PERFORMANCE ANALYSIS OF FREE SPACE OPTICAL (FSO) COMMUNICATION LINK UNDER WEAK TURBULENCE

A thesis submitted in partial fulfillment of the requirements for the degree of

Bachelor of Science

in

Electrical, Electronic and Communication Engineering

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CERTIFICATE OF APPROVAL

The thesis titled **'Performance Analysis of Free Space Optical (FSO) Communication Link Under Weak Turbulence'** submitted by the group under mention, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Bachelor of Science in Electrical, Electronic and Communication Engineering on December, 2017.

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This is our original work under the supervision of Dr. Satya Prasad Majumder and was not submitted elsewhere for the award of any other degree or any other publication.

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ABSTRACT

This thesis investigates the performance of terrestrial free-space optical communication (FSO) system based on the On-Off keying (OOK) and Pulse Position Modulation (PPM) in the presence of atmospheric turbulence and pointing error. The performance analysis is carried out on basis of the bit error rate (BER). Optical signal traversing the atmospheric channel suffers from attenuation due to scattering and absorption by aerosols, fog, atmospheric gases and precipitation. The effect of atmospheric turbulence of an FSO system is presented analytically and experimentally verified both in case of single hop (with OOK modulation) and multiple hop (with PPM modulation). Atmospheric turbulence has a significant impact on the quality of a laser beam propagating through the atmosphere over long distances. Turbulence causes intensity scintillation and beam wander from propagation through turbulent eddies of varying sizes and refractive index. This can severely impair the operation of target designation and FSO communications systems. In this thesis, analysis of BER is done under weak atmospheric turbulence i.e. Log-normally distributed and transmission using single hop and multi-hop which is established on amplify-and-forward relays. We illustrate combined probability density function for multi-hop FSO system. Changing the modulation order, the BER performance is analyzed. Using multiple hop, the performance is also investigated and power penalty, the total transmission distance are also calculated as the derived curves for a fixed BER in this thesis. Finally, the numerically found results show that the multiple hop transmission along with PPM is a good solution for obtaining desired Bit Error Rate (BER) under the effects of weak turbulence and pointing error than OOK based single hop.

TABLE OF CONTENTS

LIST OF ABBREVIATIONS

FSO	Free Space Optical
FOC	Fiber Optic Communications
LOS	Line of Sight
ROI	Return On Investment
RF	Radio Frequency
IRT	Index-of-Refraction Turbulence
EMI	Electro-Magnetic Interference
LAN	Local Area Network
TIF	Turbulence Induced Fading
MAN	Metropolitan Area Network
SNR	Signal to Noise Ratio
BER	Bit Error Rate
IM/DD	Intensity Modulation Direct Detection
LED	Light Emitting Diode
LASER	Light Amplification by Stimulated Emission of Radiation
PDF	Probability Density Function
SINR	Signal to Interference and Noise Ratio
AWGN	Additive White Gaussian Noise
PPM	Pulse Position Modulation
OPPM	Optical Pulse Position Modulation

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CHAPTER 1
INTRODUCTION

1.1 Communication System

Transfer of information from one place to another separated by a few kilometers over a transmission or wireless medium is known as communication system. Communication systems can be of different types. Some communication systems use modulation techniques where the information is modulated to an electromagnetic wave which acts as carrier and is transmitted with the help of it, at the receiving end this signal is demodulated to achieve the original message. Other kinds of communication systems involve the use of optical light rays to transmit and receive information over a certain distance.

1.2 Optical Communication

Optical communication system uses transmitter which encodes the information into optical signal and at the receiving end, the optical signal is decoded to receive the original information. This kind of communication can be wireless or it can have a medium like optical fiber or submarine cable, through which the information is transmitted.

1.2.1 Fiber Optic Communication(FOC)

Fiber optic communication is a kind of communication system where a waveguide is used. The thin hair like waveguides can transport optical energy, the information to be transmitted is therefore first converted to optical signal. Main limitation of this system is the dispersion and scattering of optical signal but it is widely used at present because of high data rate and bandwidth.

1.2.2 Free-Space-Optical (FSO) Communication

FSO communication is a system that uses visible or infrared rays to transmit data over a distance, applying the line of sight (LOS) technology. In recent days FSO is frequently used in designing communication channel models. Here instead of using thin glass fibers the required information is transmitted through air/atmosphere.

1.3 Merits and Limitations of FSO

Due to its significant advantages over radio wave and micro wave like last-mile access, fiber backup etc. [1]. Here no spectrum licensing is required which saves cost. Even no frequency coordination with other users are required. Accuracy in this communication system is more and interference with other systems is not an issue since it is a line of sight communication. But this system needs clear line of sight communication path to function properly. And atmospheric turbulence affects the system severely and deteriorates its performance. Atmospheric turbulence creates fluctuation of received optical signal specially for link ranges longer than 1 km. Another drawback of using FSO is the effect of pointing error on its performance. To solve the turbulence related problem, as well as to broaden the coverage of the system multiple-hop transmission technique is considered as an effective option [2-4].

1.4 Review of Previous Work

As FSO is very popular now-a-days, studies related to FSO channel link performances are quite common. Many studies have been made in this field including BER vs. SNR for multi-hop FSO channel [12]. Popular models such as Gamma-Gamma distributions and Log-Normal channel models have been studied for investigating the effects of turbulence [1], [13]. Other papers have investigated the outage probability of a multi-hop FSO communication system in the weak turbulence region and pointing error induced fading [6].

1.5 Objectives with Specific Aims

The objectives of this thesis are:

- To create an appropriate model for FSO under weak turbulence using PPM modulation.
- To find out the BER of this model.
- To compare the performance of system model using OOK and PPM modulation for a single hop.
- To find out the improvement of performance when multi-hop is used in the model for PPM modulation.
- To analyze the receiver sensitivity for different order of PPM modulation.
- To calculate the energy over a PPM bit.

1.6 Organization of Thesis

This thesis consists of eight chapters, Chapter 1 is a detail brief about very basic Free Space Optical (FSO) Communication system, review of previous works and main objectives of this thesis.

Chapter 2 is a brief overview of advantages, applications of Free Space Optical (FSO) Communication, transmitters, receivers, transmitting medium and effects of atmospheric condition on FSO Communication channel.

Chapter 3 involves about a brief discussion about atmospheric turbulence channel models. The mathematical models are derived for log normal turbulence channel, gamma-gamma turbulence channel and the negative exponential turbulence channel.

chapter 4 describes OOK and PPM modulation technique used for FSO link for deriving mathematical model for BER performance analysis.

Chapter 5 is a overview of system model for single hop and multiple hop.

Chapter 6 is concentrated about the derivation for mathematical model for calculating BER and also energy over a bit for single hop (with OOK modulation technique) and multiple hop (with PPM modulation technique) in weak atmospheric turbulence channel.

Chapter 7 represents the analytical results of BER performance for single hop with OOK modulation and multiple hop with PPM modulation (varying the modulation order) in weak atmospheric channel. Power penalty and maximum allowable transmission along with energy over a PPM bit distance are also shown in this chapter. Analytically how improvement in BER can be achieved is briefly discussed here with simulation results used in MATLAB

Chapter 8 provides us conclusions and some proposals for future work.

CHAPTER 2

FREE SPACE OPTICAL COMMUNICATION LINK

2.1 Introduction

The idea behind this chapter is to show the basic that how the information transfer is done via free space optics which is an essential part of telecommunications for its different types of advantages. Other terminologies will be described later.

2.2 Free Space Optical Communication System

Free Space Optical (FSO) Communication is a LOS communication technology between two points by transmitting information via light. The technology is used where connectivity of optical fiber is difficult because of high costs or other atmospheric weather conditions. If we have to consider a technology that can be installed worldwide license-free, can be installed in a very less time, that offers a very fast high speed technology,then it is free space optical communication (FSO) [21].

The line-of-sight technology approach uses of light between two points to provide optical connections. High speed data, voice, video can be sent through air simultaneously enabling fiber optic connectivity[15]. Information passes through at a light speed. Over the last two decades free-space optical communication (FSO) has become very popular in conjunction to radio frequency communication for its numerous advantages and uses.

With the need of higher bandwidth and less BER, the Free Space Communication(FSO) has become an absolute technology. FSO is the next frontier for net-centric connectivity, as bandwidth, spectrum and security issues favor its adoption as an adjust to radio frequency (RF) communications [22], [23].

2.3 Application of FSO Communication System

FSO provides vastly improved EMI behaviour using light instead of microwaves. FSO is very hard to intercept having improved security. Some of the most useful applications where FSO plays an important role are:

- LAN-to-LAN connections in a city, for example in Metropolitan Area Network [23].
- LAN-to-LAN connections on campuses at fast FE or GE speeds [23].
- To cross a public road or other barriers which the sender and receiver do not own [23].
- Speedy service delivery of high bandwidth access to the optical fiber networks [23].
- Temporary network installation (for events or other purposes) [23].
- As an alternative or upgrade add-on to existing wireless technologies.
- Reestablish high-speed connection quickly (disaster recovery).
- As a safety add-on for important fiber connections (redundancy) [25].
- For communications between spacecrafts, including elements of a satellite constellation [24].

2.4 Advantages of FSO Communication System

FSO plays a very vital role in information transfer mostly used for transmitting telecommunication signals. It has huge bandwidth, secure protocol and very encrypted data. Some of the major advantages can be implied as:

- Very easy to install [15].

- Requires no i.e. it is license-free long-range operation (in contrast with radio communication) [26].
- Very high bit rates [26].
- Low bit error rates [26].
- Very less affected by EMI [27].
- Very secure operation and easily decrypted at the receiver [26].
- Can be upgraded easily [26].
- Requires no security software upgrades [26].
- Uses very low power for transmitting information [27].
- Very flexible to use [15].

For the above advantages, presently FSO communication systems are mostly used as the requirement of transmission of long distance and high capacity (bandwidth).

2.5 Main Challenges in FSO Communication System

Though FSO has many advantages, it faces some difficulties too while transmitting the information through air without the deployment of fiber cables. FSO is mainly affected by weather condition like smog, fog, rain, cloud etc. [16]. Different buildings or constructions are also barrier to FSO because it is a LOS (Line of Sight) technology.

So in case of designing an FSO model we must consider the barriers so that its performance does not degrade for the receiver to understand clearly. Some of the causes of performance degradation is stated as below:

2.5.1 Fog

Weather conditions affect FSO severely and among the weather particles fog affects the FSO link mostly. Other weather particles don't affect as much as fog. So fog must be considered strongly whether designing the FSO link. It is a vapor composed of water droplets and light characteristics may be changed by it through a combination of absorption, scattering, and reflections [28]. While designing the FSO, we must model such that it adds network redundancies and does not degrade the performance.

2.5.2 Rain

The performance of FSO can be degraded by rain particles which causes due to rain drops and wavelength of this type is wavelength independent [29]. Attenuation i.e. fluctuations of the transmitted signal is the result of rain droplets. Different types of rain affects the FSO channel differently. Like in case of heavy rain, optical beam characteristics can be changed or the light beam may be restricted likely (absorbed, scattered, and reflected) [27].

2.5.3 Cloud

Clouds, part of telecommunication channel, cause wave attenuation and spatial widening. These effects results to decrease the signal to noise ratio (SNR). During propagation of the optical signal through thin clouds, almost all the radiation power passes but it also widens because of scattering process. Calculation of attenuation parameter caused by clouds is very difficult due to diversity and inhomogeneities of the particles [30].

