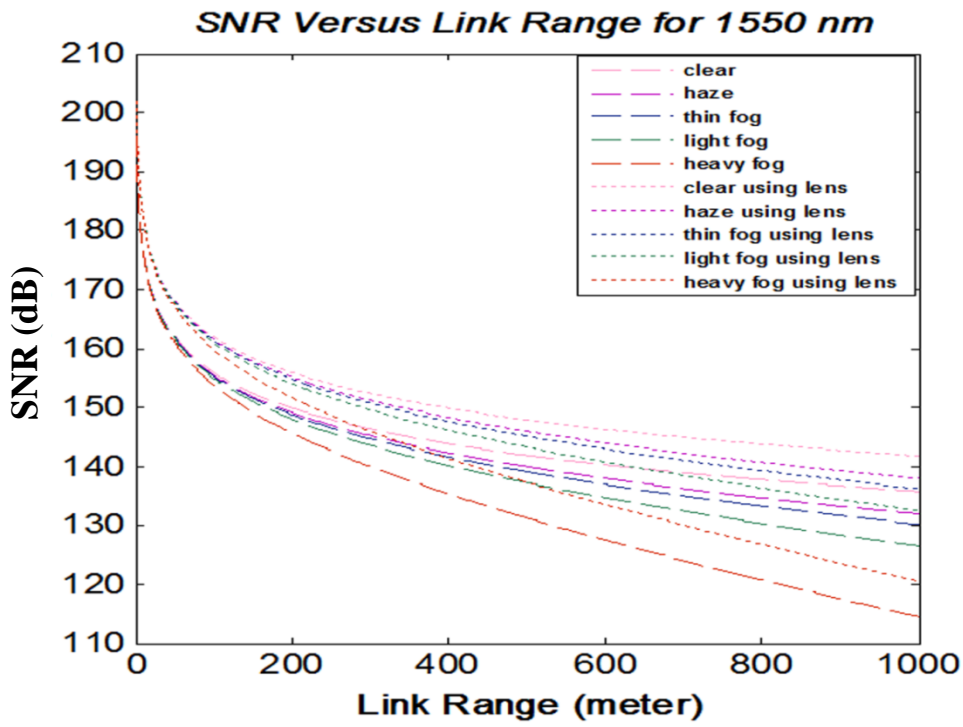


Figure 5.12: SNR Versus Link Range in different atmospheric conditions for 1550 nm.

Table 5.3: Power Received, SNR and Data Rate for different Link Range in different Atmospheric Environments with and without Lens conditions for 1550 nm.

Wavelength (nm)	Link Range (meter)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
1550	100	Clear	With lens	13.9597	16.5509	9.6898e+11	
			Without lens	7.9391	15.9488	2.4224e+11	
		Haze	With lens	13.5751	16.5124	8.8610e+11	
			Without lens	7.5545	15.9104	2.2171e+11	
		Thin Fog	With lens	13.4014	16.4951	8.5209e+11	
			Without lens	7.3808	15.8930	2.1302e+11	
		Light Fog	With lens	13.0330	16.4582	7.8278e+11	
			Without lens	7.0124	15.8562	1.9569e+11	
		Heavy Fog	With lens	11.8345	16.3384	5.9400e+11	
			Without lens	5.8139	15.7363	1.4850e+11	
		500	Clear	With lens	-0.0980	15.1451	3.8065e+10
				Without lens	-6.1186	14.5431	9.5163e+09
	Haze		With lens	-2.0211	14.9528	2.4447e+10	
			Without lens	-8.0417	14.3508	6.1118e+09	
	Thin Fog		With lens	-2.8897	14.8660	2.0015e+10	
			Without lens	-8.9103	14.2639	5.0039e+09	
	Light Fog		With lens	-4.7319	14.6817	1.3096e+10	
			Without lens	-10.7525	14.0797	3.2740e+09	
	Heavy Fog		With lens	-10.724	14.0825	3.2953e+09	
			Without lens	-16.7449	13.4804	8.2383e+08	
	1000		Clear	With lens	-6.2167	14.5332	9.3038e+09
				Without lens	-12.2373	13.9312	2.3259e+09
		Haze	With lens	-10.0628	14.1486	3.8375e+09	
			Without lens	-16.0834	13.5466	9.5939e+08	
Thin Fog		With lens	-11.8000	13.9749	2.5724e+09		
		Without lens	-17.8206	13.3729	6.4310e+08		
Light Fog		With lens	-15.4844	13.6060	1.1012e+09		
		Without lens	-21.5050	13.0044	2.7531e+08		
Heavy Fog		With lens	-27.4693	12.4080	6.9727e+07		
		Without lens	-33.4899	11.8058	1.7431e+07		

Table 5.4: Power Received, SNR and Data Rate for different Transmitter Divergence angle in different Atmospheric Environments with and without Lens conditions for 1550 nm.

Wavelength (nm)	Transmitter Divergence angle (mrad)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
1550	1	Clear	With lens	-0.1961	9.0972	3.7215e+10	
			Without lens	-6.2162	8.3976	9.3038e+09	
		Haze	With lens	-4.0422	8.6636	1.5350e+10	
			Without lens	-10.0628	7.8725	3.8375e+09	
		Thin Fog	With lens	-5.7794	8.4527	1.0289e+10	
			Without lens	-11.8000	7.6084	2.5724e+09	
		Light Fog	With lens	-9.4638	7.9596	4.4050e+09	
			Without lens	-15.4844	6.9941	1.1012e+09	
		Heavy Fog	With lens	-21.4487	5.8886	2.7890e+08	
			Without lens	-27.469	4.7098	6.9727e+07	
		1.5	Clear	With lens	-3.7179	8.7017	1.6540e+10
				Without lens	-9.7385	7.9199	4.1350e+09
	Haze		With lens	-7.5640	8.2225	6.8223e+09	
			Without lens	-13.5846	7.3194	1.7055e+09	
	Thin Fog		With lens	-9.3012	7.9828	4.5731e+09	
			Without lens	-15.3218	7.0226	1.1432e+09	
	Light Fog		With lens	-12.9856	7.4183	1.9578e+09	
			Without lens	-19.0062	6.3530	4.8945e+08	
	Heavy Fog		With lens	-24.9705	5.2029	1.2395e+08	
			Without lens	-30.9911	4.0103	3.0989e+07	
	3		Clear	With lens	-9.7385	7.9199	4.1350e+09
				Without lens	-15.7591	6.9457	1.0337e+09
		Haze	With lens	-13.5846	7.3194	1.7055e+09	
			Without lens	-19.6052	6.2403	4.2639e+08	
Thin Fog		With lens	-15.3218	7.0226	1.1432e+09		
		Without lens	-21.3424	5.9091	2.8582e+08		
Light Fog		With lens	-19.0062	6.3530	4.8945e+08		
		Without lens	-25.0268	5.1918	1.2236e+08		
Heavy Fog		With lens	-30.9911	4.0103	3.0989e+07		
		Without lens	-37.0117	2.8092	7.7474e+06		

Table 5.5: Power Received, SNR and Data Rate for different Receiver Aperture Diameter in different Atmospheric Environments with and without Lens conditions for 1550 nm.

Wavelength (nm)	Receiver Aperture Diameter (cm)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
1550	2	Clear	With lens	-20.1961	13.1353	3.7215e+09	
			Without lens	-26.2167	12.5332	9.3038e+08	
		Haze	With lens	-24.0422	12.7507	1.4207e+09	
			Without lens	-30.0628	12.1486	3.5519e+08	
		Thin Fog	With lens	-25.7794	12.5770	9.0393e+08	
			Without lens	-31.8000	11.9749	2.2598e+08	
		Light Fog	With lens	-29.4638	12.2085	3.6043e+08	
			Without lens	-35.4844	11.6063	9.0109e+07	
		Heavy Fog	With lens	-41.4487	11.0095	1.3192e+06	
			Without lens	-47.4693	10.4059	3.2982e+05	
		6	Clear	With lens	-10.6537	14.0896	3.3493e+10
				Without lens	-16.6743	13.4875	8.3734e+09
	Haze		With lens	-14.4997	13.7049	1.2786e+10	
			Without lens	-20.5203	13.1029	3.1967e+09	
	Thin Fog		With lens	-16.2369	13.5312	8.1354e+09	
			Without lens	-22.2575	12.9292	2.0338e+09	
	Light Fog		With lens	-19.9214	13.1628	3.2439e+09	
			Without lens	-25.9420	12.5607	8.1098e+08	
	Heavy Fog		With lens	-31.9063	11.9642	1.1873e+07	
			Without lens	-37.9269	11.3620	2.9683e+06	
	10		Clear	With lens	-6.2167	14.5332	9.3038e+10
				Without lens	-12.2373	13.9312	2.3259e+10
		Haze	With lens	-10.0628	14.1486	3.5519e+10	
			Without lens	-16.0834	13.5466	8.8798e+09	
Thin Fog		With lens	-11.8000	13.9749	2.2598e+10		
		Without lens	-17.8206	13.3729	5.6496e+09		
Light Fog		With lens	-15.4844	13.6065	9.0109e+09		
		Without lens	-21.5050	13.0044	2.2527e+09		
Heavy Fog		With lens	-27.4693	12.4080	3.2982e+07		
		Without lens	-33.4899	11.8058	8.2455e+06		

5.5.2 Simulation at 1300 nm

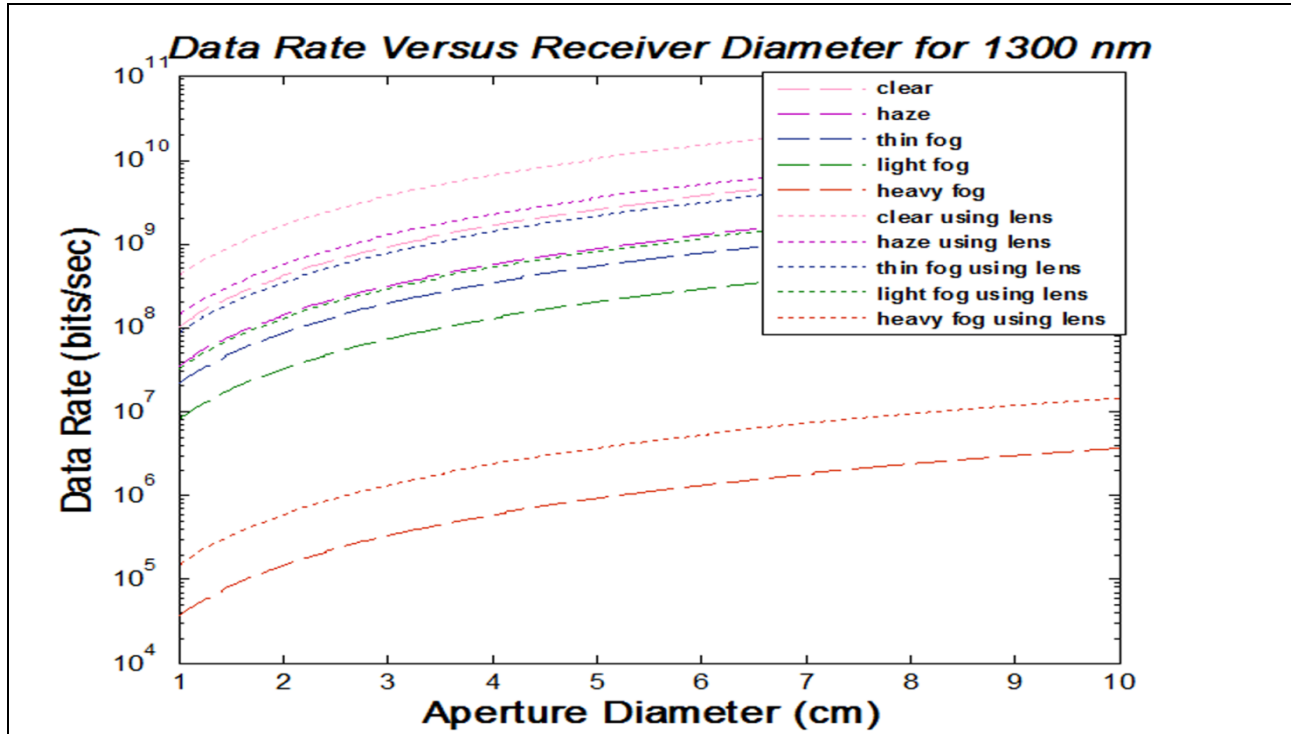


Figure 5.13: Data Rate Versus Receiver Diameter in different atmospheric conditions for 1300 nm

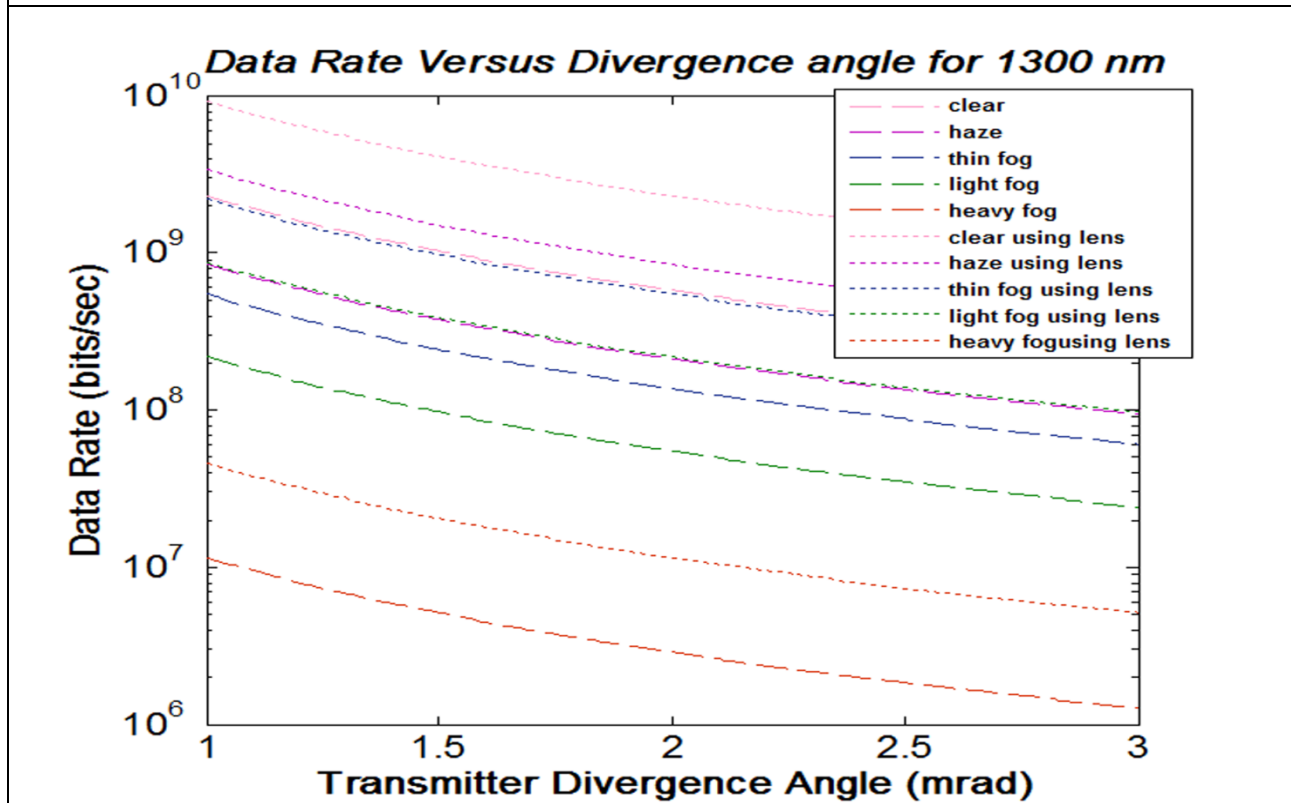


Figure 5.14: Data Rate Versus Divergence Angle in different atmospheric conditions for 1300 nm

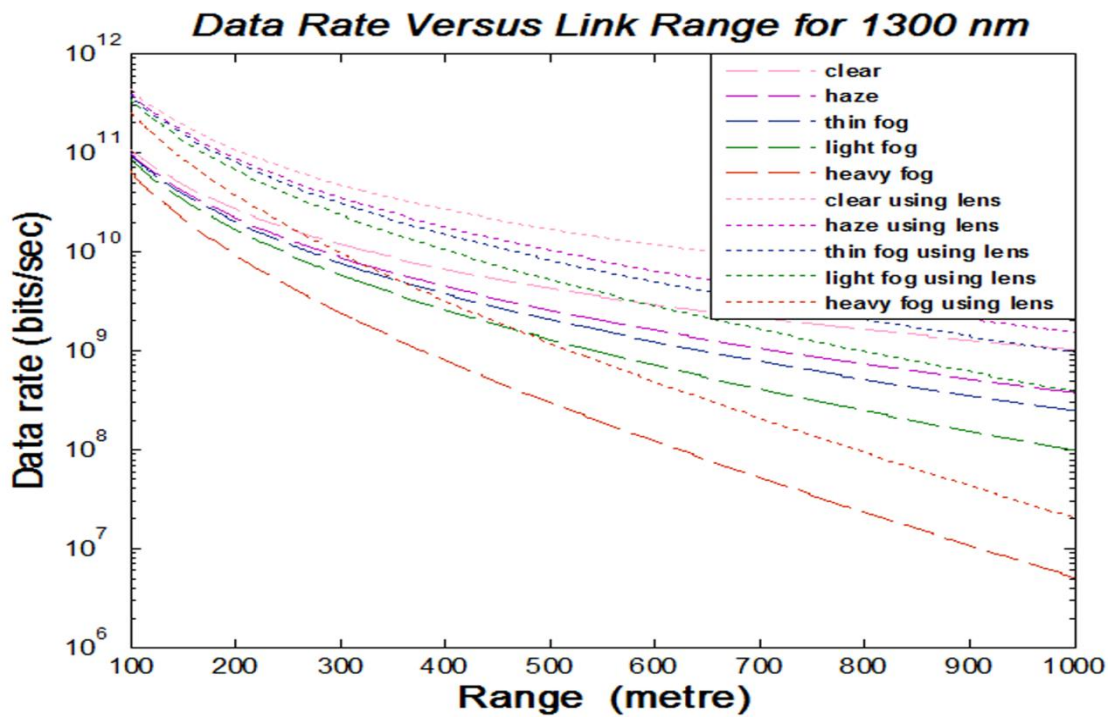


Figure 5.15: Data Rate Versus Link Range in different atmospheric conditions for 1300 nm.

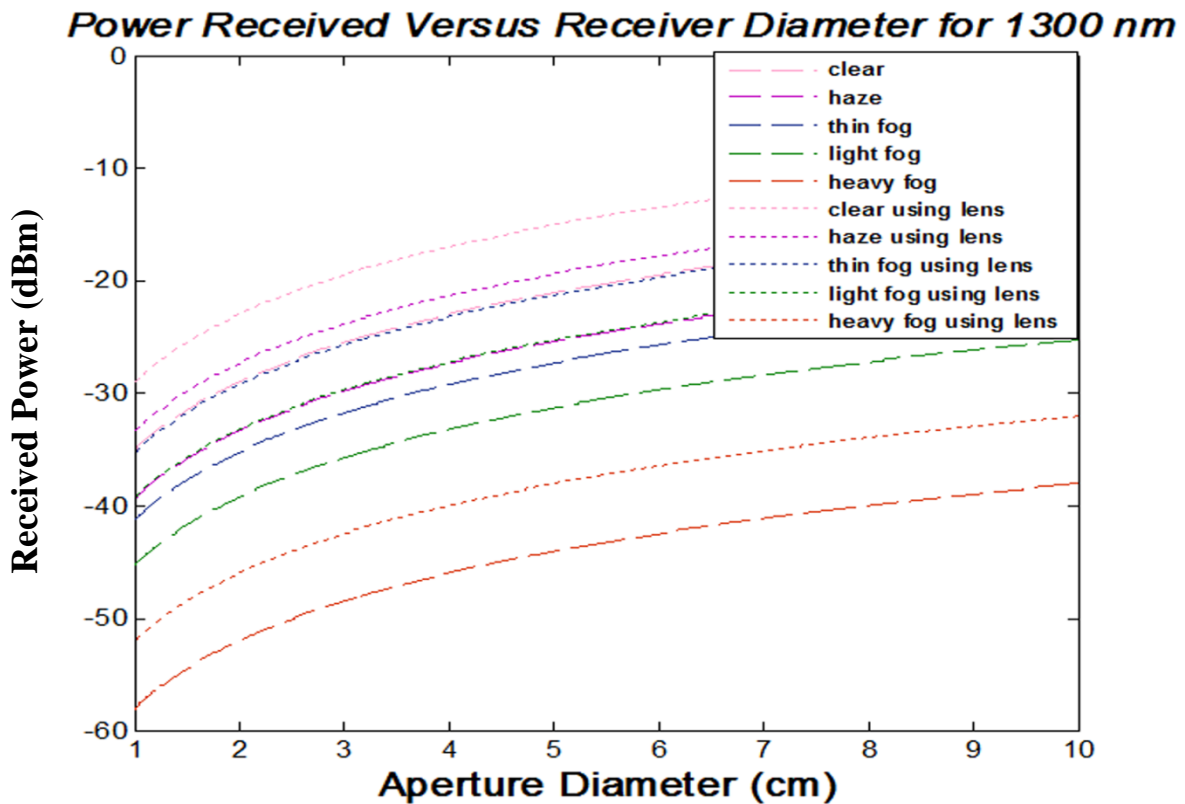


Figure 5.16: Power Received Versus Receiver Diameter in different atmospheric conditions for 1300 nm.

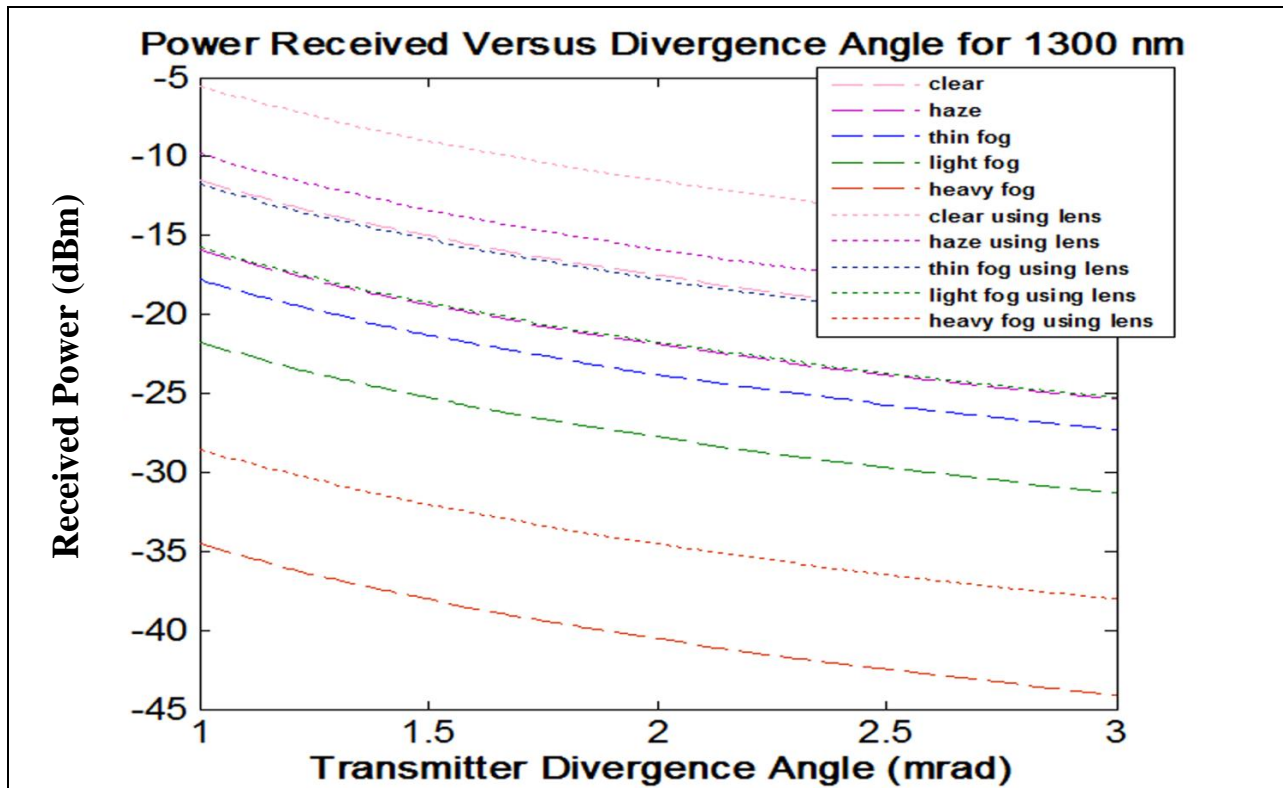


Figure 5.17: Power Received Versus Divergence Angle in different atmospheric conditions for 1300 nm.

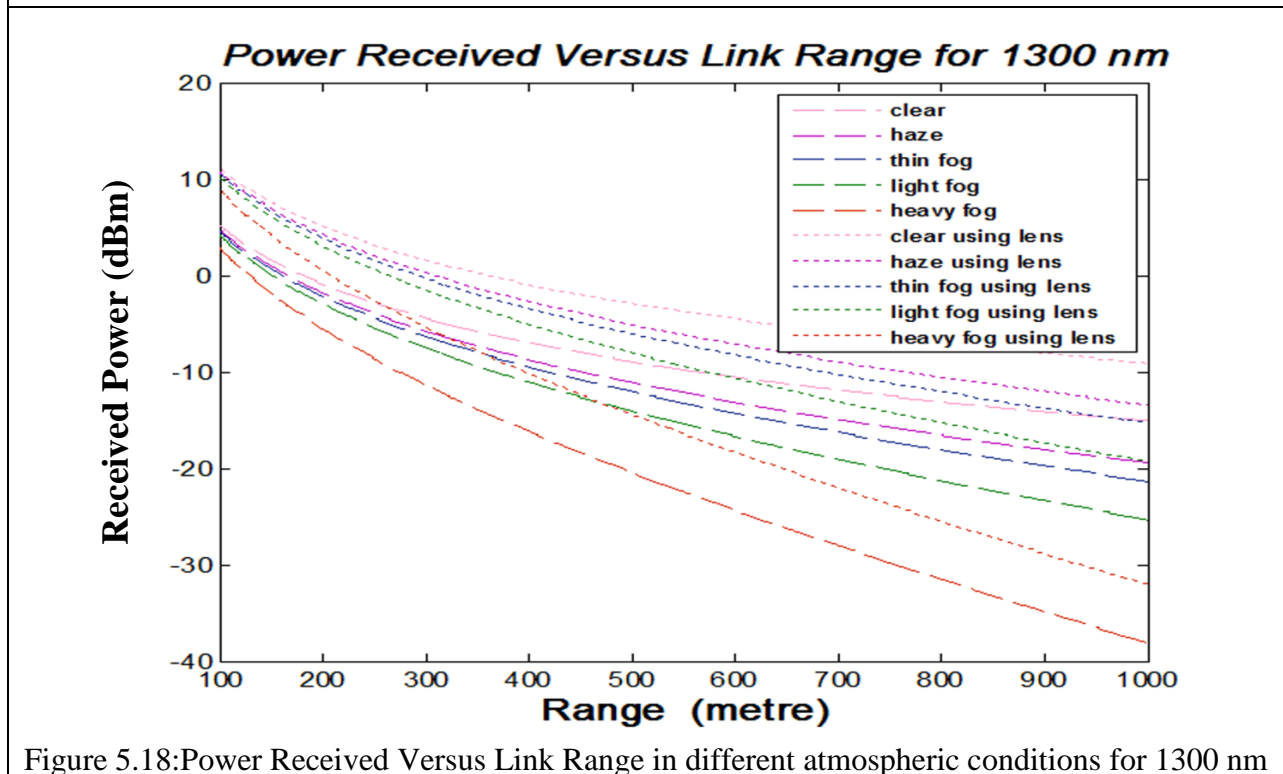


Figure 5.18: Power Received Versus Link Range in different atmospheric conditions for 1300 nm

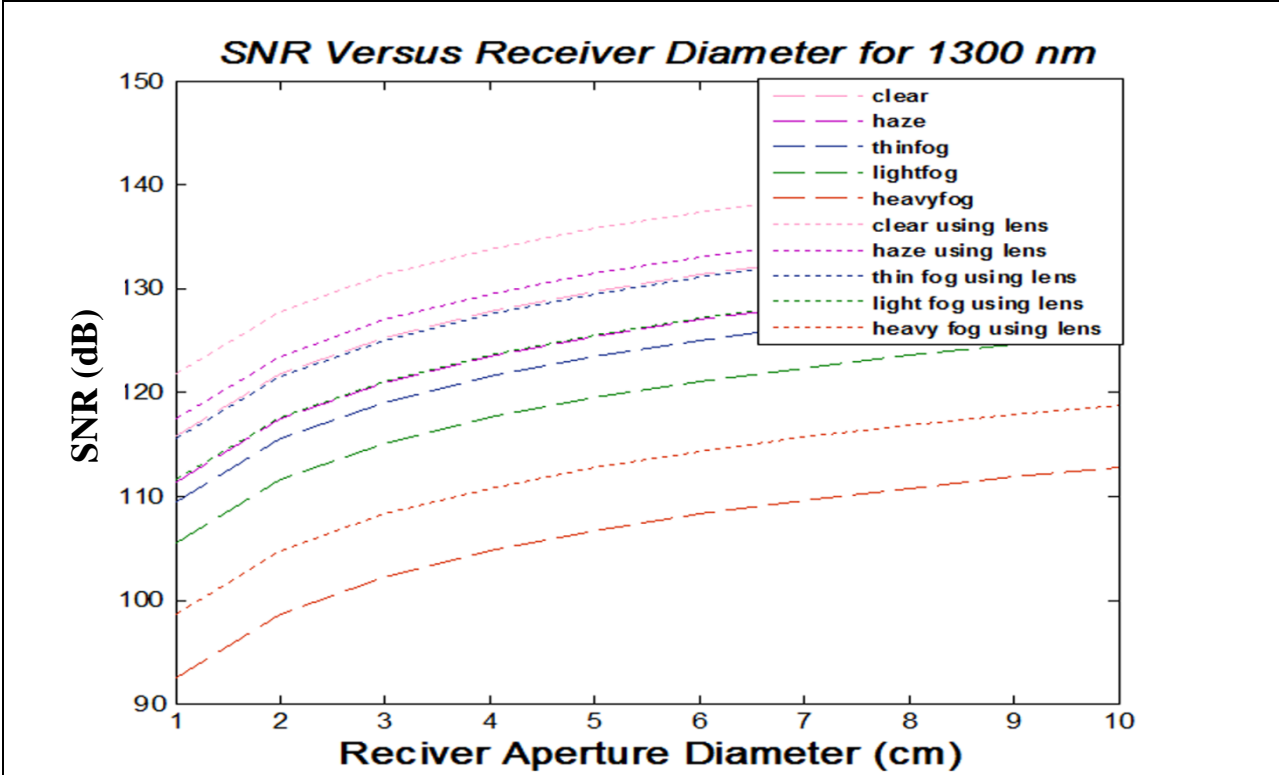


Figure 5.19: SNR Versus Receiver Diameter in different atmospheric conditions for 1300 nm.

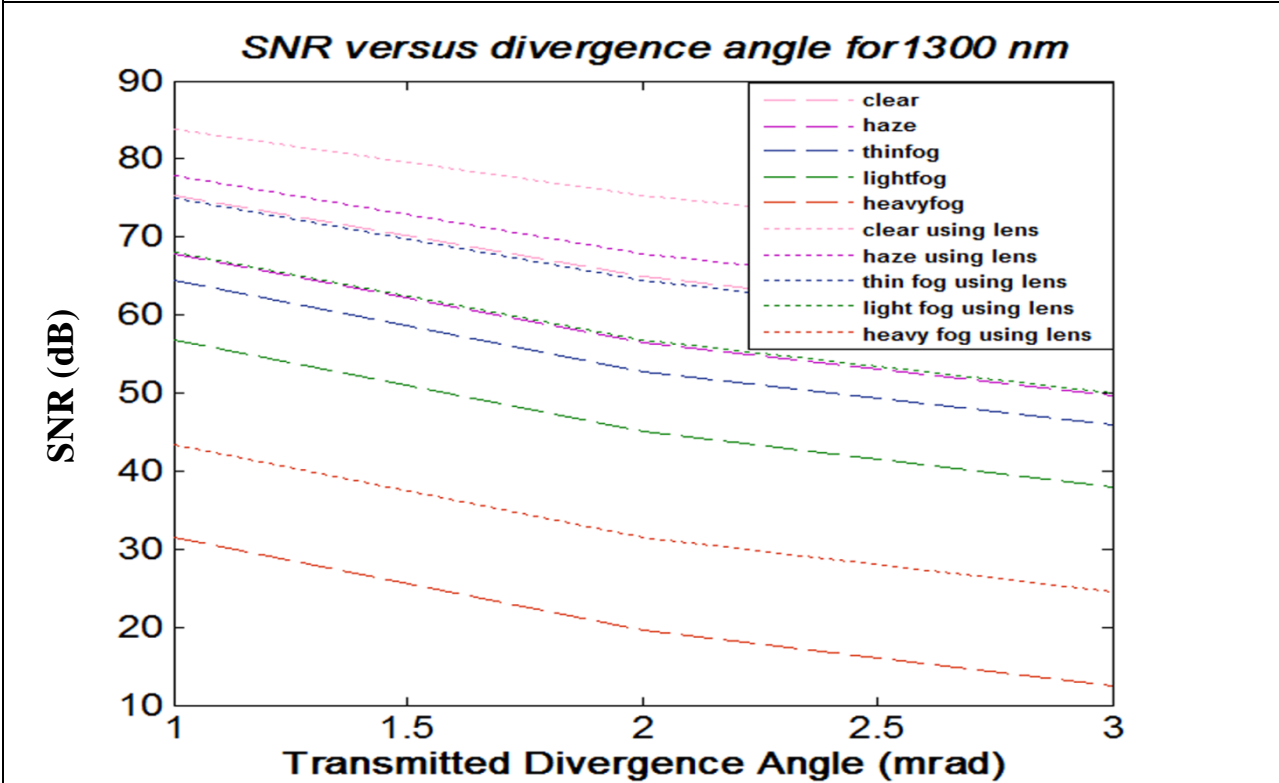


Figure 5.20: SNR Versus Divergence angle in different atmospheric conditions for 1300 nm.