The light beam is affected mainly in the two described ways:

(i) Absorption: Suspend water molecules causes absorption in the transmitted signal. This results in a degradation in the radiated power (attenuation) of the

FSO link and availability of a system is directly affected [31]. Absorption normally affects the signal or waveforms at a particular wavelength than others. Through the use of spatial diversity technique, we can get the estimated signal power to noise power i.e. SNR and minimize the absorption effects.

(ii) Scattering: The wavelength colliding with the scatterer results in to scattering effect of a signal. The type of the scattering is determined by the physical size of the scatterer. *Rayleigh Scattering* is the scattering, when the wavelength is larger than the scatterer. *Mie Scattering* is known defined as scattering When the wavelength is of comparable size to the scatterer. When the wavelength is much smaller than the scatterer, this is called *non-selective scattering*. In case of long distance, scattering causes no loss of energy, it has only a directional redistribution of energy unlike absorption which degrade the performance of the optical signal [32].

2.5.4 Scintillation

Temperature variations among different air packets can be caused due to the increase of heat in the air or the heat creation devices. As a result, a fluctuation in the signal amplitude is seen at the receiver and performance is severely affected by the FSO channel [32]. Multi-beam system is used to define the scintillation effects. This causes two primary effects on optical beams as the followings:

- **Beam Wander:** Turbulent eddies in the atmosphere that are larger the light beam causes the beam wandering effect [33].
- **Beam Spreading:** There are two types of beam spreading. One is short term and another is long term. When the beam is spread while propagation through the air, is known as beam spreading [33].

2.5.5 Physical Obstructions

Large buildings or constructions can be a barrier to a single-beam FSO system. Though short term data transmission unavailability may occur in case of working machines like cranes or flying birds, after a certain time, transmissions are automatically recovered. Diversity techniques may be applied to this solution for a greater performance because one way might be unavailable for the data transmission but others are not. Different ways suffer from different types of fading.

2.5.6 Building Sway

Since FSO is a LOS communication, the receiver and transmitter alignment is a mandatory requirement for lower BER. Multiple beam i.e. diversity technique helps us for obtaining required SNR performance, embedded security system and easy installation [34].

2.6 Block Diagram of a Basic FSO Communication System

The most simplified FSO communication system consists of a transmitter, atmospheric channel and a receiver. The block diagram of the basic FSO system is shown below:

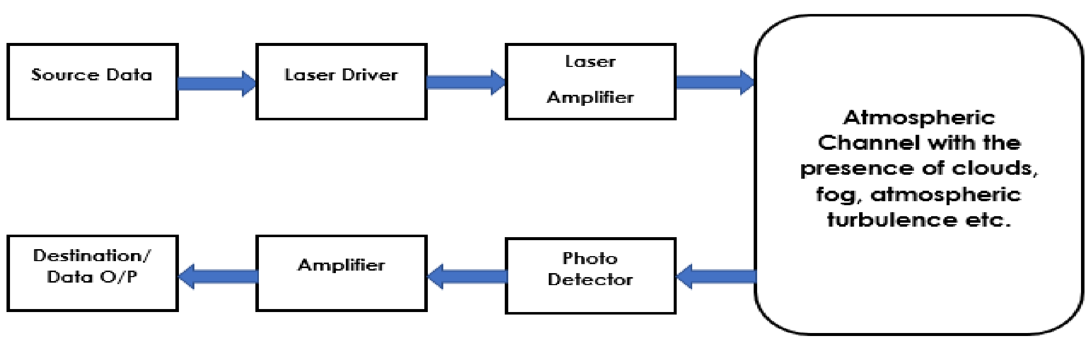


Figure 2.1: FSO System block diagram.

2.6.1 The Transmitter

The transmitter consists of several components like an optical source with modulation scheme and other electronic devices which sends the optical signal through air and the signal may be encrypted for increasing security level. The most used optical sources are LED and LASER.

Among lasers and leds, lasers are the brightest sources. Different types of lasers are available like solid lasers (YAG-Nd or ruby), gas lasers (HeNe), metal vapors excited by electronic discharge etc. Lasers are normally doped with rare earth elements for increasing its performance and then it is pumped optically. Because of the capability of direct modulation of radiant power and optical frequencies, semiconductor junction lasers and electroluminescent diodes are very popular among others [36].

- **Led**

The use of LEDs has been almost around 30 years. In the earlier, They have been used in almost every consumer-electric devices. In optical communications, they are used mostly because they have small size and offer long life. However, they have

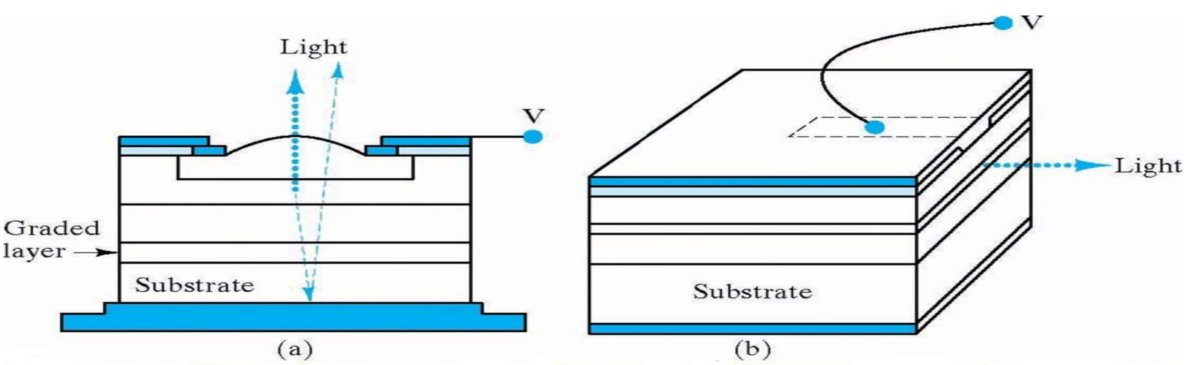


Figure 2.2: Examples of electro luminescent diode sources of incoherent light waves (a) surface emission (b) emission through edge facet (edge emitter).

some disadvantages unlike lasers, like low intensity, low modulation bandwidth and incoherent radiation etc. [36].

Among common light sources LED is largely used. When the diode is forward biased, recombination of electrons and holes is seen within the device, which causes in releasing energy in the form of photons. This is known as electro luminescence [35]. The basic surface emission is shown in Fig 2.2

Though LED-based systems have some disadvantages as stated above, they offer a number of advantages. Among which, the most obvious being expenditure and dimension. Driving of electrons is simple in LED and they are very cheap. The result is that the system design of LED is much more simple and less expensive compared to the LASERS [35].

- **Laser Diodes (LDs)**

Another light sources, semiconductor laser diodes, are developed in the 1970s. They have found numerous applications like commercial applications in compact-disc (CD)

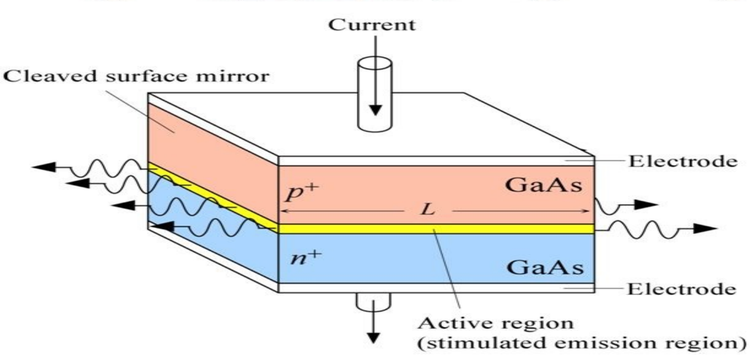


Figure 2.3: GaAs laser structure.

players, LD radiation properties as brightness, directivity, narrow spectral width etc. the gain of laser diodes is estimated by the flow of electrical current in the p-n junction. When electrons and holes recombine, some energy is released as photons in spontaneous process.

Stimulated emissions are also possible in laser diodes. Laser diodes are vastly used because of their small size and efficiency in power[15], [36]. The nominal wavelength for the laser diodes is 850 nm or 1550 nm. Observing the transmission window, it is seen that loss at 1550 nm [35].

2.6.2 The Receiver

An optical signal is passed through air, it is received by the receiver and it is converted back to electrical signal. This conversion is done by a photo detector, then the signal is amplified. Two types of detection is possible at the receiver. One is coherent and another is non-coherent. Clock generation is tough in case of coherent detection, so non-coherent detection is used in most of the case. In this thesis, we are considering the direct detection methodology (IM/DD) [35], [37].

There are different types of photo detectors. Most of them are semiconductors. The value of current or voltage in case of illumination directly depends on power (radiant). Detector volumes absorb radiant power when it comes to semiconductors. Therefore, in this case, heat is released by emitting an electron and a hole [15], [37].

In non-coherent optical signal detection, the incident photons are absorbed by the detectors and free carriers are generated accordingly. Though it is possible for a photon to pass through the photo detector without generating any free-carrier, in a well-designed photo detector, the probability of an incident photon generating the free carrier is high [15], [35].

In free-space-optical links, the photo detectors receive images of the near fields of the transmitters after propagation along trajectories, optical beams through the atmosphere and some optics elements. A first approach consists of using detectors with both sensitive areas apertures large enough to capture these images whatever the sizes and displacements of the beams under conditions of maximum illumination [37]. A second approach, technically more sophisticated, consists of using the photo-detectors adapted to optical-fiber links and fixing them in the image plane of an auto-focusing optical system. Under these conditions the incident field remains inside the perimeter of the detector sensitive area and the incident radiant power is close to a maximum [15].

For the free space optical communication (FSO), the most popular photo detectors are p-i-n photo-diode and avalanche photo-diode.

- **P-I-N Photodiodes**

A photo-diode is a type of photo detector capable of converting light into either current or voltage, depending upon the made of operation. A PIN diode is a diode with a wide, lightly doped intrinsic semiconductor region between a p-type semiconductor and an n-type semiconductor region [37].

A PIN diode functions under high-level injection. In other words, the intrinsic (i)

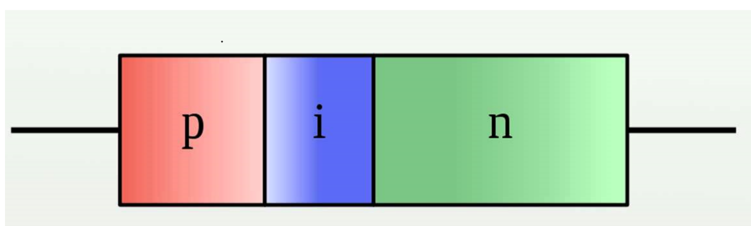


Figure 2.4: P-I-N photo-diode.

region is flooded with charge carriers from the 'p' and 'n' region. When the diode is a forward biased, the injected carrier concentration. Due to this high level injections, which in turn is due to the depletion process, the electric field extends deeply (almost the entire length) into the region [37]. This electric field helps in speeding up of the transport of charge from 'p' to 'n' region, which results in faster operation of the diode, making it a suitable device for higher frequency operation [35], [15].

Incident photons trigger a photo-current I_p in the external circuitry by pumping energy photo-current which is proportional to the incident optical power.

A p-i-n photo-diode is the most commonly used light detector in today's optical communication systems because of its ease in fabrication, low noise, low voltage and relatively large bandwidth [35], [37].