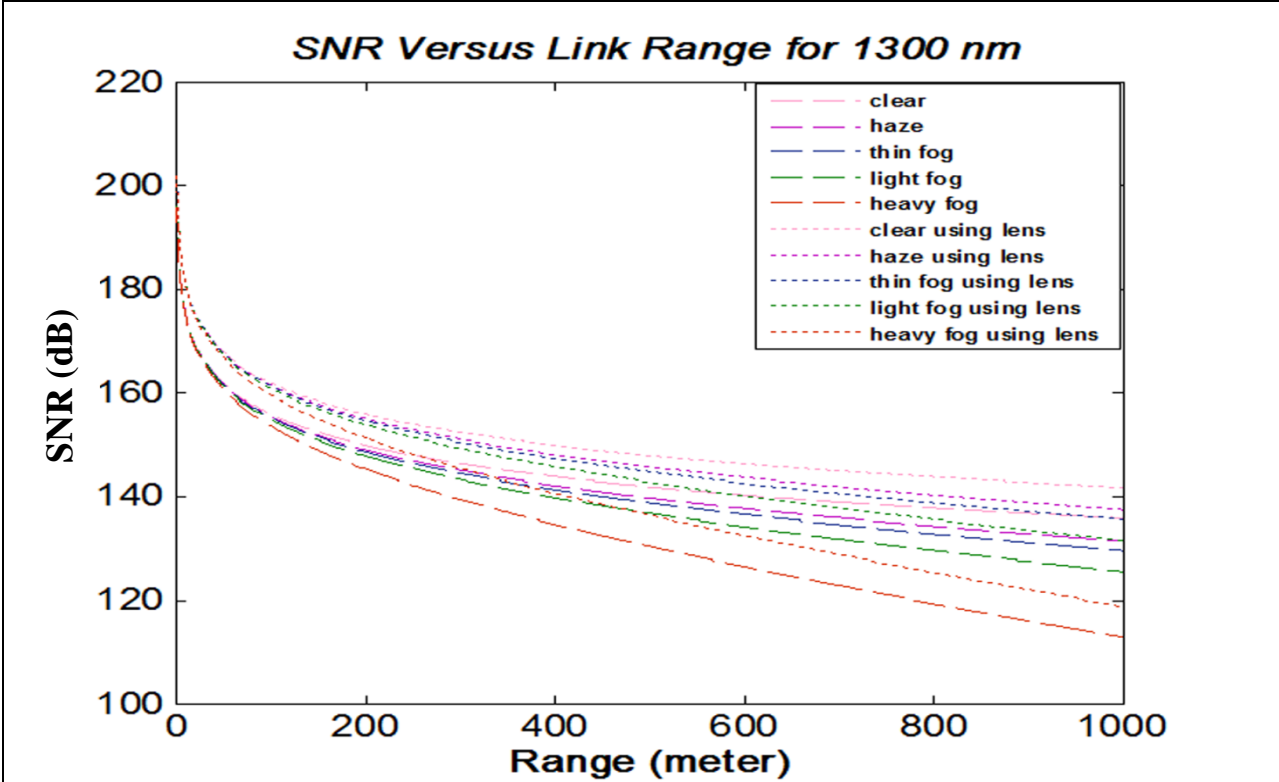


Figure 5.21: SNR Versus Link Range in different atmospheric conditions for 1300 nm.

Table 5.6: Power Received, SNR and Data Rate for different Link Range in different Atmospheric Environments with and without Lens conditions for 1300 nm.

Wavelength (nm)	Link Range (meter)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
1300	100	Clear	With lens	11.2247	16.2010	4.3293e+11	
			Without lens	5.2041	15.5990	1.0823e+11	
		Haze	With lens	10.7892	16.1575	3.9162e+11	
			Without lens	4.7686	15.5554	9.7906e+10	
		Thin Fog	With lens	10.5992	16.1385	3.7486e+11	
			Without lens	4.5786	15.5364	9.3715e+10	
		Light Fog	With lens	10.2004	16.0986	3.4197e+11	
			Without lens	4.1798	15.4965	8.5493e+10	
		Heavy Fog	With lens	8.92199	15.9707	2.5477e+11	
			Without lens	2.9013	15.3687	6.3692e+10	
		500	Clear	With lens	-2.8532	14.7932	1.6928e+10
				Without lens	-8.8738	14.1911	4.2321e+09
	Haze		With lens	-5.0308	14.5754	1.0253e+10	
			Without lens	-11.0514	13.9734	2.5633e+09	
	Thin Fog		With lens	-5.9809	14.4804	8.2386e+09	
			Without lens	-12.0015	13.8784	2.0596e+09	
	Light Fog		With lens	-7.9747	14.2811	5.2056e+09	
			Without lens	-13.9953	13.6790	1.3014e+09	
	Heavy Fog		With lens	-14.3669	13.6418	1.1946e+09	
			Without lens	-20.3875	13.0398	2.9866e+08	
	1000		Clear	With lens	-8.9971	14.1788	4.1137e+09
				Without lens	-15.0177	13.5768	1.0284e+09
		Haze	With lens	-13.3523	13.7433	1.5090e+09	
			Without lens	-19.3729	13.1412	3.7727e+08	
		Thin Fog	With lens	-15.2524	13.5533	9.7432e+08	
			Without lens	-21.2730	12.9512	2.4358e+08	
		Light Fog	With lens	-19.2401	13.1545	3.8899e+08	
			Without lens	-25.2607	12.5525	9.7247e+07	
		Heavy Fog	With lens	-32.0245	11.8760	2.0487e+07	
			Without lens	-38.0451	11.2737	5.1219e+06	

Table 5.7: Power Received, SNR and Data Rate for different Transmitter Divergence Angle in different Atmospheric Environments with and without Lens conditions for 1300 nm.

Wavelength (nm)	Transmitter Divergence angle (mrad)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
1300	1	Clear	With lens	-5.4753	8.3948	9.2558e+09	
			Without lens	-11.495	7.5356	2.3139e+09	
		Haze	With lens	-9.8305	7.7935	3.3954e+09	
			Without lens	-15.8511	6.7930	8.4886e+08	
		Thin Fog	With lens	-11.7306	7.4980	2.1922e+09	
			Without lens	-17.7512	6.4447	5.4805e+08	
		Light Fog	With lens	-15.7182	6.8168	8.7523e+08	
			Without lens	-21.7388	5.6849	2.1880e+08	
		Heavy Fog	With lens	-28.5027	4.3533	4.6097e+07	
			Without lens	-34.5233	3.1536	1.1524e+07	
		1.5	Clear	With lens	-8.9971	7.9166	4.1137e+09
				Without lens	-15.0177	6.9417	1.0284e+09
	Haze		With lens	-13.3523	7.2301	1.5090e+09	
			Without lens	-19.3729	6.1396	3.7727e+08	
	Thin Fog		With lens	-15.2524	6.9001	9.7432e+08	
			Without lens	-21.2730	5.7751	2.4358e+08	
	Light Fog		With lens	-19.2401	6.1648	3.8899e+08	
			Without lens	-25.2607	4.9954	9.7247e+07	
	Heavy Fog		With lens	-32.0245	3.6522	2.0487e+07	
			Without lens	-38.0451	2.4500	5.1219e+06	
	3		Clear	With lens	-15.0177	6.9417	1.0284e+09
				Without lens	-21.0383	5.8205	2.5710e+08
		Haze	With lens	-19.3729	6.1396	3.7727e+08	
			Without lens	-25.3935	4.9692	9.4318e+07	
Thin Fog		With lens	-21.2730	5.7751	2.4358e+08		
		Without lens	-27.2936	4.5933	6.0895e+07		
Light Fog		With lens	-25.2607	4.9954	9.7247e+07		
		Without lens	-31.2813	3.8004	2.4311e+07		
Heavy Fog		With lens	-38.0451	2.4500	5.1219e+06		
		Without lens	-44.0657	1.2464	1.2804e+06		

Table 5.8: Power Received, SNR and Data Rate for different Receiver Aperture Diameter in different Atmospheric Environments with and without Lens conditions for 1300 nm.

Wavelength (nm)	Receiver Aperture Diameter (cm)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
1300	2	Clear	With lens	-22.9765	12.7809	1.6454e+09	
			Without lens	-28.9971	12.1788	4.1137e+08	
		Haze	With lens	-27.3317	12.3453	5.6136e+08	
			Without lens	-33.3523	11.7432	1.4034e+08	
		Thin Fog	With lens	-29.2318	12.1553	3.4564e+08	
			Without lens	-35.2524	11.5531	8.6412e+07	
		Light Fog	With lens	-33.2191	11.7565	1.2954e+08	
			Without lens	-39.2401	11.1541	3.2386e+07	
		Heavy Fog	With lens	-46.0039	10.4763	5.9013e+05	
			Without lens	-52.0245	9.86895	1.4753e+05	
		6	Clear	With lens	-13.4341	13.7351	1.4809e+10
				Without lens	-19.4547	13.1331	3.7023e+09
	Haze		With lens	-17.7893	13.2996	5.0522e+09	
			Without lens	-23.8099	12.6975	1.2630e+09	
	Thin Fog		With lens	-19.6894	13.1096	3.1108e+09	
			Without lens	-25.7100	12.5075	7.7771e+08	
	Light Fog		With lens	-23.6770	12.7108	1.1659e+09	
			Without lens	-29.6976	12.1087	2.9148e+08	
	Heavy Fog		With lens	-36.4615	11.4322	5.3111e+06	
			Without lens	-42.4821	10.8295	1.3277e+06	
	10		Clear	With lens	-8.9971	14.1788	4.1137e+10
				Without lens	-15.0177	13.5768	1.0284e+10
		Haze	With lens	-13.3523	13.7433	1.4034e+10	
			Without lens	-19.3729	13.1412	3.5085e+09	
Thin Fog		With lens	-15.2524	13.5533	8.6412e+09		
		Without lens	-21.2730	12.9512	2.1603e+09		
Light Fog		With lens	-19.2401	13.1545	3.2386e+09		
		Without lens	-25.2607	12.5525	8.0967e+08		
Heavy Fog		With lens	-32.0245	11.8760	1.4753e+07		
		Without lens	-38.0451	11.2737	3.6883e+06		

5.5.3 Simulation at 850 nm

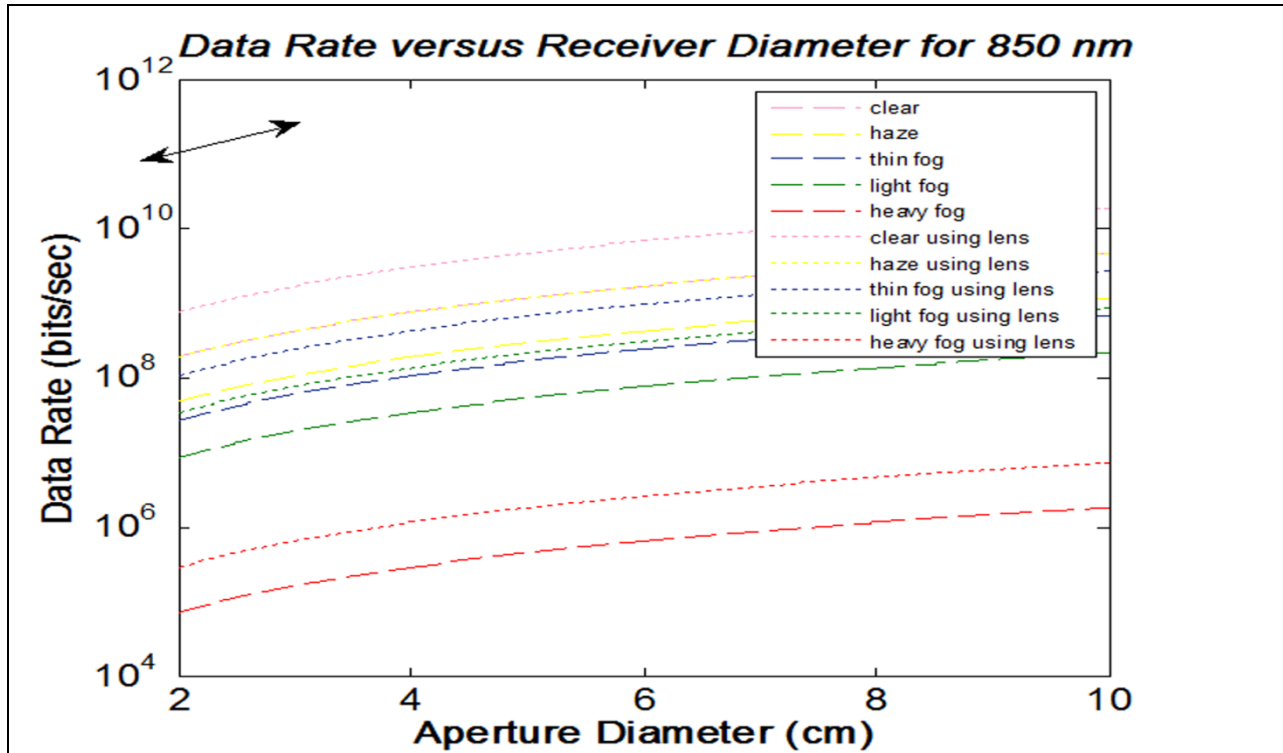


Figure 5.22: Data Rate Versus Receiver Diameter in different atmospheric conditions for 850 nm.

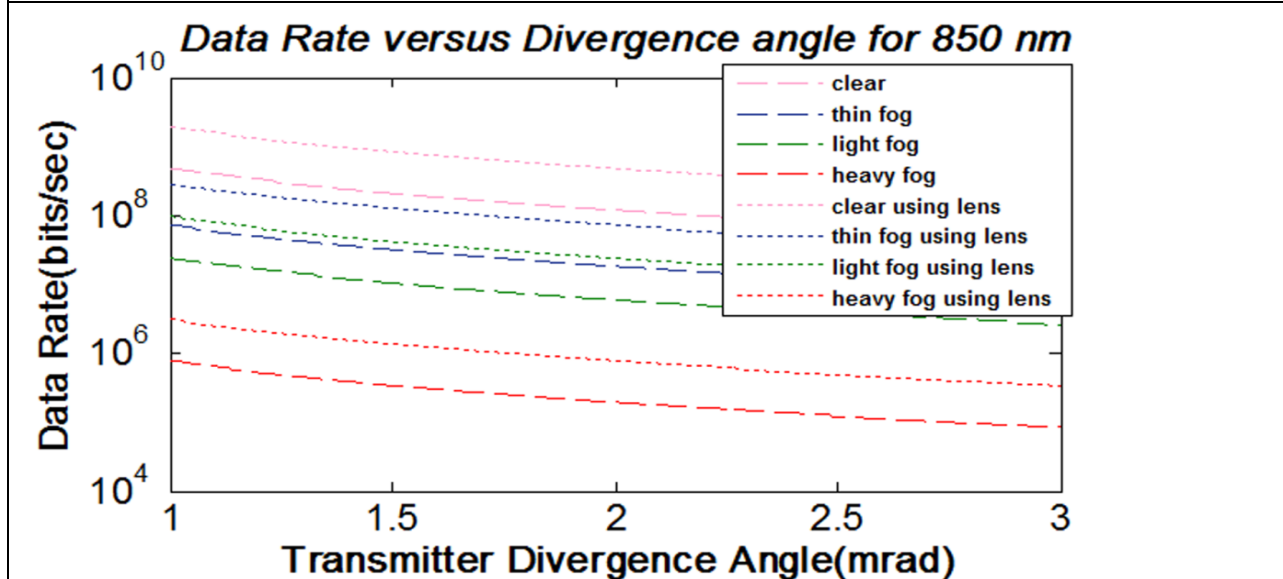


Figure 5.23: Data Rate Versus Divergence Angle in different atmospheric conditions for 850 nm.