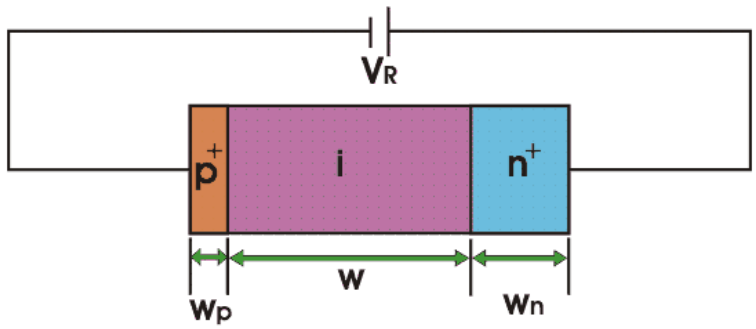


Figure 2.5: Basic p-i-n photodiode circuit.

- **Avalanche Photodiodes**

An avalanche photo-diode (APD) is a highly sensitive semiconductor electronic device that exploits the photoelectric effect to convert light to electricity. APDs can be thought of as photo-detectors that provide a built-in first stage of gain through avalanche multiplication [15]. The internal gain of the APD is obtained by having a high electric field that energizes photo-generated electrons and holes. APD has high gain due to self-multiplying mechanism, used in high end systems. But APDs are costly and need reverse bias voltage [36].

APD can amplify the photo current without an external amplifier. APD applicability and usefulness depends on many parameters. Two of the larger factors are: quantum efficiency, which indicates how well incident optical photons are absorbed and then used to generate primary primary charge carriers; and total leakage current, which is the sum of the dark current and photo-current and noise [35]. Electronic dark noise components are series and parallel noise. Series noise, which is the effect of the shot noise, is basically proportional to the APD capacitance while the parallel noise is associated with the fluctuations of the APD bulk and surface dark

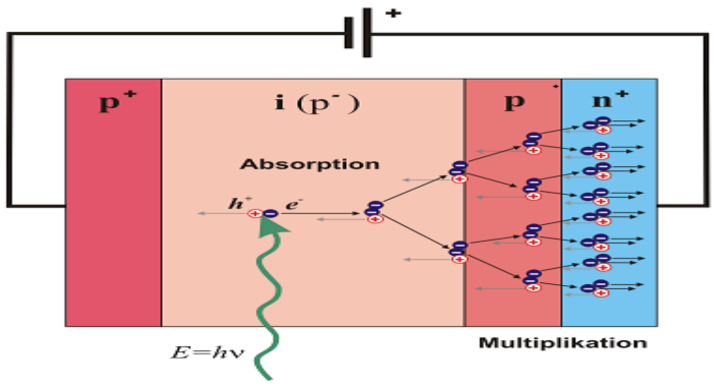


Figure 2.6: P-I-N photo-diode.

currents. Another noise source is the excess noise factor, F [15], [37]. It describes the statistical noise that is inherent with the stochastic APD multiplication process. Fig. 2.6 shows the reach-through structure of APD which offers the best available combination of high speed, low noise and capacitance and extended red response.

2.6.3 FSO Transmitting Medium

All the telecommunication signals pass through a channel, in case of FSO the transmitting medium is atmosphere. The signal passing through the air suffers from different types attenuation properties like absorption or scattering. Different types of air particles causes these types of attenuation [37]. Some of the major causes of signal degradation are:

- ✓ Attenuation of the transmitted signal while propagating through air [15].
- ✓ Absorption of the signal while passing through air particles [15].
- ✓ While passing through a large distance through atmosphere, the signal may suffer scattering [35].
- ✓ Due the variation of atmospheric temperature, scintillation effect may be severe.

So while designing a FSO transmitting medium, the effect of transmitting medium must be taken into consideration because the medium may severely affect the transmitted signal and the received signal might not be noisy. Now, The effect of atmosphere is discussed below [36]:

2.6.3.1 Atmospheric Absorption

When the transmitting signal interacts with the air particles, the signal may be absorbed [35]. Then the system reliability is lost. Let, a wavelength of λ passing through an absorbing medium of thickness dx.

Different types of problems arise from absorption of the signal, the photon may be lost or something, Now, if we want to calculate the intensity of radiation at distance x+dx, we can write[38]:

$$I(\lambda, x+dx) = I(\lambda, x) - dI_a(\lambda, x) \tag{2.1}$$

where $dI_a(\lambda, x)$ represents the light absorption by the channel, which is proportional

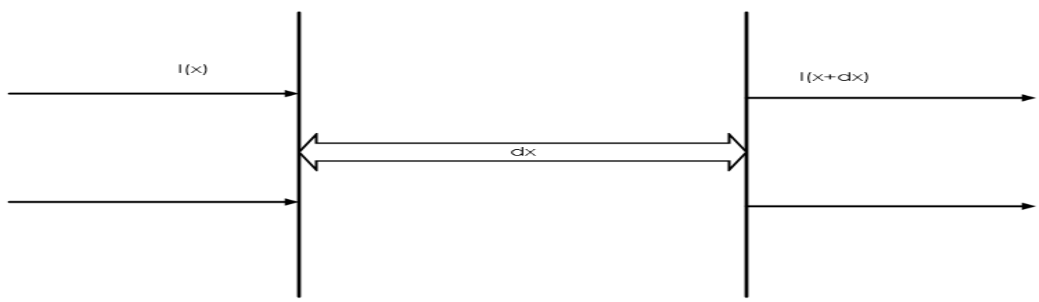


Figure 2.7: Light absorption by atmosphere for a thickness of dx.

to the intensity $I(\lambda, x)$, then $\alpha(\lambda, x)$ at this wavelength can be defined as [38]:

$$dI_a(\lambda, x) = \alpha(\lambda, x) I(\lambda, x) dx \tag{2.2}$$

2.6.3.2 Atmospheric Scattering

For calculating the the scattering effect due the atmosphere we can write the equation [38]:

$$\tau_d(\lambda, x) = \frac{I(\lambda, x)}{I(\lambda, 0)} = exp[-\int_0^x \beta(\lambda, x) dx] \tag{2.3}$$

where $\beta(\lambda,x)$ signifies the spectral scattering coefficient.

2.6.3.3 Atmospheric Turbulence due to Aerosols

Suspended air particles mainly causes atmospheric turbulence. Although atmospheric weather conditions like rain and snow can affects the signal, mostly fog causes the signal fluctuations [36].

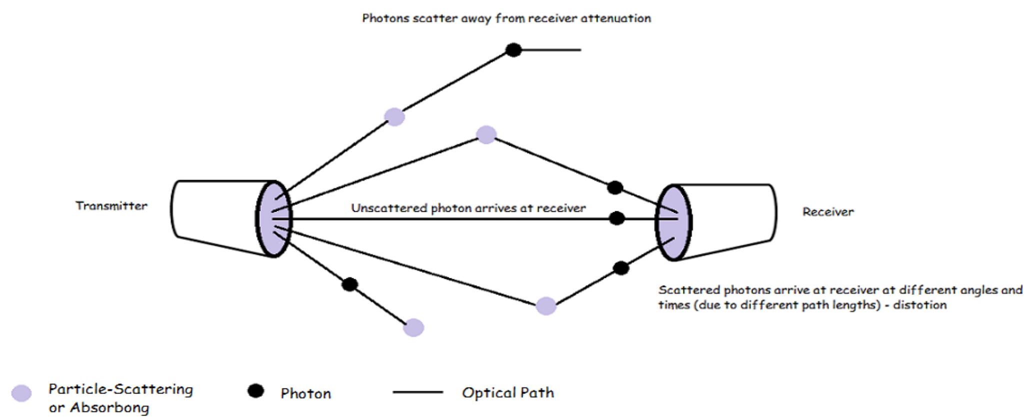


Figure 2.8: Multiple scattering showing spatial and angular spreading and variations in path length. Absorption of a photon by a particle is also shown.

The above stated problems are the limitation of a basic FSO system. Though FSO technology is affected less than the RF signal due to the atmospheric conditions [36]. So, FSO technology is commonly used worldwide. Atmospheric effect is shown in Fig. 2.8.

2.7 Intensity Modulation Direct Detection (IM/DD) System

In direct detection techniques, the radiant optical power varies with the variation of modulating signal and the reception technique of the modulating signal is direct detection method [35]. Intensity Modulated Direct Detection (IM/DD) is the most popular technique now-a-days. We use LASERS, LEDS as the optical source, Photo-detectors as the receiver and air as the transmitting medium. The direct detection method is also carried out in this thesis for analytical purpose.

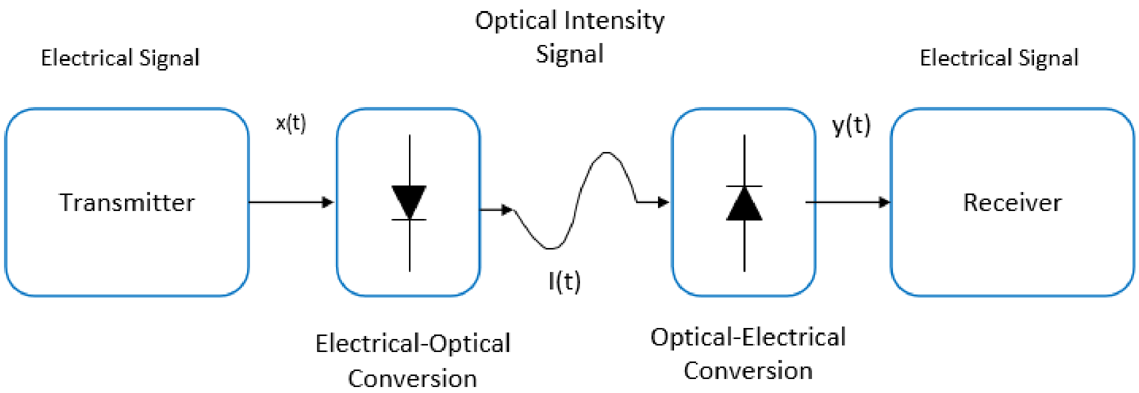


Figure 2.9: A simplified block diagram of an optical intensity direct detection communications system.

2.8 Noise

Noise is also an unavoidable problem in designing an FSO technology. There are two major electrical noises. They are thermal noise and shot noise. Thermal noise is generated due the temperature variation in the electrical devices and shot noise or poison noise is generated from the discrete nature of electric charge. These noise causes limitation of the signal and difficult to recover [1,2].

We can define thermal noise is known as [1,2]:

$$< I_{th}^2 >= 4KTB/R_L \tag{2.4}$$

where R is the resistance, K is the Boltzmann's constant, T is the absolute temperature, B is the bandwidth and R_L is the load resistance [1,2].

Moreover fluctuations of current may produce noise. Discreteness of the electric charge causes this kind of noise and it is known as shot noise. Now according to Schottky formula, we can write [1], [2], [15]:

$$< I_{sh}^2 >= 2eBI_{shot} \tag{2.5}$$

where, e is the electron charge, I_{shot} is dc current. Background light and due to leakage current shot noise may be generated [15], [35].

Total noise in a system is the addition of thermal noise and shot noise.