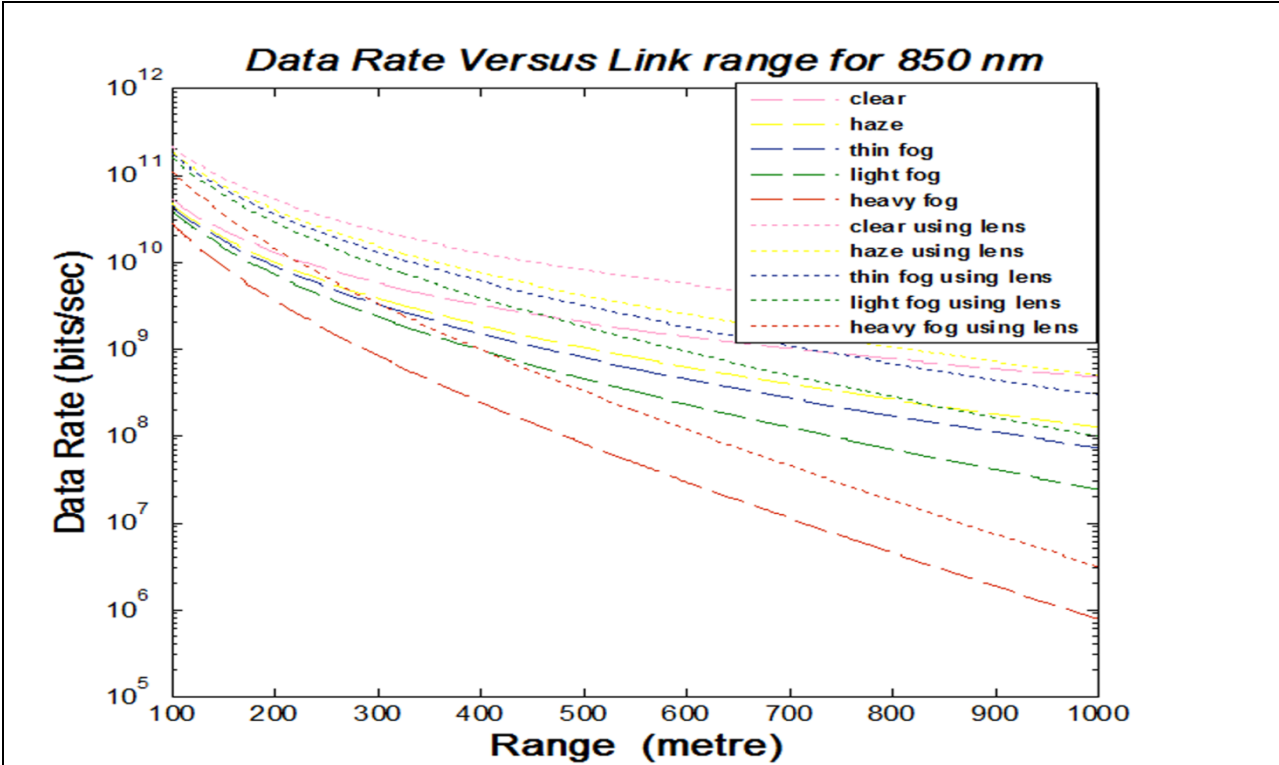


Figure 5.24: Data Rate Versus Link Range in different atmospheric conditions for 850 nm.

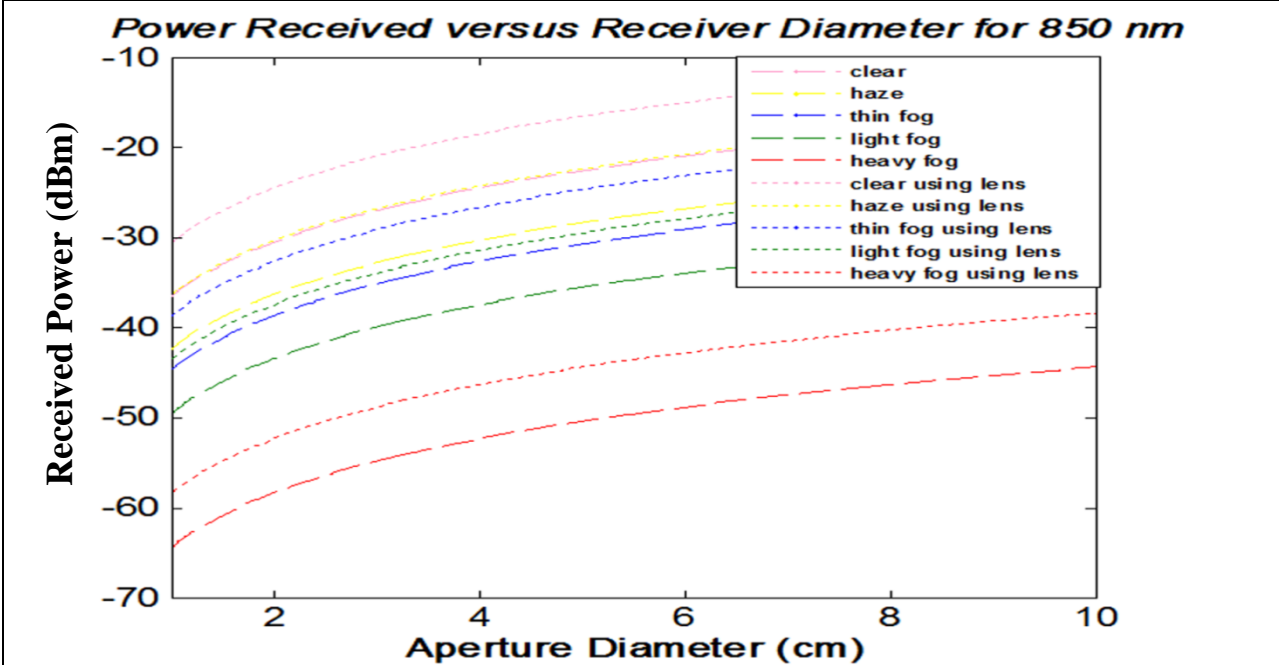


Figure 5.25: Power Received Versus Receiver Diameter in different atmospheric conditions for 850 nm.

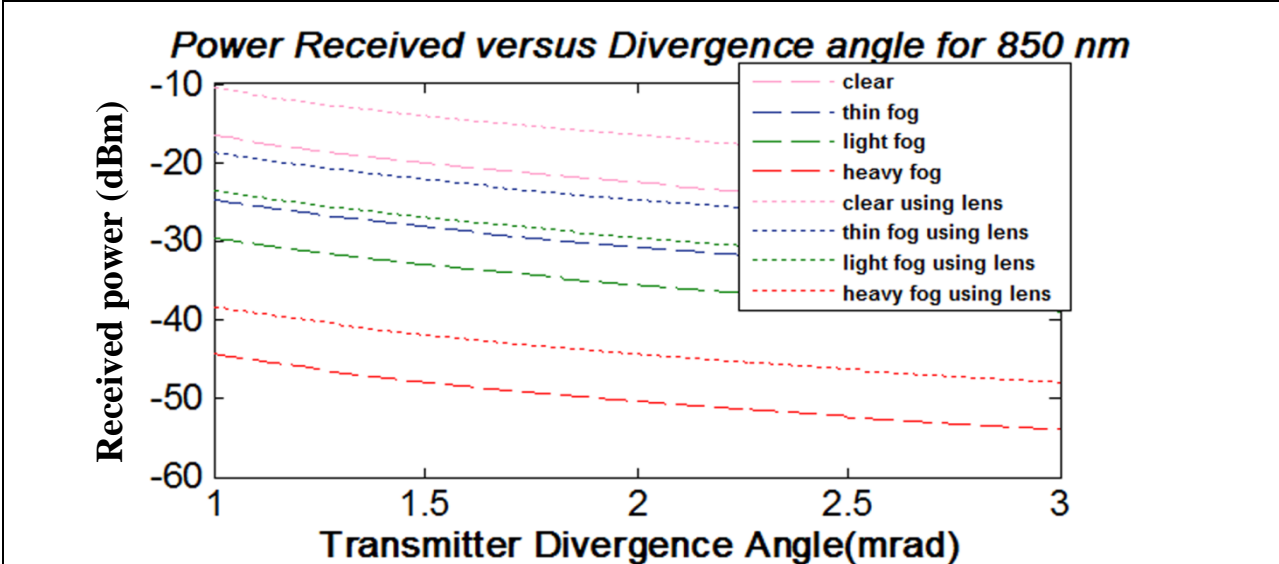


Figure 5.26: Power Received Versus Divergence Angle in different atmospheric conditions for 850 nm.

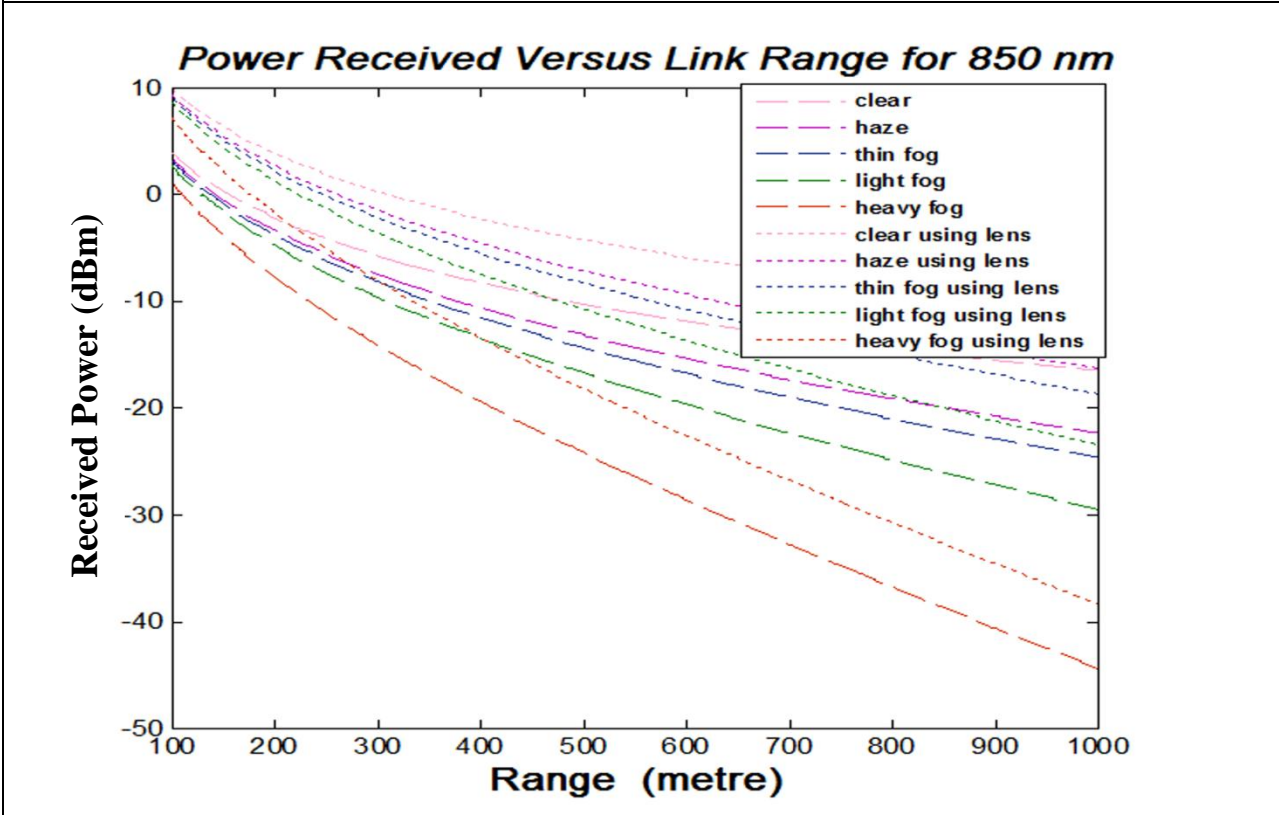


Figure 5.27: Power Received Versus Link Range in different atmospheric conditions for 850 nm.

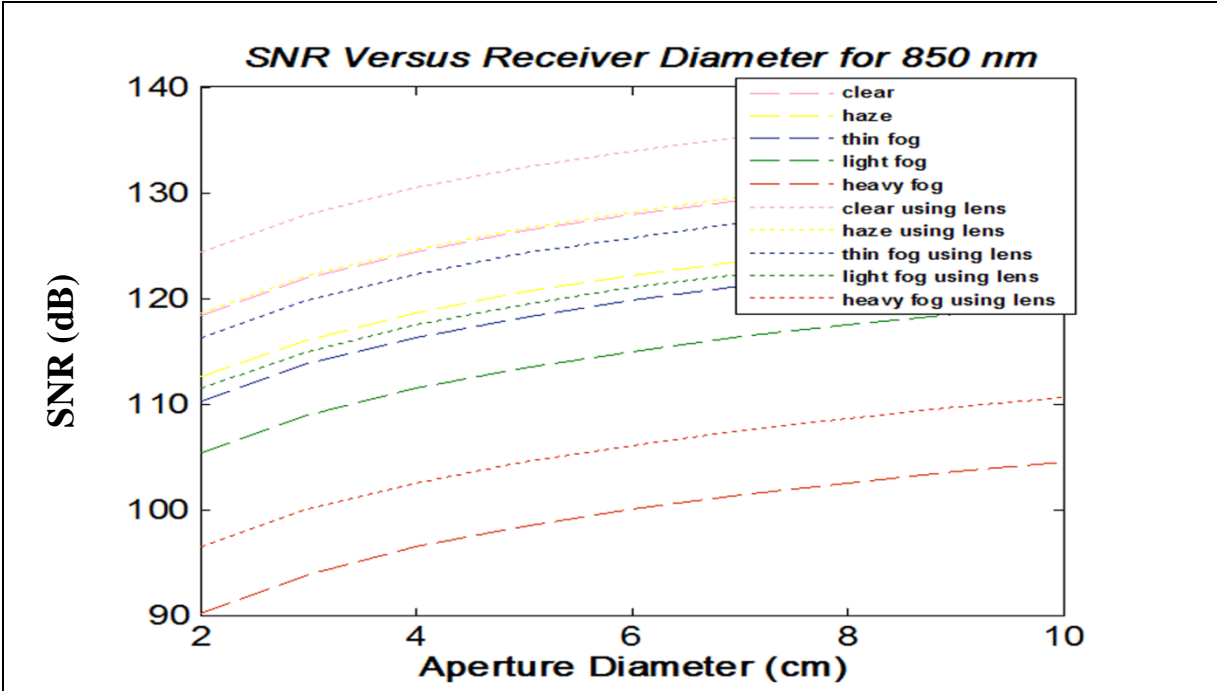


Figure 5.28: SNR Versus Receiver Diameter in different atmospheric conditions for 850 nm.

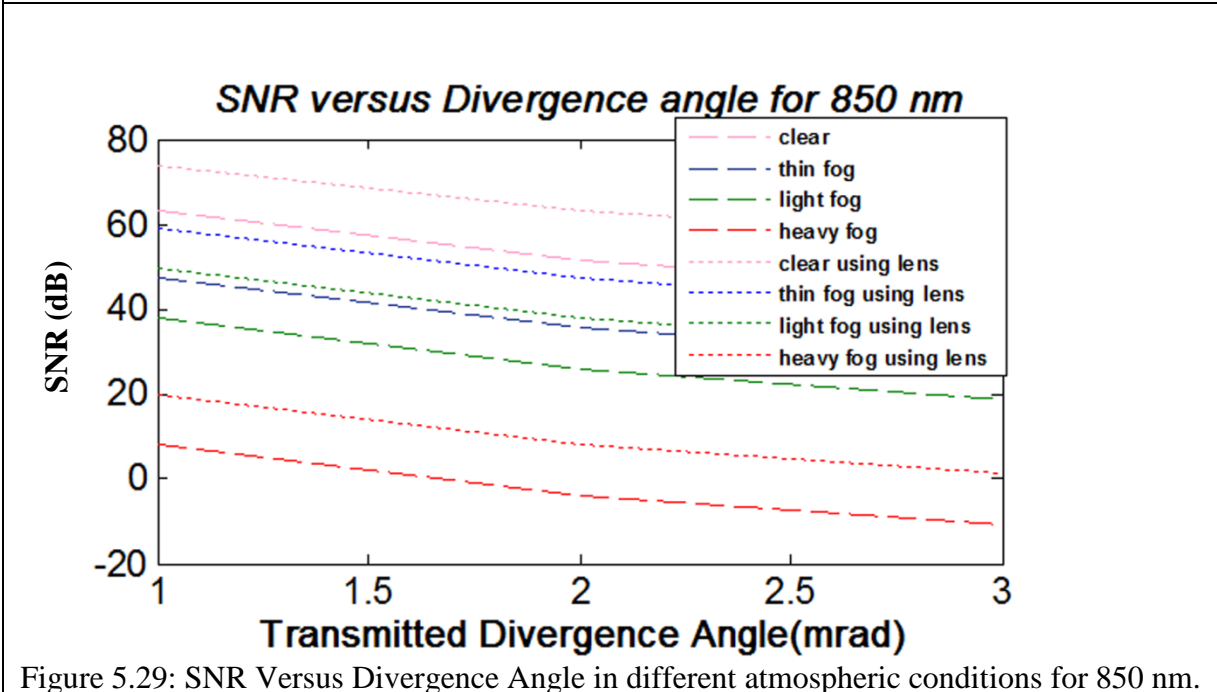


Figure 5.29: SNR Versus Divergence Angle in different atmospheric conditions for 850 nm.