2.9 Signal to Noise Ratio (SNR)

Signal to noise ratio is defined as the ratio of the signal strength to the noise power. It is a parameter for measuring a signal's performance [15], [35], [1], [2]. The higher the SNR, the better the performance. So, the ultimate goal is to improve the SNR as much as possible. The FSO system must be designed in such a way that we get our estimated SNR value.

$$SNR = \frac{SignalPowerfromphotocurrent}{detectorNoise + AmplifierNoise} \tag{2.6}$$

There are some conditions for achieving the higher SNR value like large quantum efficiency of the photo-detectors and low noise of detector and amplifier result to a very high SNR value [1], [2].

2.10 Bit Error Rate (BER)

BER is the measurement parameters for estimating a link performance. It is defined as the ratio of error bits to the correct bits. BER is Dependant on the signal and noise power i.e. Signal to Noise Ratio (SNR). Very low BER indicates that the signal strength is not good enough for the receiver and vice-versa. Designing a link for minimizing the BER is a major challenge in FSO communication system [2]. In this thesis, we put our emphasis on minimizing the BER as much as possible by a proper analytical approach.

2.11 Energy per Bit Noise Power Spectral Density Ratio (E_b/N_0)

The energy per bit to noise is the normalized SNR which is also known as SNR per bit.It is denoted by E_b/N_0. It is defined as the ratio of signal power to the user bit rate. Here E_b is the signal energy and N_0 is the noise spectral density. The unit of signal power and bit rate are watts and bits per second normally, the E_b/N_0 is dimensionless, because it is the ratio and often expressed in decibels [14].

2.12 Summary

This chapter discusses the basics of free space optical communication system along with its application, advantages, and main challenges in FSO and the effect of atmospheric turbulence on the FSO communication link.

CHAPTER 3

ATMOSPHERIC TURBULENCE CHANNEL MODELS

3.1 Introduction

The surface of earth absorbs the solar radiation. Thus this layer gets warmer and mix with the surrounding cooler air particles and causes the air temperature to fluctuate in random manner [39]. When the photon of the laser beams collide with the turbulent medium, it results in to the variation of the amplitude and phase of the optical signal which causes attenuation i.e. absorption, scattering etc. of the transmitted signal and the signal is distorted. In this chapter we will discuss some of the basic turbulent models for strong, moderate and weak region with the IM/DD in case of FSO system. These regions are categorized in terms of refractive index variation and inhomogeneities.

Since there is no universal model for atmospheric turbulence models, this chapter will emphasis on the development of the probability density function (pdf) for different regimes i.e. strong, moderate or weak. We will discuss three most important turbulence models like gamma-gamma (weak to strong regimes), log normal (weak regimes) and negative exponential models (saturate regimes).

3.2 Turbulent Atmospheric Channel

It is already known that due to variation of refractive index and inhomogeneities atmospheric turbulence effect is observed. This refractive index variation causes the temperature fluctuation in the atmosphere. Now, we can define the smallest turbulence eddies as the inner scale, l_0, and the largest turbulence eddies as the outer scale, L_0. The variation of inner scale is like on the order of a few millimeters and the outer scale is on the order of several meters. In Fig. 3.1, we can see the atmospheric channel with turbulent eddies. For modeling the turbulence model, we

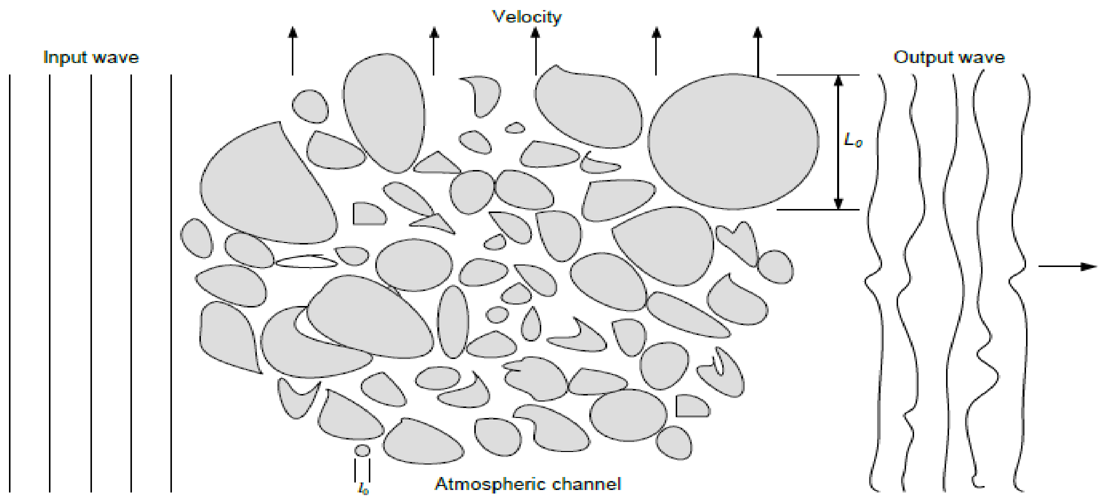


Figure 3.1: Atmospheric channel with turbulent eddies.

take the help of the 'Taylor hypothesis' [17], according of which the turbulent eddies are normally in frozen form and the local wind that is perpendicular to the direction of the propagation causes the temporal variation in the beam patterns. τ_0 is in the order of milliseconds which is proved [18]. Here τ_0 is defined as temporal coherence time. The temporal coherence time is also called as 'slow fading channel' since coherence time is greater than the symbol period.

The time and position dependent refractive index, $\eta(r,t)$, is defined as [40]:

$$\eta(r,t) = \eta_0 + \eta_1(r,t) \tag{3.1}$$

where η_0 designates the position and time independent refractive index and $\eta_1(r,t)$ denotes a turbulence induced refractive index variation component. Again from Taylor's hypnosis, the variation of the refractive index of the frozen turbulent eddies are resulted from the local wind. So, we can write the equation (3.1) as[40]:

$$\eta_1(r,t) = \eta_1(r - vt) \tag{3.2}$$

here v(r) is denotes as the atmospheric local wind velocity perpendicular to the direction of the propagation. The refractive index variation parameter C_n^2 is describes as the Hufnagel-Valley (H-V) model [19] as:

$$C_n^2 = 0.00594(v/27)^2 \times (10^{-5h})^{10} exp(-h/1000) + 2.7 \times 10^{-16} exp(-h/1500) + \hat{A} exp(-h/100) \tag{3.3}$$

here $\hat{A}$ is taken as the nominal value of $C_n^2(0)$ at the ground in $m^{-2/3}$ and h is the altitude.
Thus we can define C_n^2 as [17]:

$$C_n^2 = \frac{d\eta}{dT_e}^2 C_T^2 \tag{3.4}$$

In the frequency domain, the power spectral density of the refractive index fluctuation is related to C_n^2 [41]. So we can write :

$$\Phi_n(k) = 0.033 C_n^2 k^{-11/3} \quad 2\pi/L_0 \ll k \ll 2\pi/l_0 \tag{3.5}$$

where k is denoted as wave number.

As we stated before, there is no universal model for the turbulence model and they are very difficult to describe them mathematically because of mainly non-linearity properties in the mixing process of the particles [18]. For deriving the probability density function (pdf) of different regimes (weak, moderate or strong)some simplifications will be considered in this chapter.

3.3 Log-normal Turbulence Model

Among all the turbulence model, log-normal turbulence model is the mostly used model for describing the pdf in case of weak regime in the atmospheric turbulence. We denote the electric field as $\vec{E}$. Now using Maxwell's electro-magnetic equations for dielectric variance like the atmosphere, we can write [18]:

$$\nabla^2 \vec{E} + k^2 \eta^2 \vec{E} + 2\nabla[\vec{E}.\vec{\nabla} ln(\eta)] = 0 \tag{3.6}$$

where k is the wave number which is defined as, k= $2\pi/\lambda$ and the vector gradient operator, $\vec{\nabla} = (\frac{\delta}{\delta x})i + (\frac{\delta}{\delta y})j + (\frac{\delta}{\delta z})k$ with i, j, and k being the unit vectors along the x, y and z axes respectively.

The wave depolarization in weak turbulence regime is negligible. Even, it is also negligible for strong turbulence regime too.The we can write equation (3.6) as:

$$\nabla^2\vec{E} + k^2\eta^2\vec{E} = 0 \tag{3.7}$$

r is denoted as the position vector and E(r) is represented instead of $\vec{E}$ for simplification. In Roytov transformation, a Gaussian complex variable $\Psi(r)$ is defined for solving the above equation [42]:

$$\Psi(r) = ln[E(r)] \tag{3.8}$$

In the Roytov transformation single scattering process is assumed. From equation (3.8) and equating η_0 to unity, equation (3.7) can be considered as Riccati equation. The solution of Riccati equation is already known [42]:

$$\nabla^2\Psi + (\nabla\Psi)^2 + k^2(1+\eta_1)^2 = 0 \tag{3.9}$$

Now we want to convert $\Psi(r)$ into free space parameter $\Psi_0(r)$. So, we can write, $\Psi(r)$ = $\Psi_0(r)$ + $\Psi_1(r)$ [18]. With the help of equation (3.8) we achieve the following:

$$\Psi_1(r) = \Psi(r) - \Psi_0(r) \tag{3.10}$$

$$\Psi_1(r) = ln[E(r)] - ln[E_0(r)] = ln\left[\frac{E(r)]}{E_0(r)}\right] \tag{3.11}$$

here the electric field $E_0(r)$, is free from turbulence in free space [18]:

$$E(r) = A(r)exp(i\Phi(r)) \tag{3.12a}$$

$$E(r) = A_0(r)exp(i\Phi_0(r)) \tag{3.12b}$$

here A(r) is denoted as amplitude and $\Phi(r)$ is denoted as phase in the turbulence region and $A_0(r)$ represents the amplitude in turbulence free region and $\Phi_0(r)$ represents the phase in the turbulence free region. Combining equation (3.11) and (3.12), we finally get the following equation in the weak region:

$$\Psi_1(r) = ln\left[\frac{A(r)]}{A_0(r)}\right] + i[\Phi(r) - \Phi_0(r)] = \chi + i\delta \tag{3.13}$$

here $\Psi_1(r)$ is Gaussian distributed, χ is the variation of log-amplitude which os also Gaussian distributed. Thus assuming δ is the phase fluctuation, the pdf of χ can be written as [18]:

$$P(\chi) = \frac{1}{\sqrt{2\pi\sigma_x^2}} exp\left\{ -\frac{(\chi - E[x]^2)}{2\sigma_x^2} \right\} \tag{3.14}$$

where the expected value of χ is $E[\chi]$ and σ_x^2 is the variance. If the total traveling distance is denoted by L, we can write the variance, σ_x^2 equation as the following [17]:

$$\sigma_x^2 = 0.56k^{7/6}\int_0^L C_n^2(x)(L-x)^{5/6}dx \quad foraplanewave \tag{3.15a}$$

$$and \qquad \sigma_x^2 = 0.563k^{7/6}\int_0^L C_n^2(x)(x/L)^{5/6}(L-x)^{5/6}dx \quad forasphericalwave \tag{3.15b}$$

In terrestrial area, the C_n^2 parameter is constant and then the variance, σ_l^2 for a planer wave can be written as [17]:

$$\sigma_l^2 = 1.23C_n^2k^{7/6}L^{11/6} \tag{3.16}$$

If the turbulence free intensity is $I_0 =| A_0(r) |^2$, then the log normal intensity is given by [17]:

$$l = log_e\left|\frac{A(r)}{A_0(r)}\right|^2 \tag{3.17}$$

Hence,

$$I = I_0 exp(l) \tag{3.18}$$

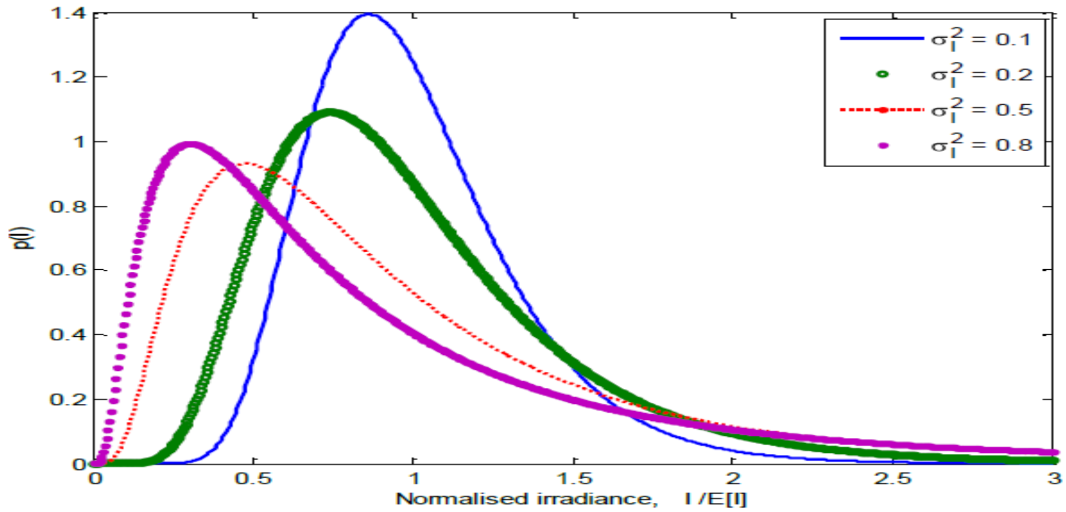


Figure 3.2: Log-normal probability density function with E(I) = 1 for a range of irradiance variance σ_l^2.

Now for calculating the pdf $P(I) = P(\chi)\left|\frac{d\chi}{dI}\right|$, and the log-normal distribution function given by (3.19) [17]:

$$P(I) = \frac{1}{\sqrt{2\pi\sigma_l^2}}\frac{1}{I}exp\left\{-\frac{(ln(I/I_0) - E[I]^2)}{2\sigma_l^2}\right\} \qquad I \geq 0 \tag{3.19}$$

So for the weak atmospheric region, this is the log normal probability distribution function.

3.4 The Gamma-Gamma Turbulence Model

Andrews et al. proposed a model in [19] that when light beam passes through the atmospheric turbulence channel, it suffers from both small scale (scattering) and large scale (refraction) effects. Large scale eddies may modulate the small scale eddies. Now if I is defined as the receiver normalized irradiance, it is the product of two independent large scale and small scale turbulent eddies, I_x and I_y respectively [19]:

$$I = I_x I_y \tag{3.20}$$

I_x and I_y help us to develop the probability density function (pdf) of Gamma-Gamma distribution because they follow the gamma distribution [19]:

$$p(I_x) = \frac{\alpha(\alpha I_x)^{\alpha-1}}{\Gamma(\alpha)} exp(-\alpha I_x) \quad I_x > 0; \alpha > 0 \tag{3.21a}$$

$$p(I_y) = \frac{\beta(\beta I_y)^{\beta-1}}{\Gamma(\beta)} exp(-\beta I_y) \quad I_y > 0; \beta > 0 \tag{3.21b}$$

By transformation of the variable $I_y = I/I_x$, the conditional pdf given by (3.22) is:

$$p(I/I_x) = \frac{\beta(\beta I/I_x)^{\beta-1}}{I_x\Gamma(\beta)} exp(-\beta I/I_x) \quad I > 0 \tag{3.22}$$

For calculation of unconditional distribution, the conditional probability, $p(I/I_x)$ is avaraged. Then we finally get Gamma-Gamma irradiance distribution function.

$$p(I) = \int_0^\infty p(I/I_x)p(I_x)dx$$

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{(\alpha+\beta)}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I}) \quad I > 0 \tag{3.23}$$

here α denotes the large scale eddies and β represents the small scale eddies.

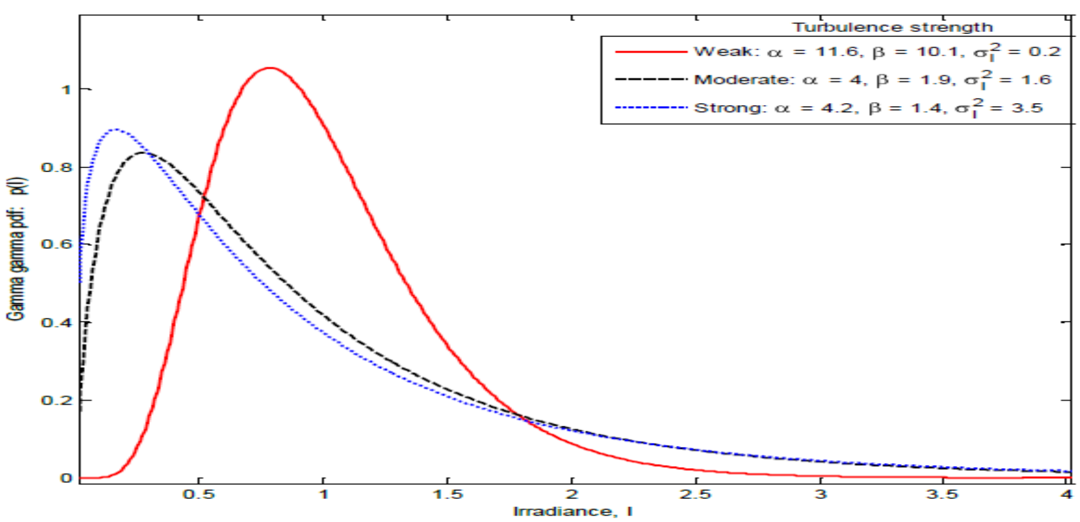


Figure 3.3: Gamma-Gamma probability density function for three different turbulence regimes, namely weak, moderate and strong.

$K_n(.)$ is defined as the modified Bessel function of the 2^{nd} kind of order n and gamma function is represented by Γ. Finally assuming the photo detector is to be a plane wave, then the probability density functions (pdfs) of α and β are given by [43]:

$$\alpha = \left[exp\left(\frac{0.49\sigma_l^2}{(1+1.11\sigma_l^{12/5})^{7/6}} \right) - 1 \right]^{-1} \quad (3.24a)$$

$$\beta = \left[exp\left(\frac{0.51\sigma_l^2}{(1+0.69\sigma_l^{12/5})^{5/6}} \right) - 1 \right]^{-1} \quad (3.24b)$$

3.5 The Negative Exponential Turbulence Model

While traveling (in saturation regime) large distance i.e. some kilometers, the light beam suffers from scattering effect severely. Now the amplitude variation in this region while traversing the atmospheric turbulence channel is known to follow Rayleigh distribution [18]: Then we model a new turbulence model named as Negative Exponential channel model as follows:

$$p(I) = \frac{1}{I_0} exp(-I/I_0) \qquad I_0 > 0 \quad (3.25)$$

here the mean received irradiance, E[I] = I_0. The value of scintillation index, S.I.→1 in the saturation regime. It is noteworthy that other For weak to strong turbulence

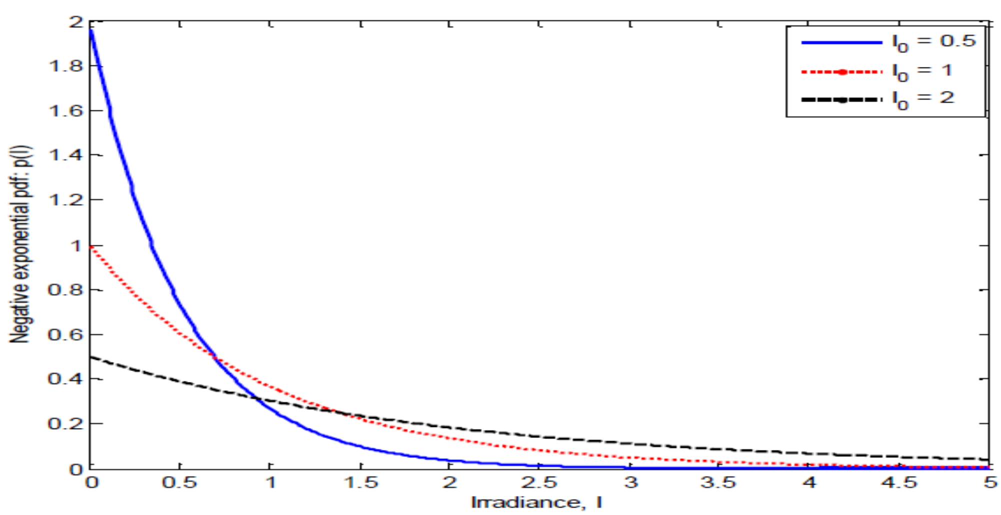


Figure 3.4: Negative exponential probability density function for different values of I_0.

model log-normal-Rician and the I–K distributions are also popular and the K-model is only useful for strong atmospheric turbulence region. Then for different values of I_O the probability density function of Negative Exponential turbulence channel is shown in Fig. 3.4.

3.6 Summary

The very basics of three most important turbulence channel models are discussed in this section in free space communication (FSO) link. Among them, the log normal distribution is valid for weak atmospheric turbulence region.Where multiple scattering is observed, gamma-gamma channel model is very useful. These pdfs will help us for further investigation in case of estimation of the bit error rate (BER). Later on we mathematically modeled the the BER equation in case of weak atmospheric turbulence. So if we want to investigate the performance of a FSO link we must choose the proper pdf according to our regime i.e. strong, moderate or weak.

CHAPTER 4
FSO MODULATION TECHNIQUES

4.1 Introduction

While traveling through atmospheric turbulence channel, the signal is distorted for which recovering the signal at the receiver end may be difficult. So for long distance transmission, we can follow up a technique called modulation, so that the signal can travel more distance than without modulation scheme without being affected. Then the signal will be more distorted. Different types of modulation scheme are shown in Fig. 4.1. This chapter will cover two important modulation technique i.e. OOK (On-

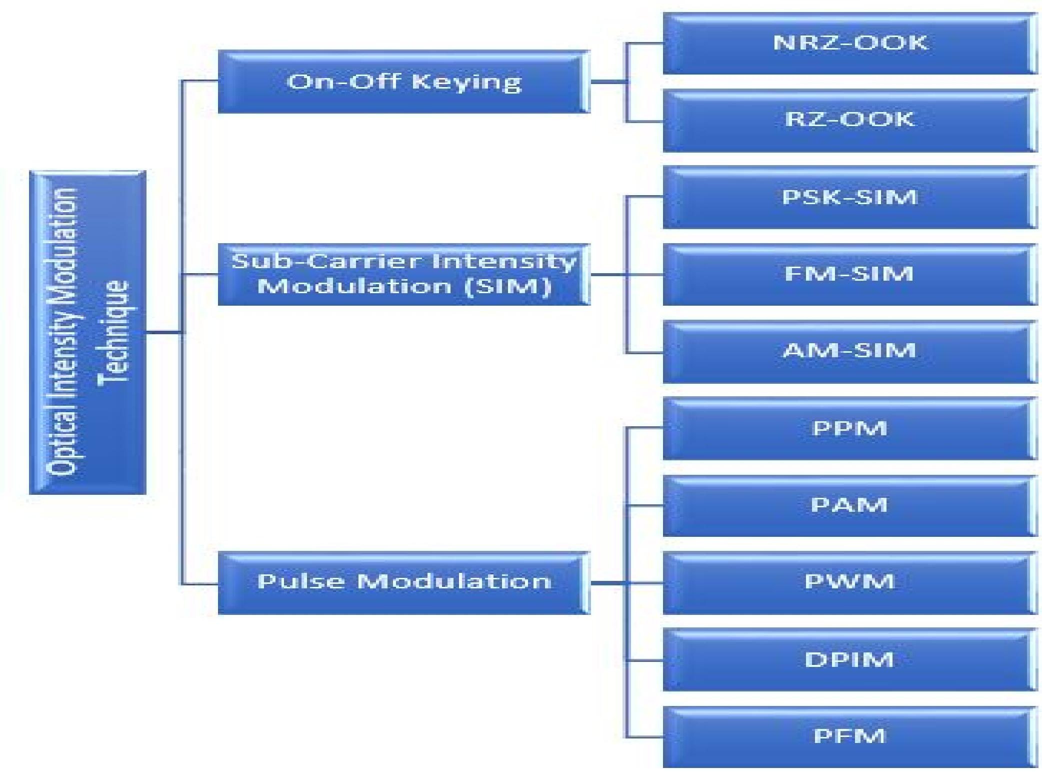


Figure 4.1: Modulation tree.