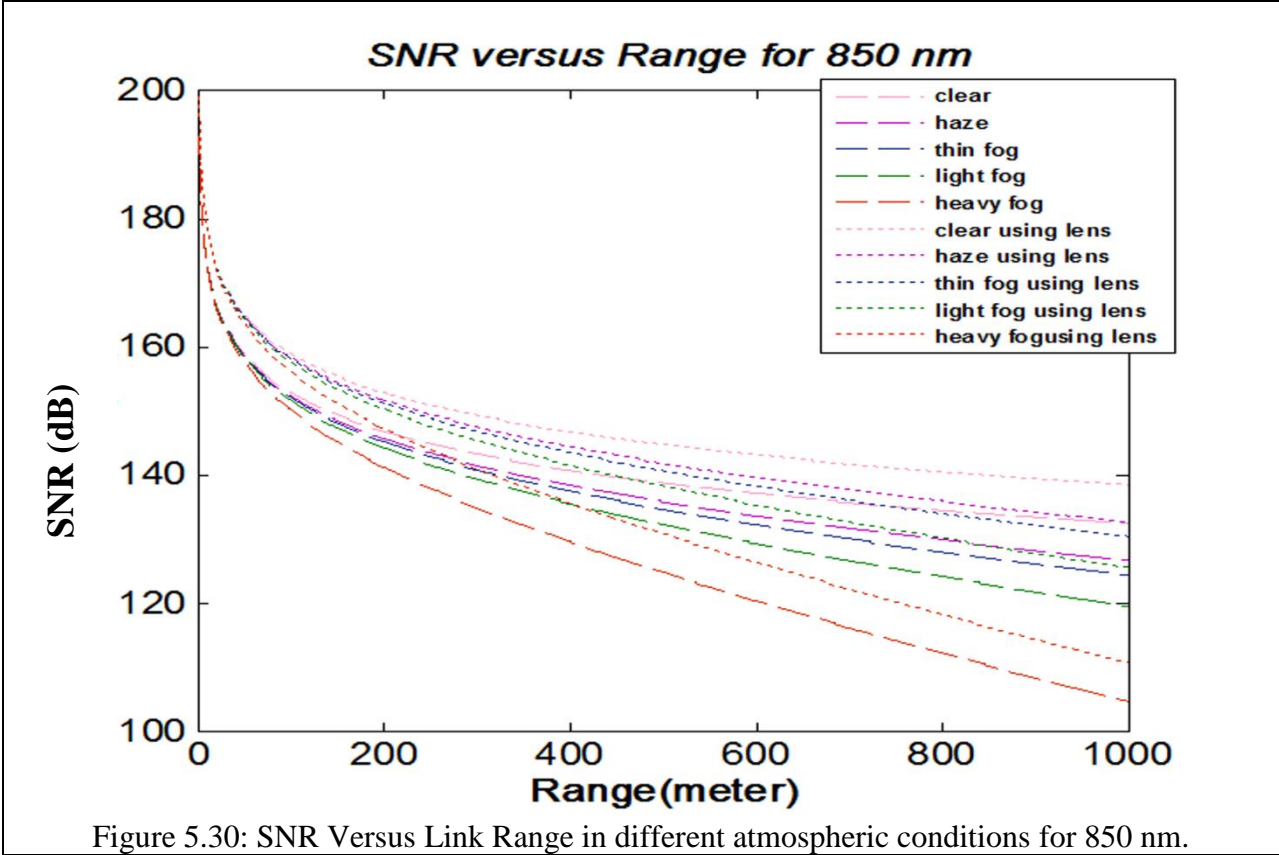


Table 5.9: Power Received, SNR and Data Rate for different Link Range in different Atmospheric Environments with and without Lens conditions for 850 nm.

Wavelength (nm)	Link Range (meter)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
850	100	Clear	With lens	9.9507	15.889	2.1110e+11	
			Without lens	3.9301	15.2870	5.2776e+10	
		Haze	With lens	9.3706	15.831	1.8470e+11	
			Without lens	3.3500	15.2290	4.6177e+10	
		Thin Fog	With lens	9.1358	15.807	1.7498e+11	
			Without lens	3.1152	15.2055	4.3747e+10	
		Light Fog	With lens	8.6550	15.759	1.5665e+11	
			Without lens	2.6344	15.1575	3.9162e+10	
		Heavy Fog	With lens	7.1650	15.610	1.1115e+11	
			Without lens	1.1444	15.0085	2.7788e+10	
		500	Clear	With lens	-4.2257	14.471	8.0696e+09
				Without lens	-10.246	13.8694	2.0174e+09
	Haze		With lens	-7.1263	14.181	4.1379e+09	
			Without lens	-13.146	13.5793	1.0344e+09	
	Thin Fog		With lens	-8.3003	14.064	3.1578e+09	
			Without lens	-14.320	13.4619	7.8947e+08	
	Light Fog		With lens	-10.7040	13.823	1.8155e+09	
			Without lens	-16.724	13.2215	4.5389e+08	
	Heavy Fog		With lens	-18.1542	13.078	3.2659e+08	
			Without lens	-24.174	12.4765	8.1647e+07	
	1000		Clear	With lens	-10.4926	13.844	1.9061e+09
				Without lens	-16.513	13.2427	4.7654e+08
		Haze	With lens	-16.2939	13.264	5.0122e+08	
			Without lens	-22.314	12.6625	1.2530e+08	
Thin Fog		With lens	-18.64182	13.029	2.9190e+08		
		Without lens	-24.662	12.4278	7.2976e+07		
Light Fog		With lens	-23.44935	12.549	9.6491e+07		
		Without lens	-29.469	11.9470	2.4122e+07		
Heavy Fog		With lens	-38.34966	11.058	3.1221e+06		
		Without lens	-44.370	10.4551	7.8054e+05		

Table 5.10: Power Received, SNR and Data Rate for different Transmitter Divergence Angle in different Atmospheric Environments with and without Lens conditions for 850 nm.

Wavelength (nm)	Transmitter Divergence angle (mrad)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
850	1	Clear	With lens	-10.4926	7.3993	1.9346e+09	
			Without lens	-16.5132	6.3312	4.8365e+08	
		Haze	With lens	-16.2939	6.3723	5.0122e+08	
			Without lens	-22.3145	5.2121	1.2530e+08	
		Thin Fog	With lens	-18.6418	5.9266	2.9190e+08	
			Without lens	-24.6624	4.7490	7.2976e+07	
		Light Fog	With lens	-23.4493	4.9887	9.6491e+07	
			Without lens	-29.4699	3.7936	2.4122e+07	
		Heavy Fog	With lens	-38.3496	2.0203	3.1221e+06	
			Without lens	-44.3702	0.8165	7.8054e+05	
		1.5	Clear	With lens	-14.0144	6.7914	8.5982e+08
				Without lens	-20.0350	5.6575	2.1495e+08
	Haze		With lens	-19.8157	5.7000	2.2276e+08	
			Without lens	-25.836	4.5164	5.5691e+07	
	Thin Fog		With lens	-22.1636	5.2417	1.2973e+08	
			Without lens	-28.1842	4.0497	3.2434e+07	
	Light Fog		With lens	-26.9711	4.2910	4.2885e+07	
			Without lens	-32.9917	3.0910	1.0721e+07	
	Heavy Fog		With lens	-41.8714	1.3162	1.3876e+06	
			Without lens	-47.8920	0.1122	3.4691e+05	
	3		Clear	With lens	-20.0350	5.6575	2.1495e+08
				Without lens	-26.0556	4.4729	5.3738e+07
		Haze	With lens	-25.8363	4.5164	5.5691e+07	
			Without lens	-31.8569	3.3175	1.3922e+07	
Thin Fog		With lens	-28.1842	4.0497	3.2434e+07		
		Without lens	-34.2048	2.8487	8.1085e+06		
Light Fog		With lens	-32.9917	3.0910	1.0721e+07		
		Without lens	-39.0123	1.8879	2.6803e+06		
Heavy Fog		With lens	-47.8920	0.1122	3.4691e+05		
		Without lens	-53.9126	-1.0918	8.6727e+04		

Table 5.11: Power Received, SNR and Data Rate for different Receiver Aperture Diameter in different Atmospheric Environments with and without Lens conditions for 850 nm.

Wavelength (nm)	Receiver Aperture Diameter (cm)	Different Atmospheric Conditions	Lens Technique	Power Received (dBm)	S/N Ratio (dB)	Data Rate (bits/sec)	
850	2	Clear	With lens	-24.4720	12.4468	7.6247e+08	
			Without lens	-30.4926	11.8447	1.9061e+08	
		Haze	With lens	-30.2733	11.8666	1.9081e+08	
			Without lens	-36.2939	11.2643	4.7704e+07	
		Thin Fog	With lens	-32.6212	11.6318	1.0787e+08	
			Without lens	-38.6418	11.0293	2.6968e+07	
		Light Fog	With lens	-37.4287	11.1508	3.4344e+07	
			Without lens	-43.4493	10.5475	8.5860e+06	
		Heavy Fog	With lens	-52.3290	9.64945	2.8939e+05	
			Without lens	-58.3496	9.01407	7.2348e+04	
		6	Clear	With lens	-14.9295	13.4011	6.8622e+09
				Without lens	-20.9501	12.7990	1.7155e+09
	Haze		With lens	-20.7309	12.8209	1.7173e+09	
			Without lens	-26.7515	12.2188	4.2934e+08	
	Thin Fog		With lens	-23.0787	12.5861	9.7084e+08	
			Without lens	-29.0993	11.9840	2.4271e+08	
	Light Fog		With lens	-27.8863	12.1053	3.0909e+08	
			Without lens	-33.9069	11.5031	7.7274e+07	
	Heavy Fog		With lens	-42.7866	10.6140	2.6045e+06	
			Without lens	-48.8072	10.0081	6.5113e+05	
	10		Clear	With lens	-10.4926	13.8448	1.9061e+10
				Without lens	-16.5132	13.2427	4.7654e+09
		Haze	With lens	-16.2939	13.2646	4.7704e+09	
			Without lens	-22.3145	12.6625	1.1926e+09	
Thin Fog		With lens	-18.6418	13.0298	2.6968e+09		
		Without lens	-24.6624	12.4278	6.7420e+08		
Light Fog		With lens	-23.4493	12.5491	8.5860e+08		
		Without lens	-29.4699	11.9470	2.1465e+08		
Heavy Fog		With lens	-38.3496	11.0586	7.2348e+06		
		Without lens	-44.3702	10.4551	1.8087e+06		

5.6 Result and Summary

Investigation's of free space optical communication system in different weather condition by using a Fresnel lens technique offers high quality results and performance which has been shown in all simulation figures. Following Tables from 5.12 to 5.14 shows improvement in various parameters in heavy fog condition, as heavy fog degrade optical signal severely.

Table 5.12: Improvement in power received and S/N ratio at different link range

Wave-length (nm)	Link Range (meter)	Atmospheric Condition	Lens Technique	Power Received (dBm)	Improvement (%)	S/N Ratio (dB)	Improvement (%)
1550	100	Heavy Fog	With lens	11.83	104	16.33	4
			Without lens	5.81		15.73	
	500	Heavy Fog	With lens	-10.72	36	14.08	5
			Without lens	-16.74		13.48	
	1000	Heavy Fog	With lens	-27.46	18	12.40	5
			Without lens	-33.48		11.80	

Table 5.13: Improvement in power received and S/N ratio at different Transmitter divergence

Wave-length (nm)	Divergence Tx (mrad)	Atmospheric Condition	Lens Technique	Power Received (dBm)	Improvement (%)	S/N Ratio (dB)	Improvement (%)
1550	1	Heavy Fog	With lens	-21.44	22	5.88	25
			Without lens	-27.4		4.70	
	1.5	Heavy Fog	With lens	-24.97	19	5.20	30
			Without lens	-30.99		4.01	
	3	Heavy Fog	With lens	-30.99	16	4.01	43
			Without lens	-37.01		2.80	

Table 5.14: Improvement in power received and S/N ratio at different receiver diameter

Wave-length (nm)	Diameter Rx (cm)	Atmospheric Condition	Lens Technique	Power Received (dBm)	Improvement (%)	S/N Ratio (dB)	Improvement (%)
1550	4	Heavy Fog	With lens	-41.44	12.6	11.00	5.76
			Without lens	-47.46		10.40	
	6	Heavy Fog	With lens	-31.90	15.8	11.96	5.28
			Without lens	-37.92		11.36	
	10	Heavy Fog	With lens	-27.46	17.9	12.40	5.08
			Without lens	-33.48		11.80	

From the results shown in figure 5.4, figure 5.5 and figure 5.6, the data rate of more than 10 Gbits/s is delivered for diverse parameters in different atmospheric conditions at 1550 nm. The data rate goes down with a rising transmitter divergence angle and range, while it increases with an increase in diameter of the receiver for the environment circumstances under study. It has been seen that results in all weather conditions are improved by using lens technique. The received signal power in different weather condition like heavy fog, light fog, thin fog, haze and clear has been shown for receiver aperture diameter, transmitter divergence angle, and link range at 1550 nm in figure 5.7, figure 5.8 and figure 5.9

It can be inferred that received signal power increases with increasing receiver diameter and decreases on increasing divergence angle of transmitter along with range for the condition under work. It has been shown that results in all weather condition are improved by using lens technique.

The simulation results are revealed in figure 5.10, figure 5.11 and figure 5.12 to observe the signal to noise characteristics in different atmospheric conditions. When the diameter of receiver increases, then signal to noise ratio increases for the system under consideration. Results indicate that heavy fog attenuates more optical signal than the other weather conditions.

5.7 Conclusion

This research is focused on the atmospheric effect on optical beam in free space optical communication. This analysis is based on data rate, received signal and signal to noise ratio in heavy fog, thin fog, light fog, haze and clear condition. Effect of link range, transmitter divergence angle and receiver aperture diameter on the signal to noise ratio, data rate and received signal has been shown in the simulation results. Simulation results shows that received signal, data rate and signal to noise ratio decreases with transmitter divergence angle, link range and these parameters increases with receiver aperture diameter. Fog has severe effect on the optical link as it attenuates more optical signal, this can be seen in the tables 5.3 to 5.5. By the introduction of Fresnel lens technique, non coherent light source like LED are also utilized instead of LASER in optical wireless communication. For present technique, the result of free space optical communication has been improved and data rate of approximately 10 Gb/s has been achieved.

Now a day, demand of FSO deployment increases for civil applications, but the provision of long range FSO links covering several kilometers with 99.999% availability in all weather condition especially in fog remains a difficult task.

Chapter 6

Conclusion and Future Work

This chapter gives a summary of the results which has been done so far. The objective and aim of the research, outlined in chapter 1, are reviewed and their achievement addressed. Also, in this chapter the scope for further research is given.

6.1 Conclusions

FSO technology can be quickly deployed to produce immediate service to the customers at a low initial investment, without any licensing hurdle under high speed, high information transfer communication. Although FSO is not popular in India at the instant, FSO features a tremendous scope for preparation firms like CISCO, lightweight POINTE etc. Few alternatives have created vast investment to push this technology within the market. It's solely a matter of time before the customers realized the advantages of FSO and therefore the technology deployed in massive scale.

Optical wireless communication systems are among the foremost secure networking transmission technologies. This technology provides higher information measure solutions to fulfill the requirements of companies and people. Optical wireless systems provide an optical connectivity in free space at a price effective, quick with high reliability in bound circumstances. With its low price installation and support large bandwidth, optical wireless operates very close to infrared wavelength and used as an alternate communication technology to connect high capability network. Free space optical communication has tough intercept capability. Following are some technical benefits

- Simplicity of deployment.
- License free communication.
- Bit rate high.
- Bit error rates are low.
- Protection by electromagnetic interference.
- Full duplex operation.
- Protocol transparency.

- High security.