Off Keying) and PPM (Pulse Position Modulation) because later on these modulation technique will be used for the derivation of the bit error rate (BER). As we know BER is an important parameter for designing a FSO link so that we can acquire a desired SNR level during the transmission of the information. Due to the limitation of the transmitter optical power, the performance of modulation techniques is calculated in terms of average photo-detector received power. The fundamental condition for selecting a modulation scheme is that it must be power efficient. Also the bandwidth requirement is an important parameter in selecting the modulation scheme.

Among the modulation schemes if we consider the simplicity, then it comes to the OOK modulation technique. In case of FSO this modulation scheme is very popular. It is mainly chosen for its ease of implementation and simplicity in design [20]. If we consider PPM modulation scheme, it is more useful because it suffers less from atmospheric turbulence than OOK modulated signal. But the problem is that, in case of PPM modulated signal it requires higher bandwidth than OOK and the design of transmitter and receiver is quite complex for FSO link in case of larger transmission distance.

4.2 On-Off Keying

As we discussed above, OOK is very simple modulation technique. It can use either non-return-to-zero (NRZ) or return-to-zero (RZ) pulse formats. Pick power of optical pulse, $\alpha_e P_T$ represents a '0' in NRZ-OOK whereas peak power P_T represents a '1' while data transmission. The typical range of α_e is $0 \leq \alpha_e < 1$. But in case of OOK-RZ as the pulse duration is lower than the bit duration, this improves the amount of received power. But in this case, the problem is that it requires higher bandwidth [43].

4.3 Pulse Position Modulation

Pulse position modulation is an orthogonal modulation technique from Fig.4.1. This PPM modulation technique is not as simple as OOK modulation technique, the transmitter and receiver requires complex design, but it improves the FSO link performance by improving the power efficiency than OOK though it requires excess bandwidth. PPM is mainly based on the design of M possible symbols. There are $log_2 M$ data bits there. If M-arry PPM indicates the order of PPM modulation scheme. Each symbol has a constant power P_T. The data or information is encrypted in the symbol. Then we can write the slot duration T_s as:

$$T_S = \frac{T log_2 M}{M} \tag{4.1}$$

In Fig. 4.2 we show the PPM of 16 order and 4-bit OOK modulation technique. The

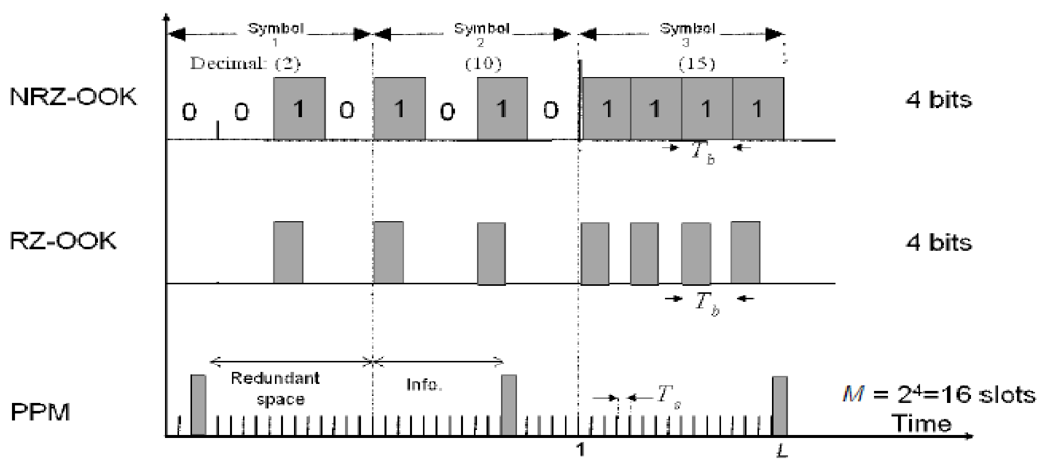


Figure 4.2: Time waveforms for 4-bit OOK and 16-PPM.

transmitter sends the optical signal in the air by modulating, so to recover the original signal we need to demodulate it at the receiver side. So the photo-detector must have proper symbol and slot synchronization to get the original data without distortion or time delay. In deep laser communication, it is very popular modulation technique since it is power efficient in free-space-optical (FSO) communication [44]. While detecting the transmitted signal at the receiver, the energy in each slot is detected by the photo-detector. In direct detection method, it means to count the no. of released electrons in each time slot.

Now, if we want to compare the modulation schemes between the OOK and PPM, then we can write:

Table 4.1: Comparison of FSO modulation techniques.

On-Off Keying	**Pulse Position Modulation**
Simple to implement	Power efficient
Synchronization not required	Synchronization required
Adaptive threshold required in fading channels	Adaptive threshold not required in fading channels
Suboptimal with fixed threshold	High bandwidth requirement

4.4 Summary

This chapter summarizes the modulation schemes of On-Off Keying (OOK) and Pulse Position Modulation (PPM). By selecting the proper modulation scheme, we can reduce the channel fading effect and increase signal strength. So, to select the modulation scheme, we must consider the simplicity, power efficiency and bandwidth efficiency. In case of OOK, the transmitter and receiver design is very simple and easy to implement. But the BER is more compared to the PPM modulation scheme and it is power efficient. If we want to improve the link performance, we can use PPM modulation technique, but PPM has very poor bandwidth efficiency which we can not neglect. Thus to model the expressions for different modulation schemes in free-space-communication (FSO), we need to know about their basic working principle. So, we must select the proper modulation technique as per our requirement or for analyzing purpose.

CHAPTER 5
SYSTEM MODEL

In this section FSO system model under consideration is described. Two separate analysis was carried out one is FSO communication under weak atmospheric turbulence for a typical single hop transmitter receiver system with OOK modulation and another is multi-hop relay based FSO system with Optical Pulse Position Modulation (OPPM). For both case weak atmospheric turbulence is considered.

5.1 Single Hop

An FSO system consisting of a source terminal node (S) with one transmitter aperture for transmitting data to the receiver and one destination node (D) with one receiver aperture (for receiving the transmitted data from the transmitter hop) is assumed. Type of modulation considered is OOK and aforementioned system model is portrayed in Fig. 5.1. Transmitter consists of an Optical PPM (OPPM) modulator. An FSO system with OPPM modulation direct detection with loss between any two hops or nodes due to atmospheric turbulence and pointing error is assumed between $(k-1)^{th}$ and k^{th} hops. There are N+1 nodes for N hops.

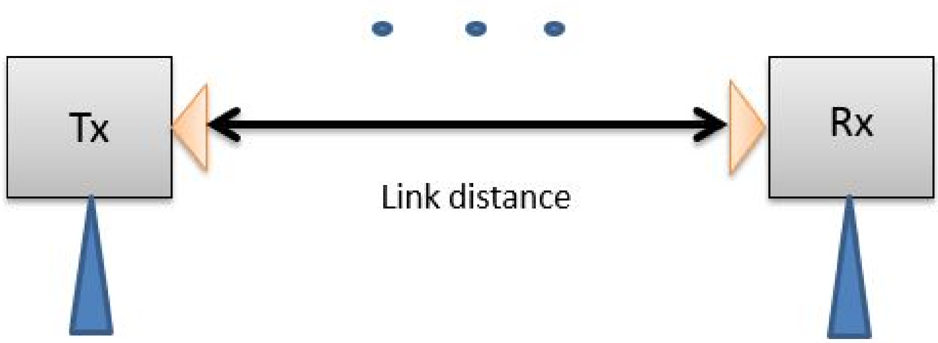
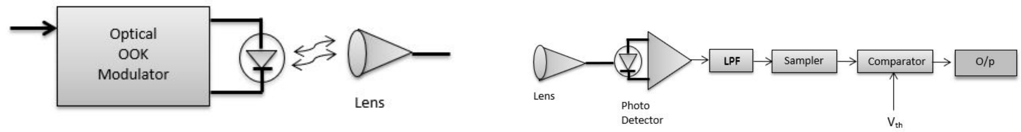


Figure 5.1: An FSO link with a Tx and Rx.



(a) *OPPM Transmitter.* (b) *OPPM Reciverer.*

Figure 5.2: Optical PPM Tx and Rx.

5.2 Multiple Hop

An FSO system consisting of a source terminal (S) with one transmitter aperture for transmitting data to the 1^{st} hop), seven hops with one receiver aperture (for receiving the tx data sent from the source or from the $(k-1)^{th}$ hop) and one transmitter aperture (for transmitting signals to the receiver or to the next hop) and one desti-

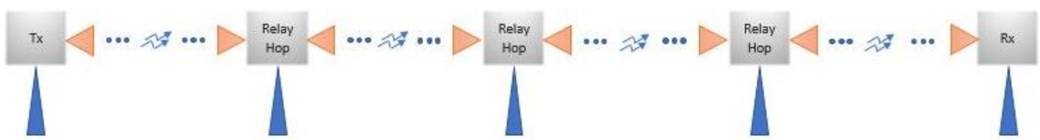
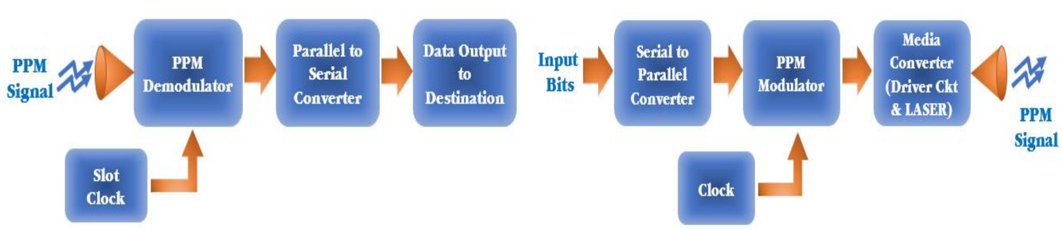


Figure 5.3: An FSO link with Multiple Hops.

nation node (D) with one receiver aperture (for receiving the tx data by the seventh hop) is assumed. Type of modulation used is OPPM and aforementioned system model is portrayed in Fig. 5.3 and Fig. 5.4. Transmitter consists of an Optical PPM (OPPM) modulator. An FSO system with OPPM modulation direct detection with loss between any two hops or nodes due to atmospheric turbulence and pointing error is assumed between $(k-1)^{th}$ and k^{th} hops. There are N+1 nodes for N hops. In the



(a) *OPPM Transmitter.* (b) *OPPM Receiver.*

Figure 5.4: Optical PPM Tx and Rx.

source terminal, there is a PPM modulator which consists of a serial to parallel converter followed by a PPM modulator. A laser diode is driven by this OPPM modulator output for media conversion. Then the PPM modulated optical signal is transmitted. The transmitted optical signal is received by a relay node which amplifies the signal and retransmits to the next relay node. Finally, the optical signal is received by the optical receiver at the destination and demodulation is carried out by optical PIN Photo Diode (PD) and PPM demodulator.

5.3 FSO Channel Fading Model

One of the main challenges of FSO channel model is turbulence induced fading (TIF), which occurs due to changes of temperature and pressure. For distance dependent turbulence fading, there are some popular channel models. We have considered pointing error and weak turbulence. Since The property of each of the hops is considered same, the PDF of each hop is considered same.

5.3.1 Atmospheric Turbulence-Induced fading

Due to variation of refractive index, the optical signal is affected severely due to inhomogeneities the performance of the signal is degraded. We here discuss weak turbulence with popular distribution model of log normal distribution [7].

$$f^a_{h_{k-1,k}}(h^a_{k-1,k}) = \frac{1}{2h^a_{k-1,k}\sqrt{2\pi\sigma_x^2}} exp\left(- \frac{(ln(h^a_{k-1,k})+2\sigma_x^2)^2}{8\sigma_x^2} \right) \tag{5.1}$$

where σ_x^2 is the turbulence induced variance and can be calculated by [10]:

$$\sigma_x^2 = 1.33k^{7/6}C_n^2(L)^{11/6} \text{ and } {\sigma_x}^2 < 1.2 \tag{5.2}$$

5.3.2 Pointing Error

We consider a model of misalignment fading in which the receiver radial displacement is Rayleigh distributed. The probability density function (PDF) then can be written as [7]:

$$f_{h^{p}_{k-1,k}}(h^{p}_{k-1,k}) = \frac{\gamma^2}{A_0^{\gamma^2}\,(h^{a}_{k-1,k})^{\gamma^2-1}} \tag{5.3}$$

where $\gamma = w_{zeq}/2\sigma_s$ is the ratio between equivalent beam radius w_{zeq} and pointing error displacement standard deviation σ_s at the receiver [7].

$$A_0 = [erf(v)^2] and \qquad w^2_{zeq} = w^2_z \frac{\sqrt{\pi} erf(v)}{2vexp(-v^2)} \tag{5.4}$$

Here $v = \sqrt{\pi}a/\sqrt{2}w_z$. w_z is the Gaussian beam radius at a distance z and $z = L_{k-1,k}$

5.3.3 Channel Statistical Model

Considering both the PDF of weak turbulence and pointing error we generalize $h_{k-1,k}$ as the channel state (for single hop). where $h_{k-1,k} = h^a_{k-1,k} \times h^p_{k-1,k}$. So the probability distribution function is expressed as [7]:

$$f_{h_{k-1,k}}(h_{k-1,k}) = \int f_{h_{k-1,k}|h^a_{k-1,k}}(h_{k-1,k} \mid h^a_{k-1,k}) \times f^a_{h_{k-1,k}}(h^a_{k-1,k}) dh^a_{k-1,k} \tag{5.5}$$

where we define $h^a_{k-1,k}$ as turbulence state, $f_{h_{k-1,k}}(h_{k-1,k})$ as the PDFs of parameter, $f^a_{h_{k-1,k}}(h^a_{k-1,k})$ as the PDF of weak atmospheric turbulence and $f_{h_{k-1,k}|h^a_{k-1,k}}(h_{k-1,k} \mid h^a_{k-1,k})$ as the conditional PDF. This is the equation for single hop. Here,

$$f_{h_{k-1,k}|h^a_{k-1,k}}(h_{k-1,k} \mid h^a_{k-1,k}) = \frac{1}{h^a_{k-1,k}} f^p_{k-1,k}\left(\frac{h_{k-1,k}}{h^a_{k-1,k}}\right)$$
$$= \frac{\gamma^2}{A_0^{\gamma^2}}(h^a_{k-1,k})\left(\frac{h_{k-1,k}}{h^a_{k-1,k}}\right)^{\gamma^2-1} ; 0 \le h \le A_0 h^a_{k-1,k} \tag{5.6}$$

Substituting Equation (5) and (6) we get,

$$f_{h_{k-1,k}}(h_{k-1,k}) = \frac{\gamma^2}{A_0^{\gamma^2}}(h_{k-1,k})^{\gamma^2-1}\int_{(h_{k-1,k})A_0}^{\infty} f^a_{h_{k-1,k}}(h^a_{k-1,k})\frac{1}{2h^a_{k-1,k}\sigma_x\sqrt{2\pi\sigma_x^2}} \times exp\left(-\frac{(ln(h^a_{k-1,k})+2\sigma_x^2)^2}{8\sigma_x^2}\right) \tag{5.7}$$

Considering weak turbulence $\sigma_x^2 \leq 0.3, f^a_{h_{k-1,k}}(h^a_{k-1,k})$ is Log-Normally Distributed. So, finally from equation (7) we can write,

$$f_{h_{k-1,k}}(h_{k-1,k}) = \frac{\gamma^2}{2A_0^{\gamma^2}}(h_{k-1,k})^{\gamma^2-1} \times erfc\left(\frac{ln\frac{(h_{k-1,k})}{A_0}+\mu}{\sqrt{8}\sigma_x}\right)e^{(2\sigma_x^2\gamma^2(1+\gamma^2))} \tag{5.8}$$

where $\mu = 2\sigma_x^2(1+2\gamma^2)$ is the mean. Finally, for calculating overall PDF, we convolute the combined PDF, $f_{h_{k-1,k}}(h_{k-1,k})$, k times for $(k+1)^{th}$, $(1 \leq k+1 \leq N)$ hop as,

$$f_{h_{0,k}}(h_{0,k}) = f_{h_{0,k-1}}(h_{0,k-1}) \circledast f_{h_{0,k-1}}(h_{0,k-1}) \tag{5.9}$$

where $f_{h_{0,k-1}}(h_{0,k-1})$ can be found as:

$$f_{h_{0,k-1}}(h_{0,k-1}) = f_{h_{0,k-2}}(h_{0,k-2}) \circledast f_{h_{0,k-2}}(h_{0,k-2}) \tag{5.10}$$

Similarly $f_{h_{0,k-2}}(h_{0,k-2})$ can also be found in aforementioned method of re-convolving upto k times.

CHAPTER 6
PERFORMANCE ANALYSIS

This chapter deals with the incorporation of our assumptions for channel statistical model and system model in order to get an analytical result for practical scenario of Optical Free Space transmission under weak atmospheric turbulence. It is understandable that due to the effect of the atmospheric turbulence the performance will degrade and it is probable that BER will be high. In this chapter two separate analysis are carried out. One is for Single-hop-FSO Link and another is for Multiple-hop-FSO link.

6.1 Single-Hop-FSO Link Analysis

At first portion of our thesis work we analyzed a typical simple FSO link with one receiver and one transmitter as mentioned above in Chapter 5. which will be discussed in this section. Modulation scheme is considered to be Optical On-Off-Keying or Intensity Modulation. We have first found out the SNR Performance and then Conditional BER and lastly Average BER which is described in details in the following subsections.

6.1.1 Effect of Turbulence Variance

For weak atmospheric turbulence the channel statistical model is considered to be Log Normally distributed in chapter 5. Where the $\sigma_x{}^2$ is actually is Roytov Variance and given by the equation (5.2). In order to find the link distance for $\sigma_x{}^2 < 1.2$ it can be derived:

$$L = \frac{\sigma_x{}^2}{\left(1.2 \times C_n{}^2 \times k^{6/7}\right)^{6/11}} \tag{6.1}$$

6.1.2 Signal to Noise Ratio

For OOK modulation the transmitted signal is [2]:

$$s(t) = \sqrt{2P_t}e^{j\omega_c t} \times a_k \tag{6.2}$$

where P_t is the transmitted signal power. ω_c is the carrier frequency of optical signal and a_k is the k^{th} bit. Due to randomness of nature (variation of refractive index) the signal does not remain same while transmitting through channel. We here consider Shot noise and Thermal noise both as the noise factor. I_s is defined as the output signal of the photo-current from the photo-diode in the receiver [1,2].

$$\begin{bmatrix} I_d \end{bmatrix} = \begin{bmatrix} I^s_{a_k='1'} \\ I^n_{a_k='0'} \end{bmatrix} = \begin{bmatrix} R_d P_r I + n_o \\ n_o \end{bmatrix} \tag{6.3}$$

where $I^s_{a_k='1'}$ is the received signal and $I^n_{a_k='0'}$ is denoted as non signal parameter i.e. on time and off time of OOK modulator. Here R_d is the receiver sensitivity. The power received by the photo diode is not as same as transmitted power due to atmospheric attenuation. So we calculate SNR as the ratio of signal power to noise power, If the signal power is $(I^s_{a_k='1'})^2$ then [1,2],

$$(I^s_{a_k='1'})^2 = (R_d P_r I)^2 \tag{6.4}$$

Here R_d is the receiver sensitivity ; P_r is the received power;
The Shot noise is given by [1,2] :

$$\sigma^2_{shot} = 2qR_d P_r IB \tag{6.5}$$

where B = R_b is the effective electrical Bandwidth of LPF at the receiver; q is the electron charge;

And the Thermal noise is expressed by [1,2] :

$$\sigma^2_{thermal} = \tfrac{4k_BT}{R_L}B \tag{6.6}$$

k_B is Boltzman Constant ; T is the receiver temperature and R_L is the load resistor. Combining these two noise from equation (15) and (16), we get the total noise given by [1,2] :

$$\sigma^2_n = \sigma^2_{shot} + \sigma^2_{thermal} \tag{6.7}$$

So finally we calculate signal to noise ratio i.e. SNR by the expression:

$$SNR(I) = \frac{(R_dP_rI)^2}{2qR_dP_rIB + \frac{4k_BT}{R_L}B} \tag{6.8}$$

6.1.3 Bit Error rate

So the conditional BER can be calculated [2] :

$$BER_{OOK}(I) = \frac{1}{2}erfc\left(\frac{\sqrt{SNR(I)}}{2\sqrt{2}}\right) \tag{6.9}$$

So the average BER can be calculated by integrating equation while multiplying each value with its corresponding probability as: [1]:

$$BER_{OOK_{avg}} = \int BER_{OOK}(I) \times f_I(I)dI \tag{6.10}$$

Where $f_I(I)$ represents the PDF of Log-normal distribution for weak atmospheric turbulence.

6.2 Multi-Hop-FSO Link Analysis

At later portion of our thesis work we analyzed complicated Multi-hop-FSO link with one receiver, one transmitter with an number of relay nodes in between which also has mentioned above in Chapter 5, which will be discussed in this section. Modulation scheme is considered to be Optical Pulse Position Modulation (PPM). We also considered pointing error at the receiver. We have first found out the SNR Performance and then Conditional BER then Average BER which is described in details in the following subsections.