To achieve the research aim, a set of objectives was designed as stated below, all of which are completed as a part of the research and the results obtained are summarized.

- To investigate the potential of FSO, as a mean of combating atmospheric turbulence induced scintillation (fading) phenomenon which significantly deteriorate the performance of FSO system.

Firstly, the optical link has been composed by utilizing free space from which optical fibre cable is displaced by beam of laser. Personal computer generates GBIC Ethernet signal that has changed by LVPECL signal for interfacing with the transmitter and vice-versa on the other end at the receiver section. A text message from a PC has been sent and received effectively at the receiver side.

This analysis is based on data rate, received signal and signal to noise ratio in heavy fog, thin fog, light fog, haze and clear atmospheric conditions. Effect of receiver aperture diameter, transmitter divergence angle and link range on the S/N ratio, rate of data and received signal has been shown in the simulation results. Simulation results shows that S/N ratio, rate of data and received signal decreases with link range, transmitter divergence angle and these parameters increases with receiver aperture diameter. Fog has severe effect on the optical link as it attenuates more optical signal. By the introduction of Fresnel lens technique, non coherent light source like LED are also utilized instead of LASER in free space optical communication. For this technique, the performance of optical wireless has been improved and data rate of approximately 10 Gb/s has been achieved.

It is additionally inferred that for optical wireless connections in the environment, fog is the most constraining element as contrasted and the misfortunes acquired by rainfall and snowfall. This data can demonstrate exceptionally helpful when specific fade margin required that can significantly affect the optical wireless connections accessibility. FSO technology is given a possibility to encounter a developing innovation that holds extraordinary guarantee in future.

- To Study the performance and the applicability of FSO & hybrid RF/FSO scheme to combat atmospheric turbulence in FSO system.

Hybrid FSO/RF based communication additionally been used to enhance a high-data transfer capacity linkages between the two points or multi-points.

FSO communication range has usually inadequate because of heavy fog, so the system availability decreases with distance. Then an option has to employ an RF technology as backup beside with FSO technology. But the execution of FSO has limited capability due to atmospheric instability, for example, substantial fog. The execution of RF technology has debarred mainly because of rain, as rain drops size measurements similar to the wavelength of RF. Consequently, RF and FSO systems supplement each other. So range and accessibility of the hybrid FSO/RF technology could enhance altogether.

The method for executing a FSO/RF frame has to utilize the redundant link controller (RLC). The RLC serves two possibilities. To begin with, it gives the FSO/RF framework with all the time connectivity. This implies that when circumstance are such that one technology starts to come up short and alternate technology starts to assume control, not a solitary piece is lost, regardless of the possibility that how quickly technology exchange as a result of changing climate conditions.

Simulation model has been developed in Matlab for performance analysis of optical wireless system. Random data series has been generated from Bernoulli generator for a particular user, then data is encoded using Hadamard code for single user, and then the encoded data has passed through free space channel with AWGN. Generated binary data has been transmitted at the rate of 5000 samples per second. Then data has been received at receiver where it is decoded and user data has been retrieved. The analysis of BER by using Gaussian channel has been considered. The performance of AWGN channel has been best as it has BER lower as compared to other channels.

Then BER has been evaluated by this model that comes less than 10^{-3} , which has considered being excellent. From the simulation results, the received power has been reduced to approximately half compared to transmitted power.

- To estimate atmospheric-fading loss by threshold approach taking into account lognormal statistics of the power received of on-off keying modulated link.

To fulfill this objective, an improved expression of scintillation loss has been evaluated using threshold power approach. This expression takes into account the loss due to scintillation when Gaussian wave propagates through atmospheric turbulence. Results show that probability of fading and losses due to scintillation are considerably lower when threshold power level is set low. This approach is based on the theory that due to fading and within a certain time interval, the received optical signal power or its intensity drops below the receiver sensitivity (threshold

level). The threshold approach reduces the complication in analysis of fading as it does not require a complete and in depth investigation of a particular receiver performance.

Results show that losses due to scintillation and probability of fading are considerably low when threshold power level is low. The scintillation loss without difficulty exceeds 18 dB for minimum threshold power when power scintillation index is less than one, as compared to other threshold levels. When some portion of total data loss is considered then by threshold method, the losses due to scintillation can be evaluated according to newly evaluated equation. This approach is not restricted to Gaussian waves, spherical or plane waves but can be implemented to other beams whenever power scintillation index is known.

- To study the influence of scintillation caused by turbulence by using Rytov scintillation theory.

The effect of scintillation for Gaussian wave can be minimized by aperture averaging technique, so here we show the effect of aperture averaging on Gaussian beam wave for different turbulence strength of atmosphere.

Here we considered the three regime of turbulence for Gaussian beam wave and results show the effect of aperture averaging bound by different propagation scenarios. At the receiver side, the aperture averaging effect depends on receiving aperture diameter as averaging ability of the receiving system increases by increasing receiving aperture radius and depends on different propagation conditions defined by structure parameter C_n^2 . Results show that aperture averaging effect becomes lower for higher atmospheric turbulence strength.

6.2 Future Scope

Specific topics for further work have been identified throughout the thesis. The flexibility and variety in FSO approaches has a capability to play significant role in near future.

Following are the range constraining elements, cause a weakened received signal and prompt higher of error in number of bit received known as bit error rate (BER)

- Fog.
- Atmospheric absorption.
- Beam dispersion.
- Snow.
- Rain.
- Scintillation.

- Shadowing.
- Wind.
- Pollution, Dust and Smog.

To overcome these kinds of issues, exploration ought to concentrate on multi-beam or multi-way models, which utilize more than one sender and more than one collector. Some cutting edge devices in FSO additionally have bigger fade margin. Atmospheric attenuation, which is exponential in nature, limit down the range of FSO devices to a few kilometres. FSO empowers high rate of transmission of audio, video and other information through free space.

Later on it is conjecture that this innovation will be executed in copiers, fax machines, overhead projectors, bank ATMs, MasterCard's, amusement consoles and head sets.

Some other future scopes are

- FSO ought to have multi-beam sending process. It overcomes atmospheric attenuation and interim beam deterrents by covering excess infrared beams.
- Wireless communication can be made possible in any weather by combining FSO with 60 GHz millimeter-wave.
- FSO items ought to have advanced beam-controlling components.
- **Improvement by Using Amplifiers and Optical Interconnects:** Opto-electronic components when consolidated with FSO have high transfer speed, low power distribution. Optoelectronic components are electrical to optical and optical to electrical components that source, recognize and control light. Interconnects like vertical depression surface emanating lasers (VCSELs) empower fast FSO. VCSEL reforms optical fiber communication by enhancing productivity and expanding data speed. Laser drivers, beneficiaries (speakers), and switch circuits are incorporated on silicon chips and are incorporated into the frameworks. Information can be sustained to electrically to any of the silicon chips and directed to the VCSELs through driver circuits and can be readout electrically from every silicon chip freely. It emits a very fine beam which makes beam to transfer light easily into the fiber cable. Today's FSO system work in the close wavelength range between approximately 750 nm to 1600 nm. Typically we utilize 1550nm on account of its diverse components, for example, it is perfect for long ranges and gives us high information rates.
- **Highly developed DWDM FSO structure:** Dense Wave Division Multiplexing is one of the alluring applications in FSO. In this development, different wave beam signals can be

transmitted utilizing DWDM. By utilizing DWDM, we can get a decent transmission over single channel. This multiplexing technique sends the information from different transmitters into a common channel. In this multiplexing, at the most 96 different wavelength light signals or channels can be multiplexed and transmitted. It is a system for expanding the data transfer capacity of an optical system correspondence. The transfer speed is cut up into wavelength channels, each of which conveys an information stream exclusively. There are distinctive models utilized for executing this procedure.

- FSO/MMW should be used in mobile wireless network to solve/ease the “Mobile Wireless Backhaul Dilemma”. MMW and FSO transmission systems offer a viable alternate backhaul solution for short/medium distance by rapidly increasing density of mobile wireless base stations, shorter distances between base stations and constantly increasing demand for backhaul capacity. For this FSO and MMW radio solutions are well positioned to become part of a next generation 4G/5G mobile wireless backhaul strategy.

References

- [1]. <http://www.eee.strath.ac.uk/ug-info/19984/comohl.pdf>.
- [2]. http://www.ball Aerospace.com/lasercomm_history_1950.html.
- [3]. D.T Emerson, "The work of Jagadis Chandra Bose: 100 years of mm-wave research," *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 12, 1997.
- [4]. S. Ye and R. S. Blum, "Optimized signalling for MIMO interference systems with feedback," *International Microwave Symposium Digest, IEEE MTT-S*, vol. 2, pp. 553–556, 1997.
- [5]. M.H. Engineer, "The Millimeter Wave Researches of JC Bose," *Remembering Sir JC Bose*, pp.63, 2009.
- [6]. J.C. Bose, "Collected Physical Papers," New York: Longmans, Green and Co., 1927.
- [7]. Bondyopadhyay and K. Probir, "Sir JC Bose's diode detector received Marconi's first transatlantic wireless signal of December 1901 (The "Italian Navy Coherer" Scandal Revisited)," *IETE Technical Review*, vol. 15, no. 5, pp. 377-406, 1998.
- [8]. H. Singh, A.M. Dixit, A. Mustapha, and G.R. Gerhart, G.R., "Fuzzy system reliability computation of the convoy of unmanned intelligent vehicles," in *SPIE Europe Security and Defence*, pp. 71120Z-71120Z, 2008.
- [9]. A.K. Majumdar and J.C. Ricklin, "Effects of the atmospheric channel on Free space laser Communications," *Proc. SPIE, Free-Space Laser Communication V*, vol. 5892, pp. 58920K-58920K, Aug. 2005.
- [10]. J. Singh and V.K Jain, "Performance analysis of BPPM and M-ary PPM optical communication systems in atmospheric turbulence," *IETE Technical review*, vol. 25, no. 4, pp. 146-153, 2008.
- [11]. A.K. Majumdar, C.E. Luna, and P.S. Idell, "Reconstruction of Probability Density Function of Intensity Fluctuations Relevant to Free-Space Laser Communication through Atmospheric Turbulence," *Proc. SPIE, Free Space Laser Communications VI*, vol. 6304, pp. 67090M-67090M, Sep. 2007.

- [12]. S. Qamar, and M. Lai, "Effect of Interference and Control Error on Cellular Mobile Communication Networks," *Annual Review of Communications* vol. 59, pp. 179, 2007.
- [13]. D. Kedar and S. Arnon, "Urban optical wireless communication networks: the main challenges and possible solutions," *IEEE Communications Magazine*, vol. 42, no. 5, pp. S2–S7, May 2004.
- [14]. L. C. Andrews, R. L. Phillips and C. Y. Hopen, "Laser Beam Scintillation with Applications," *SPIE Press*, Washington, 2001.
- [15]. C. Singh, J. John, Y.N. Singh, and K.K. Tripathi, "Indoor optical wireless systems: Design challenges, mitigating techniques and future prospects," *IETE Technical Review*, vol. 21, no. 2, pp. 101-117, 2004.
- [16]. H. Henniger and O. Wilfert, "An introduction to free-space optical communications," *Radioengineering*, vol. 19, no. 2, pp. 203-212, 2010.
- [17]. F. Liu, U. Vishkin, and S. Milner, "Bootstrapping free-space optical networks," *IEEE J. Sel. Areas Communications*, vol. 24, no. 12, pp. 13–22, Dec. 2006.
- [18]. I. K. Son, "Design and Optimization of Free Space Optical Networks," PhD Dissertation, Auburn University, Alabama, 2010.
- [19]. W. O. Popoola, "Subcarrier intensity modulated Free Space Optical Communication Systems," PhD dissertation, University of Northumbria, Newcastle, 2009.
- [20]. F. Nadeem, and E. Leitgeb, "Dense maritime fog attenuation prediction from measured visibility data," *Radioengineering*, vol. 19, no. 2, pp. 223-227, 2010.
- [21]. S. Vangala and H. Pishro-Nik, "Optimal hybrid rf-wireless optical communication for maximum efficiency and reliability," in *Proc. 41st Annual Conference on Information Sciences and Systems (CISS)*, Baltimore, pp. 684–689, Mar. 2007.
- [22]. D. Killinger, "Free space optics for laser communication through the air," *Optics & Photonics News*, vol. 13, No. 10, pp. 36-42, Oct. 2002.
- [23]. Acampora, Anthony, "Last mile by laser," *Scientific American*, vol. 287, no. 1 pp. 7-32, 2002.
- [24]. P. Gupta and P.R. Kumar, "The Capacity of Wireless Networks," *Information Theory, IEEE Transactions*, vol. 46, no. 2, pp. 388-404, 2000.
- [25]. R.K. Crane, "Electromagnetic Wave Propagation through Rain," *Wiley-Interscience*, New York, 1996.

- [26]. I.I. Smolyaninov, L. Wasiczko, K. Cho, C.C. Davis, "Long-distance 1.2 Gb/s optical wireless communication link at 1550 nm," *International Symposium on Optical Science and Technology, International Society for Optics and Photonics*, pp. 241-250, 2002.
- [27]. E. J. Lee and V. W. Chan, "Part 1: optical communication over the clear turbulent Atmospheric channel using diversity," *IEEE Journal on Selected Areas in Communications*, vol. 22, no. 9, pp. 1896–1906, Nov. 2004.
- [28]. B. Epple and H. Henniger, "Discussion on design aspects for free-space optical communication terminals," *IEEE Communications Magazine*, vol. 45, no. 10, pp. 62–69, Oct. 2007.
- [29]. X. Zhu and J.M. Kahn, "Free space optical communication through atmospheric turbulence channels," *IEEE Trans. Commun.*, vol. 50, no. 8, pp. 1293-1300, Aug. 2002.
- [30]. S. M. Navidpour, M. Uysal, and Mohsen Kavehrad, "BER performance of free-space optical transmission with spatial diversity," *Wireless Communications, IEEE Transactions*, vol. 6, no. 8, pp. 2813-2819, Aug. 2007.
- [31]. H. Izadpanah, T. Elbatt, V. Kukshya, F. Dolezal, and B. K. Ryu, "High-availability free space optical and rf hybrid wireless networks," *IEEE Wireless Communications*, vol. 10, no. 2, pp. 45–53, Apr. 2003.
- [32]. T.A Tsiftsis, H.G Sandalidis, G.K Karagiannidis and M. Uysal, "Optical wireless links with spatial diversity over strong atmospheric turbulence channels," *Wireless Communications, IEEE Transactions*, vol. 8, no. 2, pp.951-957, 2009.
- [33]. A.A. Hussein, A. Oka, T. T. Nguyen and Lutz Lampe, "Rateless Coding for Hybrid Free-Space Optical and Radio-Frequency Communication," *IEEE Transactions on Wireless Communications*, vol. 9, no. 3, pp. 907-913, March 2010.
- [34]. X. Zhu and J.M. Kahn, "Performance bounds for coded free-space optical communications through atmospheric turbulence channels," *Communications, IEEE Transactions*, vol. 51, no. 8 pp. 1233-1239, Aug. 2003.
- [35]. G. Baister and P. Gatenby, "Pointing, acquisition and tracking for optical space communications," *Electronics and Communication Engineering Journal*, vol. 6, no. 6, pp. 271–280, Dec. 1994.

- [36]. I. I. Kim, R. Ruigrok, and C. DeCusatis, "Wireless optical transmission of fast ethernet, FDDI, ATM, and ESCON protocol data using the TerraLink laser communication system," *Optical Engineering*, vol. 37, no. 12, pp. 3143-55, Dec. 1998.
- [37]. A. Belmonte and J. M. Kahn, "Performance of synchronous optical receivers using atmospheric compensation techniques," *Optics Express*, vol. 16, no. 18, pp. 14151-14162, Sep. 2008.
- [38]. A. Belmonte, and J.M. Kahn, "Field Conjugation Adaptive Arrays in Free-Space Coherent Laser Communications," *Journal of Optical Communications and Networking*, vol. 3, no. 11, pp. 830-838, Nov. 2011.
- [39]. E. Wainright, H.H. Refai and J.J. Sluss Jr "Wavelength diversity in free-space optics to alleviate fog effects," *Lasers and Applications in Science and Engineering, SPIE proceedings*, vol. 5712, pp. 110-118, Apr. 2005.
- [40]. E. Korevaar, Isaac I. Kim and B. McArthur, "Atmospheric propagation characteristics of highest importance to commercial free space optics," *High-Power Lasers and Applications, International Society for Optics and Photonics*, pp. 1-12, Apr. 2003.
- [41]. M. Grabner, and V. Kvicera, "Experimental Study of Atmospheric Visibility and Optical Wave Attenuation for Free Space Optics Communication," Testcom, Prague, Czech Republic, Czech Science Foundation project No. 102/08/0851, 2009.
- [42]. V. Sharma and G. Kaur, "Degradation Measures in Free Space Optical Communication and its Mitigation Techniques-a review," *International Journal of Computer Applications*, vol. 55, no. 1, Oct. 2012.
- [43]. R. N. Mahalati and J.M. Kahn, "Effect of fog on free-space optical links employing imaging receivers" *Optics Express*, vol. 20, no. 2, pp. 1649-1661, Jan. 2012.
- [44]. V. Chan, Free Space Optical Networks, www/Vincent_project.html, Jul 2011 [Apr 2013]
- [45]. Z. Hajjarian, M. Kavehrad and J. Fadlullah, "Analysis of Wireless Optical Communications Feasibility in Presence of Clouds Using Markov Chains," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 9, pp. 1526-1534, Dec. 2009.
- [46]. G. D. Fletcher, T. R. Hicks, and B. Laurent, "The SILEX optical interorbit link experiment," *IEEE J. Elec. & Comm. Engg.*, vol. 3, no. 6, pp. 273-279, 2002.

- [47]. K. E. Wilson, "An overview of the GOLD experiment between the ETS-VI satellite and the table mountain facility," TDA Progress Report 42-124, Comm. Sys. and Research Sec., pp. 9-19, 1996.
- [48]. T. Dreischer, M. Tuechler, T. Weigel, G. Baister, P. Regnier, X. Sembely, and R. Panzeca, "Integrated RF-optical TT & C for a deep space mission," *Acta Astronautica*, vol. 65, no. 11, pp. 1772–1782, 2009.
- [49]. Z. Sodnik, H. Lutz, B. Furch, and R. Meyer, "Optical satellite communications in Europe," *Proc. SPIE, Free Space Laser Comm. Tech. XXII*, vol. 7587, 2010.
- [50]. G. G. Ortiz, S. Lee, S. P. Monacos, M. W. Wright, and A. Biswas, "Design and development of a robust ATP subsystem for the altair UAV-to-ground lasercomm 2.5-Gbps demonstration," *Proc. SPIE, Free Space Laser Comm. Tech. XV*, vol. 4975, 2003.
- [51]. E. Oh, J. Ricklin, F. Eaton, C. Gilbreath, S. Doss-Hammel, C. Moore, J. Murphy, Y. Han Oh, and M. Stell, "Estimating atmospheric turbulence using the PAMELA model," *Proc SPIE, Free Space Laser Comm. IV*, vol. 5550, pp. 256–266, 2004.
- [52]. S. Doss-Hammel, E. Oh, J. Ricklin, F. Eaton, C. Gilbreath, and D. Tsintikidis, "A comparison of optical turbulence models," *Proc. SPIE, Free Space Laser Comm. IV*, vol. 5550, pp. 236–246, 2004.
- [53]. S. Karp, R. M. Gagliardi, S. E. Moran, and L. B. Stotts, "Optical Channels: Fibers, Clouds, Water, and the Atmosphere." Plenum Press, New York and London, 1988.
- [54]. A. S. Gurvich, A. I. Kon, V. L. Mironov, and S. S. Khmelevtsov, "Laser radiation in turbulent atmosphere," Nauka Press, *Moscow*, 1976.
- [55]. M. R. Chatterjee and F. H. A. Mohamed, "Modeling of power spectral density of modified von Karman atmospheric phase turbulence and acousto-optic chaos using scattered intensity profiles over discrete time intervals," *Proc. SPIE, Laser Comm. and Prop. through the Atmosp. and Oce. III*, vol. 9224, 2014.
- [56]. A. Majumdar and J. Ricklin, "Free-Space Laser Communications: Principles and Advances," Springer, vol. 2, 2008.
- [57]. H. Hemmati, ed., "Near-Earth Laser Communications," CRC Press, 2009.
- [58]. L. Yang, J. Cheng, and J. F. Holzman, "Performance of convolutional coded OOK IM/DD system over strong turbulence channels," in *Int. Conf. on Compu. Netw. and Comm.*, 2013.

- [59]. G. Z. Antonio, C. V. Carmen, and C. V. Beatriz, "Space-time trellis coding with transmit laser selection for FSO links over strong atmospheric turbulence channels," *Opt. Exp.*, vol. 18, no. 6, pp. 5356–5366, 2010.
- [60]. T. T. Nguyen and L. Lampe, "Coded multipulse pulse-position modulation for free-space optical communications," *IEEE Trans. Comm.*, vol. 20, no. 20, pp. 1–6, 2009.
- [61]. I. B. Djordjevic, B. Vasic, and M. A. Neifeld, "LDPC coded OFDM over the atmospheric turbulence channel," *Opt. Exp.*, vol. 15, no. 10, pp. 6332–6346, 2007.
- [62]. F. Xu, M. A. Khalighi, and S. Bourennane, "Coded PPM and multipulse PPM and iterative detection for free-space optical links," *J. Opt. Comm. and Net.*, vol. 1, no. 5, pp. 404–415, 2009.
- [63]. E. Ali, V. Sharma, and P. Hossein, "Hybrid channel codes for efficient FSO/RF communication systems," *IEEE. Trans. Comm.*, vol. 58, no. 10, pp. 2926–2938, 2010.
- [64]. K. Prasad and R. Patel, "Performance analysis of Ethernet based on an event driven simulation algorithm," in *IEEE Proceedings of the 13th Conference on Local Computer Networks*, pp. 253-267, 1988.
- [65]. F. C. Jain, "Laser diode assembly with tunnel junctions and providing multiple beams." U.S. Patent No. 5,212,706, 1993.
- [66]. M.E. Testorf, and M.A Fiddy, "Simulation of light propagation in planar-integrated free-space optics," *Optics Communications*, vol. 176, no. 4, pp. 365-372, 2000.
- [67]. B. Ramamurthy, K.K. Ramakrishnan, and R.K. Sinha, "Cost and reliability considerations in designing the next-generation IP over WDM backbone networks," in *IEEE Proceedings of 20th International Conference on Computer Communications and Networks (ICCCN)*, pp. 1-6, 2011.
- [68]. V. Kumar, A.K. Sharma, and R.A. Agarwala, "Nonlinear cross-talk in dispersive PCM optical communication systems," *IETE journal of research*, vol. 51, no. 2, pp. 101-105, 2005.
- [69]. Z. Bielecki, B. Kolosowski, J. Mikolajczyk, "Free Space Optical Data Link using quantum cascade laser," *PIERS Conference*, pp. 108-111, Jul. 2008.
- [70]. Keith Wilson, "Optical Communications for Deep Space Missions" *IEEE communications magazines*, vol. 38, no. 8, pp. 134-139, Aug. 2000.

- [71]. M. Pauer, P.J Winzer, and W.R Leeb, "Bit error probability reduction in direct detection optical receivers using RZ coding," *Journal of Light-wave Technology*, vol. 19, no. 9, pp. 1255 – 1262, 2001.
- [72]. Weichel, "Laser beam propagation in the atmosphere," SPIE Press, vol. 3, pp. 25-39, 1990.
- [73]. A. Upadhyay and R.B. Pachori, "Instantaneous voiced/non-voiced detection in speech signals based on variational mode decomposition," *Journal of the Franklin Institute*, vol. 352, no. 7, pp. 2679-2707, 2015.
- [74]. Steve Hranilovic, "Wireless optical communication systems," Springer Science & Business Media, 2006.
- [75]. S. Kumar, and J.S. Yadav, "Moving Object Segmentation in Dynamic Environment by Reducing Impulsive Noise from Background Model," *International Journal of Computer Applications*, vol. 118, no. 22, 2015.
- [76]. D. Borah, A. Boucouvalas, C. Davis, S. Hranilovic, and K. Yiannopoulos, "A review of communication-oriented optical wireless systems," *EURASIP Journal on Wireless Communications and Networking*, vol. 2012, no. 1, pp. 1-28, 2012.
- [77]. I. I. Kim and E. Korevaar, "Availability of free space optics (FSO) and hybrid FSO/RF systems," *ITCom 2001: International Symposium on the Convergence of IT and Communications. International Society for Optics and Photonics*, pp. 84-95, Nov. 2001.
- [78]. L. B. Stotts, L. C. Andrews, P. C. Cherry, J. J. Foshee, P. J. Kolodzy and W. K. McIntire, "Hybrid optical RF airborne communications," *Proc. IEEE*, vol. 97, No. 6, pp. 1109-1127, 2009.
- [79]. H. Moradi, M. Falahpour, H. H. Reafi, P. G. LoPresti, and M. Atiquzzaman, "Availability modeling of FSO/RF mesh networks through turbulence-induced fading channels," in *Proc. IEEE Conference on Computer Communications Workshops (INFOCOM 2010)*, pp. 1-5, 2010.
- [80]. H. Moradi, M. Falahpour, H. H. Refai, P. G. LoPresti, and M. Atiquzzaman, "On the capacity of hybrid FSO/RF links," *Global Telecommunications Conference (GLOBECOM 2010), Proc. IEEE International Conference*, pp. 1-5, 2010.
- [81]. R. Luna, D. K. Borah, R. Jonnalagadda, and D. G. Voelz, "Experimental demonstration of a hybrid link for mitigating atmospheric turbulence effects in free space optical

- communication," *IEEE Photonics Technology Letters*, vol. 21, no. 17 pp. 1196-1198, 2009.
- [82]. R.M. Goody and Y.L. Yung, "Atmospheric Radiation: Theoretical Basis," Oxford University Press, 2nd edition, 1989.
- [83]. M.E. Thomas and D.D. Duncan, "Atmospheric transmission. Atmospheric propagation of radiation handbook," SPIE Press, vol. 2, 1993.
- [84]. A.S. Jursa, "Handbook of Geophysics and the Space Environment," Air Force Geophysics Laboratory, Air Force Systems Command, United States Air Force, 1985.
- [85]. G.P. Anderson et.al, "FASCODE/MODTRAN/LOWTRAN: Past/Present/Future," *18th Annual Review Conference on Atmospheric Transmission Models, Hanscom Air Force Base MA*, pp. 6-8, June 1995.
- [86]. ONTAR Corporation (<http://www.ontar.com/>).
- [87]. X. Liu, "Free-space optics optimization models for building sway and atmospheric interference using variable wavelength," *Communications, IEEE Transactions.*, vol. 57, no. 2, pp. 492- 498, Feb. 2009.
- [88]. W. Kogler, P. Schrotter, U. Birnbacher, E. Leitgeb, O. Koudelka, "Hybrid Wireless Networks—High Availability with combined Optical/Microwave links," *Proceedings of the Conference of Telecommunications and Mobile Computing (TCMC03), Graz*, April 2002.
- [89]. A. Salim, S.S Carroll and J. Atai, "Limits of intrusion detection system in a gigabit optical link," *Optical Engineering*, vol. 49, No. 4, pp. 045005-1-045005-4, April 2010.
- [90]. 'SFF-8053 Specification for GBIC (Gigabit Interface Converter) revision 5.5'. , Small Form Factor Committee, This is an internal working document of the SFF Committee, an industry ad hoc group, September 27, 2000.Retrieved June 21, 2011.
- [91]. G. Clark, H. Willebrand, and M. Achour, "Hybrid Free Space Optical / Microwave Communication Networks: A Unique Solution For Ultra High-Speed Local Loop Connectivity," *Information Technologies 2000, International Society for Optics and Photonics*, pp. 46-54, 2001.
- [92]. S.G. Narasimhan, and S.K Nayar, "Vision and the Atmosphere," *International Journal of Computer Vision*, vol. 48, no. 3, pp. 233-254, 2002.
- [93]. H.A. Willebrand and B.S Ghuman, "Fiber Optic without Fiber," *Light Pointe Communications*, 2001.

- [94]. O. Bouchet, H. Sizun, C. Boisrobert and F.D. Fornel, "Free-space optics: propagation and communication," John Wiley & Sons, Vol. 91, 2010.
- [95]. R.S. Kaler, and S. Singh, "Placement of optimized semiconductor optical amplifier in fiber optical communication system," *Elsevier Science, Optik-International Journal for light and Electron Optics*, vol.119, no. 6, pp. 296-302, May 2008.
- [96]. V.D. Hulst, "Light scattering by small particles," Courier Corporation, 1957.
- [97]. I. I. Kim, B. McArthur, and E. Korevaar, "Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications," *Proc. SPIE*, vol. 4214, pp. 26- 37, 2001.
- [98]. D. Atlas, "Shorter Contribution Optical Extinction by Rainfall," *Journal of Meteorology*, vol. 10, no. 6, pp. 486-488, 1953.
- [99]. S.S. Muhammad, P. Kohldorfer, and E. Leitgeb, "Channel Modeling for Terrestrial Free Space Optical Links," *Transparent Optical Networks, Proceedings of IEEE 2005 7th International Conference*, vol. 1, pp. 407-410, 2005.
- [100]. J.B. Mason, "Light Attenuation in Falling Snow," ASLUR Lab-0013, Aug. 1978.
- [101]. O'Brien and W. Harold, "Visibility and Light Attenuation in Falling Snow," *Journal of Applied Meteorology*, vol. 9, no. 6, pp. 671-683, 1970.
- [102]. S. Bloom, "The Last mile Solution: hybrid FSO radio," Air fiber Whitepaper, May 2002.
- [103]. H. Schuster, H. Willebrand, S. Bloom, and E. Korevaar, "Understanding the performance of Free Space Optics," *Journal of Optical Networking*, vol. 2, no. 6, pp.176-200, 2003.
- [104]. F. Giannetti, M. Luise, and R. Reggiannini, "Mobile and personal communications in the 60 GHz band: a survey," *Wireless Personal Communications*, vol. 10, no. 2, pp.207-243, Jul. 1999.
- [105]. R. C. Daniels and R. W. Heath, "60 GHz wireless communications: emerging requirements and design recommendations," *Vehicular Technology Magazine, IEEE*, vol. 2, no. 3, pp. 41-50, Sep. 2007.
- [106]. R. C. Daniels, J. N. Murdock, T. S. Rappaport, and R. W. Heath, "60 GHz wireless: up close and personal," *Microwave Magazine, IEEE*, vol. 11, no. 7, pp. 44-50, Dec. 2010.

- [107]. N. Guo, R. C. Qiu, S. S. Mo, and K. Takahashi, "60-GHz millimeter-wave radio: principle, technology, and new results," *EURASIP Journal on Wireless Communications and Networking*, vol. 2007, no. 1, pp. 68253(1)-68253(8), Dec. 2006.
- [108]. B. He and R. Schober, "Bit-interleaved coded modulation for hybrid RF/FSO systems," *Communications, IEEE Transactions*, vol. 57, no. 12, pp. 3753-3763, Dec. 2009.
- [109]. L. C. Andrews, R. L. Philips, *Laser Beam Propagation through Random Media*, 2nd Edition, SPIE Press, Bellingham, 2005.
- [110]. A. K. Majumder and J. C. Ricklin, "Free-space laser communications", Springer Publication, New York, 2008.
- [111]. http://www.lightpointe.com/downloads/datasheets/Airebeam_G60.pdf.
- [112]. J. Schothier, "WP3-study: the 60 GHz channel and its modeling," Tech.Report IST-2001- Broadway, May 2003.
- [113]. Bobby Barua, "Comparison the performance of free space optical communication with OOK and BPSK modulation under atmospheric turbulence", *International Journal of Engineering Science and Technology*, vol. 3, no. 5, pp. 4391-4399, May 2011.
- [114]. V. Jyoti and R. S. Kaler. "Design and implementation of 2-dimensional wavelength/time codes for OCDMA," *Optik-International Journal for Light and Electron Optics*, vol. 122, no. 10 pp. 851-857, 2011.
- [115]. A. Ahmed and S. Hranilovic, "Outage Capacity Optimization for Free-Space Optical Links with Pointing Errors," *IEEE Journal of light wave technology*, vol. 25, no. 7, July 2007.
- [116]. Aleksander Milev and Chavdar Minchev "A Simulation Model of an Optical Communication CDMA System," *International Conference on Computer Systems and Technologies Compo Sys. Tech.*, 2007.
- [117]. J. Malhotra, A. Sharma and R.S Kaler, "On the Performance Analysis of Wireless Receiver using Generalized-Gamma Fading Model," *Springer's signals and communication Journal, annals of telecommunications - annales des telecommunications*, vol. 64, no. 1-2, pp. 147-153, Feb. 2009.
- [118]. D. T. Wayne, R. L. Philips and L. C. Andrews, "Comparing the log-normal and gamma-gamma model to experimental probability density functions of aperture averaging data,"

- Proceedings of the 10th conference on Free-Space Laser Communications, SPIE*, p.p 78140K-78140K, 2010.
- [119]. V. A. Banakh and V. L. Mironov, "Lidar in a Turbulent Atmosphere," Artech House, Boston, 1987.
- [120]. J. L. Bufton, "Scintillation statistics measured in an earth-space-earth retroreflector link," *Applied optics*, vol. 16, no. 10, pp. 2654-2660, 1977.
- [121]. J. L. Bufton and R.S. Iyer, "Scintillation statistics caused by atmospheric turbulence and speckle in satellite laser ranging," *Applied optics*, vol. 16, no. 9, pp. 2408-2413, 1977.
- [122]. J. W. Goodman, "Statistical Optics," Wiley Publication, New York, 1985.
- [123]. T.W. Lawrence, T.W. Goodman, E.M. Johansson, J.P. Fitch, "Speckle imaging of satellites at the us air force maui optical station," *Applied optics*, vol. 31, no. 29, pp. 6307, 1992.
- [124]. V.I. Tatarskii, "Wave Propagation in a Turbulent Medium," McGraw-Hill Publication, New York, 1961.
- [125]. A. Ishimaru, "Wave Propagation and Scattering in Random Media," IEEE Press, New York, 1997.
- [126]. K.S. Gochelashvili, V.I. Shishov, "Saturated fluctuations in the laser radiation intensity in a turbulent medium, " *Zh. Eksp. Theor. Fiz.* vol. 66, 1974.
- [127]. R.X. Fante, "Inner-scale size effect on the scintillations of light in the turbulent atmosphere," *Journal of Optical Society America*, vol. 73, no. 3, pp. 277-281, 1983.
- [128]. R.G. Frehlich, "Intensity covariance of a point source in a random medium with a Kolmogorov spectrum and an inner scale of turbulence," *J. Opt. Soc. Am.*, vol. 4, no. 2, pp. 360-366, 1987.
- [129]. Z.S. Wu, H.Y. Wei, R.K. Yang and L.X. Guo, "Study on scintillation considering inner- and outer-scales for laser beam propagation on the slant path through the atmospheric turbulence," *Progress In Electromagnetics Research*, vol. 80, pp. 277-293, 2008.
- [130]. J. Li, Y. Chen, S. Xu, Y. Wang, M. Zhou, Q. Zhao, Y. Xin, F. Chen, "Average intensity and spreading of partially coherent four-petal Gaussian beams in turbulent atmosphere," *Progress in Electromagnetic Research B*, vol. 24, pp. 241-262, 2010.

- [131]. F. Wang, Y. Cai, H.T. Eyyuboglu and Y.K. Baykal, "Average intensity and spreading of partially coherent standard and elegant Laguerre-Gaussian beams in turbulent atmosphere," *Progress In Electromagnetic Research*, vol. 103, no. 33-36, 2010.
- [132]. H.T. Eyyuboglu and Y.L. Bayka, "Scintillation characteristics of cosh-Gaussian beams," *Applied Optics*, vol. 46, no. 1099-1106, 2007.
- [133]. H.T. Eyyuboglu, Y. Bayka and Y. Cai, "Scintillation calculations for partially coherent general beams via extended Huygens–Fresnel integral and self-designed Matlab function," *Applied Physics B*, vol. 100, pp. 597-609, 2010.
- [134]. A.N. Kolmogorov, "The local structure of turbulence in an incompressible viscous fluid for very large Reynolds numbers," *C. R. Acad. Sci. V.R.S.S.*, vol. 30, pp. 301-305 1941.
- [135]. A.N. Kolmogorov, "Dissipation of energy in the locally isotropic turbulence," *C. R. Acad. Sci. V.R.S.S.*, vol. 32, pp. 16-18, 1941.
- [136]. A.M. Obukhov, "On the energy distribution in the spectrum of a turbulent flow," *C. R. Acad.Sci. V.R.S.S.*, vol. 32, no. 1, pp. 19-21, 1941.
- [137]. A.M. Yaglom, "Laws of small-scale turbulence in atmosphere and ocean," in commemoration of the 40th anniversary of the theory of locally isotropic turbulence, *IZVESTIYA AKADEMII NAUK SSSR FIZIKA ATMOSFERY I OKEANA*, vol. 17, no. 12, pp. 1235-1257, 1981.
- [138]. A.N. Kolmogorov, "A refinement of previous hypotheses concerning local structure of turbulence in a viscous incompressible fluid at high Reynolds number," *Journal of Fluid Mechanics*, vol. 13, no. 1, pp. 82-85, 1962.
- [139]. L.C. Andrews and R.L. Phillips, "Laser Beam Propagation Through Random Media," SPIE Press, Bellingham, 1998.
- [140]. J.C. Ricklin and F.M. Davidson, "Atmospheric turbulence effects on a partially coherent Gaussian beam: implications for free-space laser communication," *J. Opt. Soc. Am. A*, vol. 19, no. 9, pp. 1794-1803, 2002.
- [141]. J.C. Ricklin and F.M. Davidson, "Atmospheric optical communication with a Gaussian Schell beam," *J. Opt. Soc. Am. A*, vol. 20, no. 5, pp. 856-866, 2003.
- [142]. B.E. Saleh and M.C. Teich, "Fundamentals of Photonics," John Wiley & Sons, New York, 1991.
- [143]. S. Orazeo, "Principle of Lasers," 5th Edition, Springer, 2010.

- [144]. H.T. Eyyuboglu, Y. Baykal, "Average intensity and spreading of cosh-Gaussian laser beams in the turbulent atmosphere," *Applied Optics*, vol. 44, no. 6, pp. 976-983, 2005.
- [145]. E. Karimi, G. Zito, B. Piccirillo, L. Marrucci, and E. Santamoto, "Hypergeometric-gaussian modes," *Optics Letters (OSA)*, vol. 32, No. 21, pp. 3053-3055, 2007.
- [146]. R. Barrios and F. Dios, "Wireless Optical Communications through the Turbulent Atmosphere," *A review, Optical communication system, InTech Europe*, pp. 3-40, Rijeka, Croatia, 2012.
- [147]. J.H. Churnside, "Aperture averaging of optical scintillations in the turbulent atmosphere," *Appl. Opt.*, vol. 30, pp.1982–1994, 1991.
- [148]. L.C. Andrews, M.A. Al-Habash, C.Y. Hopen and R.L. Phillips, "Theory of optical scintillation: Gaussian-beam wave model," *Waves in Random and Complex Media*, vol. 11, no. 3, pp. 271–291, 2001.
- [149]. N. Perlot, D. Giggenbach, H. Henniger, J. Horwath, M. Knapik and K. Zettl, "Measurements of the beam-wave fluctuations over a 142-km atmospheric path," *Proceedings-SPIE The international society for engineering*, vol. 6304, pp. 63041O, 2006.
- [150]. N. Perlot, D. Giggenbach, H. Bischl, F. David, "Discussion of direct detection Rx-power statistics as derived from intensity distributions and comparison with measurements," *Proceedings-SPIE The international society for engineering*, vol. 4976, pp. 107-115, 2003.
- [151]. N. Perlot and D. Fritzsche, "Aperture-averaging: Theory and measurements", *Proceedings-SPIE The international society for engineering*, vol. 5338, pp. 233–242, 2004.
- [152]. L.C. Andrews, "Aperture-averaging factor for optical scintillations of plane and spherical waves in the atmosphere," *Journal of Optical Society America A*, vol. 9, no. 4, pp. 97–600, 1992.
- [153]. N.J. Xiang, and Zhen-sen wu, "Scintillation Index of a Gaussian Schell-Model Beam of slant atmosphere Turbulence", *Progress in Electromagnetics Research M*, vol. 30, pp. 153-165, 2013.
- [154]. V.I. Tatarskii, "The effects of the turbulent atmosphere on wave propagation," Jerusalem: Israel Program for Scientific Translations, 1971.

- [155]. L.C. Andrews, R.L. Phillips and C.Y. Hopen, "Aperture averaging of optical scintillations: power fluctuations and the temporal spectrum," *Waves in Random Media*, vol. 10, no. 1, pp. 53-70, 2000.
- [156]. G.R. Ochs and R.J. Hill, "Optical-scintillation method of measuring turbulence inner scale.," *Applied Optics*, vol. 24, no. 15, pp. 2430-2432, 1985.
- [157]. A.R. Weeks, J. Xu, R.R. Phillips, L.C. Andrews, C.M. Stickley, G. Sellar, J.S. Stryjewsky and J.E. Harvey, "Experimental verification for an eight-element multiple-aperture equal-gain coherent laser receiver for laser communications," *Applied Optics*, vol. 37, no. 21, pp. 4782-4788, 1998.
- [158]. R.K. Tyson, "Adaptive optics and ground-to-space laser communications," *Applied Optics*, vol. 35, no. 19, pp. 3640-3646, 1996.
- [159]. B.M. Levine, E.A. Martinsen, A. Wirth, A. Jankevics, M. Toledo-Quinones, F. Landers and T.L. Bruno, "Horizontal line-of-sight turbulence over near-ground paths and implications for adaptive optics corrections in laser communications," *Applied Optics*, vol. 37, no. 21, pp. 4553-4560, 1998.
- [160]. R.K. Tyson, "Indirect measurement of a laser communications bit-error-rate reduction with low-order adaptive optics," *Applied Optics*, vol. 42, no. 21, pp. 4239-4243, 2003.
- [161]. A.J. MacGovern, D. A. Nahrstedt, and M.M. Johnson, "Atmospheric propagation for tactical directed energy application," *AeroSense 2000, Proc. SPIE*, vol. 4034, pp. 128-139, 2000.
- [162]. J.C. Ricklin, S. Bucaille, and F.M. Davidson, "Performance loss factors for optical communication through clear air turbulence," *Optical Science and Technology, SPIE's 48th Annual Meeting*, vol. 5160, pp. 1-12, 2004.
- [163]. H.T. Yura and W.G. McKinley, "Optical Scintillation Statistics for IR ground-to-space laser communication systems," *Applied Optics*, vol. 22, no. 21, pp. 3353-3358, 1983.
- [164]. D. Giggenbach and H. Henniger, "Fading-loss assessment in atmospheric free-space optical communication links with on-off keying," *Optical Engineering*, Vol. 47, no. 4, pp. 046001-046001, 2008.
- [165]. R. Gagliardi and S. Karp, "Optical Communications," John Wiley & Sons, 1995.
- [166]. D. Heatley, D. Wisely, I. Neild and P. Cochrane, "Optical wireless: the story so far," *IEEE communications magazine*, vol. 36, no. 12, pp. 72-74, 1998.

- [167]. J. C. Juarez, A. Dwivedi, A. R. Hammons Jr., S.D. Jones, V. Weerackody and R. A. Nichols, "Free-space optical communications for next-generation military networks," *IEEE Communications Magazine*, vol. 44, no. 11, pp. 46-51, 2006.
- [168]. J. Hamkins, "The Capacity of Avalanche Photodiode-Detected Pulse-Position Modulation," *Telecommunications and Mission Operations Progress Report 138*, pp. 1–15, 1999.
- [169]. H. Hemmati, Ed., "Deep Space Optical Communications," John Wiley & Sons, New Jersey, 2006.
- [170]. L. Andrews, R. Phillips, R. Sasiela and R. Parenti, "Beam wander effects on the scintillation index of a focused beam," *Defense and Security, Proceedings of SPIE*, vol. 5793, 28-37, May 2005.
- [171]. D. Fried, "Aperture averaging of scintillation," *Journal of the Optical Society of America*," vol. 57, no. 2, pp. 169-175, 1967.
- [172]. J. H. Churnside, R. J. Hill, "Probability density of irradiance scintillations for strong path-integrated refractive turbulence," *Journal of the Optical Society of America A*, vol. 4, no. 4, pp. 727-733, 1987.
- [173]. M. C. Roggemann, B. Welsh and B.R. Hunt, "Imaging Through Turbulence," CRC Press, New York, 1996.
- [174]. F. Dios, J. Rubio, A. Rodriguez and A. Comern, "Scintillation and beam-wander analysis in an optical ground station-satellite uplink," *Applied Optics*, vol. 43, no. 19, pp. 3866-3873, 2004.
- [175]. S. A. Zabidi, W. Al-Khateeb, Md. R. Islam, and A. W. Naji, "The effect of weather on free space optics communication (FSO) under tropical weather conditions and a proposed setup for measurement," *IEEE International Conference on Computer and Communication Engineering (ICCCE)*, Kuala Lumpur, Malaysia, May 2010.
- [176]. L. I. Ying-Chun, Zhao Yum, Sun Hua-yanand and Guo Hui-Chao, "Influence of Atmospheric Propagation on Performance of Laser Active Imaging System," *Journal of Physics: Conference Series*, vol. 276, no. 1, p.p 012133, 2011.
- [177]. S. A. Zabidi, W. Al-Khateeb, Md. R. Islam and A. W. Naji, "Investigating of rain attenuation impact on free space optics propagation in tropical region," *IEEE 4th*

- International Conference on Mechatronics (ICOM)*, Kuala Lumpur, Malaysia, May 2011.
- [178]. A. Jabeena, S. S. Reddy, B. S. Praneeth and P. Arulmozhivarman, "Laser based optical transceiver for data transfer of free space optical communication," *European Journal of Scientific Research*, vol. 67, no. 2, pp. 294-300, 2012.
- [179]. J. B. Regis and W. G. Donald, "Voice and Data Communications Handbook", 3rd ed., McGraw-Hill, New York, 2001.
- [180]. Y. Cojan, and J. C. Fontanella, "Propagation du rayonnement dans l'atmosphère," *Techniques de l'ingénieur. Electronique*, vol. E4030, pp. 1–31 1995.
- [181]. D. Harris, "The attenuation of electromagnetic waves due to atmospheric fog," *International journal of infrared and millimeter waves*, vol. 16, no. 6, pp. 1091-1108, 1995.
- [182]. Martin Grabner, "Vaclav Kvicera, Experimental Study of Atmospheric Visibility and Optical Wave Attenuation for Free space optics communication," Czech Science Foundation project No. 102/08/0851.
- [183]. P. Kruse, L. McGlauchlin and R. McQuistan, "Elements of Infrared Technology: Generation, transmission and detection". John Wiley & Sons, 1962
- [184]. Al Naboulsi and Maher, "Fog attenuation prediction for optical and infrared waves," *Optical Engineering* vol. 43, no. 2, pp. 319-329, 2004.
- [185]. Anguita, M. A. Neifeld and B. Vasic, "Spatial correlation and irradiance statistics in a multiple-beam terrestrial free-space optical communication link," *Applied Optics*, vol. 46, no. 26, pp. 6561-6571, 2007.
- [186]. S. Haas, J. Shapiro, V. Tarokh, "Space-time codes for wireless optical communications," *EURASIP Journal on Applied Signal Processing*, vol. 2002, no. 3, pp. 211-220, 2002.
- [187]. Z. Zhao, S. Lyke and M. Roggemann, "Adaptive optical communication through turbulent atmospheric channels," *Proceedings of IEEE International Conference on Communications*, May 2008.
- [188]. R. K. Tyson, "Principles of Adaptive Optics," Academic Press, Inc., New York, 1991.
- [189]. D.K. Killinger, J.H. Churnside, and L.S. Rothman, "Atmospheric Optics," *OSA Handbook of Optics*, Chapter 44, 1995.
- [190]. E.J. McCartney, "Optics of the Atmosphere," Wiley Publication, New York, 1969.

- [191]. Arends and C. Thomas, "Optical data link," U.S. Patent 4,330,870, May 18, 1982.
- [192]. S. Shaik, "A preliminary weather model for optical communications through the atmosphere," *Telecommunications and Data Acquisition Report*, vol. 1, pp. 212-218, 1988.
- [193]. A. K. Majumdar, "Free-space laser communication performance in the atmospheric channel," *Journal of Optical and Fiber Communications Reports*, vol. 2, no. 4, pp. 345-396, 2005.
- [194]. S.B. Alexander, "Optical communication receiver design," SPIE Optical Engineering Press, Washington, USA, 1997.
- [195]. S.D. Personick, "Receiver design for digital fiber optic communication systems, I & II," *Bell system technical journal*, vol. 52, no. 6, pp. 843-874, 1973.
- [196]. P. Oswald and C.K. Madsen, "Deterministic Analysis of Endless Tuning of Polarization Controllers," *Journal of Lightwave Technology*, vol. 24, no. 7, pp. 2932-2939, 2006.
- [197]. H. Nyquist, "Thermal agitation of electric charge in conductors," *Physical Review*, vol. 32, no. 1, pp. 110-113, 1928.
- [198]. G.P. Agrawal, "Nonlinear Fiber Optics," 2nd edition, Academic Press, San Diego, CA, 1995.
- [199]. G. Keiser, "Optical Fiber Communications," McGraw - Hill, 3rd edition, 2000.
- [200]. M.A.A. Ali, "Transmission of Optical Signals for Wireless Communications under Snow Attenuation Effect," *International Journal of Electronics and Communication Engineering & Technology (IJE CET)*, Vol. 4, No. 3, pp. 244-255, 2013.