6.2.1 Signal to Noise Ratio

For PPM of M order modulation the transmitted signal is [8]:

$$s(t) = \sqrt{2P_t}e^{j\omega_c t} \times a_k \tag{6.11}$$

where P_t is the transmitted signal power. ω_c is the carrier frequency of optical signal and a_k is the k^{th} bit. Due to randomness of nature (variation of refractive index) the signal does not remain same while transmitting through $(k-1)^{th}$ hop to k^{th} hop. We here consider Shot noise and Thermal noise both as noise factors. I_s is defined as the output signal of the photo-current from the photo-diode in the k^{th} node [9].

$$\begin{bmatrix} I_k \end{bmatrix} = \begin{bmatrix} I_k^s \\ I_k^n \end{bmatrix} = \begin{bmatrix} R_d P_r h_{k-1,k} + n_k^s \\ n_k^n \end{bmatrix} \tag{6.12}$$

where I_k^s is the received signal and I_k^n is denoted as non signal parameter i.e. on time and off time of PPM modulation time slots. The power received by the photo diode is not as same as transmitted power due to atmospheric attenuation. So we calculate SNR as the ratio of signal power to noise power, If the signal power is I_s^2 then [9],

$$I_s^2 = (R_d P_r h_{k-1,k})^2 \tag{6.13}$$

where R_d is the receiver sensitivity ; P_r is the received optical power;
The Shot noise is given by [8] :

$$\sigma_{shot}^2 = 2qR_dP_rh_{k-1,k}\Delta f \tag{6.14}$$

where Δf = $Be/2$ is the effective electrical Bandwidth; q depicts electron charge ;
And Thermal noise is expressed by [8] :

$$\sigma_{thermal}^2 = \frac{8K_BT}{R_L}\Delta f \tag{6.15}$$

where K_B is Boltzmann Constant ; T signifies absolute temperature and R_L denotes load resistor. Combining these two noise from Equation (15) and (16), we get the total noise given by [8]:

$$\sigma_n^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 \tag{6.16}$$

So finally we calculate SNR by the expression:

$$SNR(h_{k-1,k}) = \frac{I_s^2}{\sigma_n^2} \tag{6.17}$$

6.2.2 Energy Over a Bit

We assume L number of bits are sent in a word with the Pulse Position Modulation where pulse width $T_b = L/(2^LBr)$ [14]. Here $L = log_2M$ and Br = Bit Rate. We can now calculate the energy over a PPM bit, E_b by the equation:

$$E_b = P_r \times T_b \tag{6.18}$$

where P_r is defined as received power and T_b denotes bit period.

6.2.3 Bit Error Rate

So the conditional BER can be calculated [11] :

$$BER_{PPM}(h_{k-1,k}) = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR(h_{k-1,k})\frac{M}{2}log_2 M}\right) \tag{6.19}$$

where PPM modulation order, $M = 2^L$, and L is the number of bits per transmission word and $SNR(h_{k-1,k})$ can be shown as (17):

$$SNR(h_{k-1,k}) = \frac{(R_d P_r h_{k-1,k})^2}{2qR_d P_r h_{k-1,k}\Delta f + \frac{8K_B T}{R_L}\Delta f} \tag{6.20}$$

So the average BER can be calculated by integrating Equation (19):

$$BER_{PPM} = \int BER_{PPM}(h_{k-1,k}) \times f_{h_{k-1,k}}(h_{k-1,k}) dh_{k-1,k} \tag{6.21}$$

where $f_{h_{k-1,k}}(.)$ represents the combined PDF for Log-normal distribution and Pointing Error PDF for single hop according to Equation (8).
For multiple hop:

$$BER_{PPM} = \int BER_{PPM}(h_{0,k}) \times f_{h_{0,k}}(h_{0,k}) dh_{0,k} \tag{6.22}$$

where $f_{h_{0,k}}(h_{0,k})$ is from Equation (9):

$$f_{h_{0,k}}(h_{0,k}) = f_{h_{0,k-1}}(h_{0,k-1}) \circledast f_{h_{0,k-1}}(h_{0,k-1}) \tag{6.23}$$

CHAPTER 7
RESULTS AND DISCUSSIONS

This section deals with our findings of performance evaluation by numerically computing the aforementioned mathematical models and equations from Section 3 and 4. We have evaluated the bit error rate and some other results derived from these curves using MATLAB. At first, we considered the total transmission distance is fixed to 14 km. Then we assumed a fixed hop distance of 4 km. For both case multi-hop transmission is analyzed. Parameters those we assumed are shown in the Table below:

Table 7.1: Table of Values of Constants and parameters.

Parameters	**Values**
PIN Photo-diode Responsivity, R_d	0.85 A/w
Received Power, P_r	-35 dBm to 5 dBm
Electron Charge, q	1.6×10^{-19}C
Frequency Deviation,Δf	5 GBps
Jitter Standard Deviation, σ_s	30cm
Beam Radius, w_z	2.5 m
Refractive Index variation, C_n^2	$10^{-13}m^{-2/3}$
PD Load Resistance, R_L	100 Ω
Laser Wavelength, λ	1550nm
Total link Distance, L	14 km
Log Normal Variance, σ_x^2	$0.1 \leq \sigma_x^2 \leq 0.7$

7.1 Results from Analysis Considering Single Hop

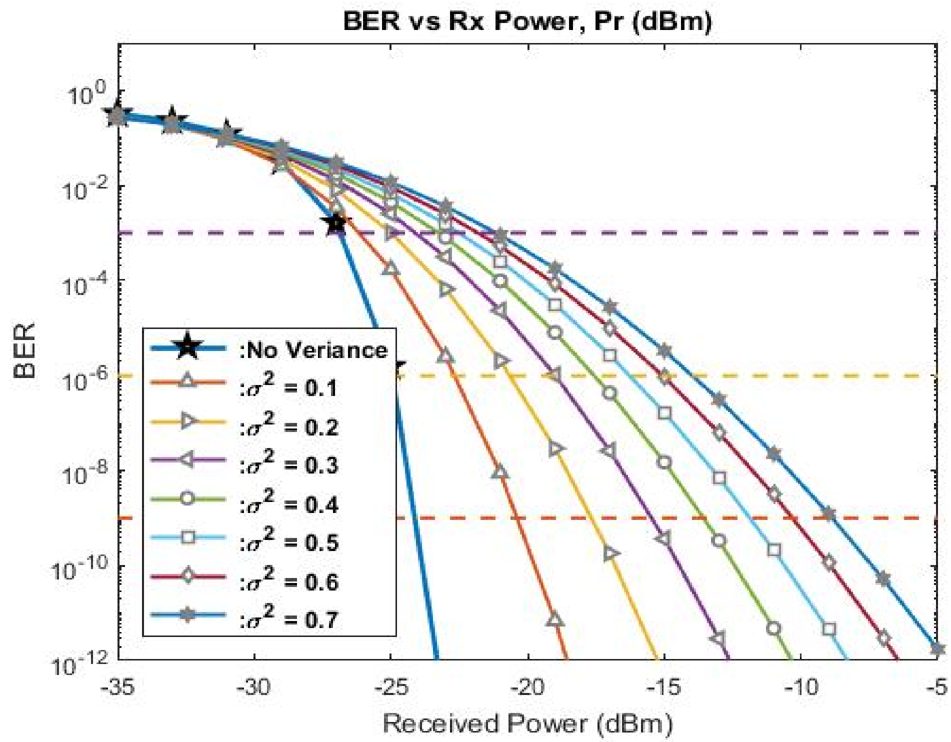


Figure 7.1: BER vs Rx Optical Power with various σ^2.

Fig.5.1 shows the plots of BER vs. Received power for various turbulence variances. It is found that the system performance degrades due to the influence of atmospheric turbulence. At higher variance, the required optical power is more at a given data rate. For example if Receiver Sensitivity is -25 dBm then for ideal case where atmospheric turbulence variance is zero the attainable BER is 10^{-6} whereas with the slight increase in atmospheric turbulence i.e. due to increase in σ^2 BER increases drastically to about 10^{-3}.For other values of receiver sensitivity it can also be seen that BER increase drastically for a increase in σ^2.

It is seen that for OOK minimum required optical power at the receiver for BER = 10^{-3} is -28dBm, less than which causes erroneous transmission of a signal and also can be seen that as aforementioned the high the turbulence induced fading is the more receiver sensitivity is required.

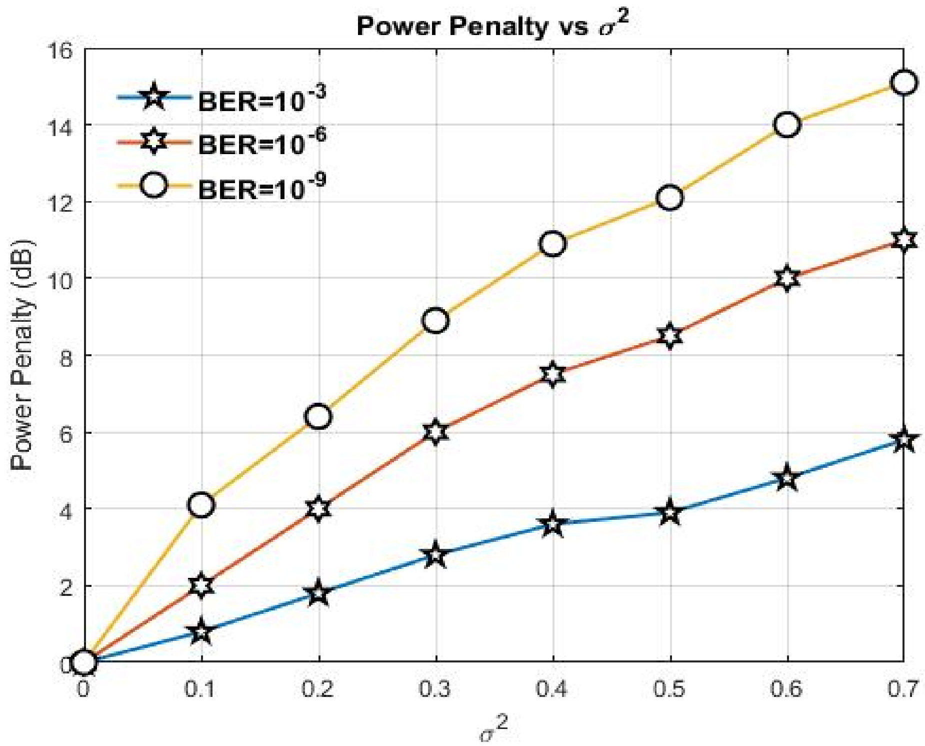


Figure 7.2: Power Penalty (dB) vs σ^2 for various required BER value.

Form Fig. 7.1 the effect of turbulence can be obtained by plotting the fading variance against the power penalty and the plots are shown in Fig. 7.2. The power penalty can be found from the difference between required optical power at the receiver (Pr) for no variance and Pr of other curves for a particular BER = 10^{-3}, 10^{-6} or 10^{-9} then these values of Power Penalty is plotted vs variance in Fig. 7.2, σ^2. It is found that power penalty increases with the increase in σ^2. It is also observed that for same turbulence level the fading penalty is higher for lower BER. For example, when the turbulence variance is 0.5 the fading penalty are 4 dB , 8.2 dB and 12.2 dB for BER of 10^{-3}, 10^{-6} and 10^{-9}, respectively.

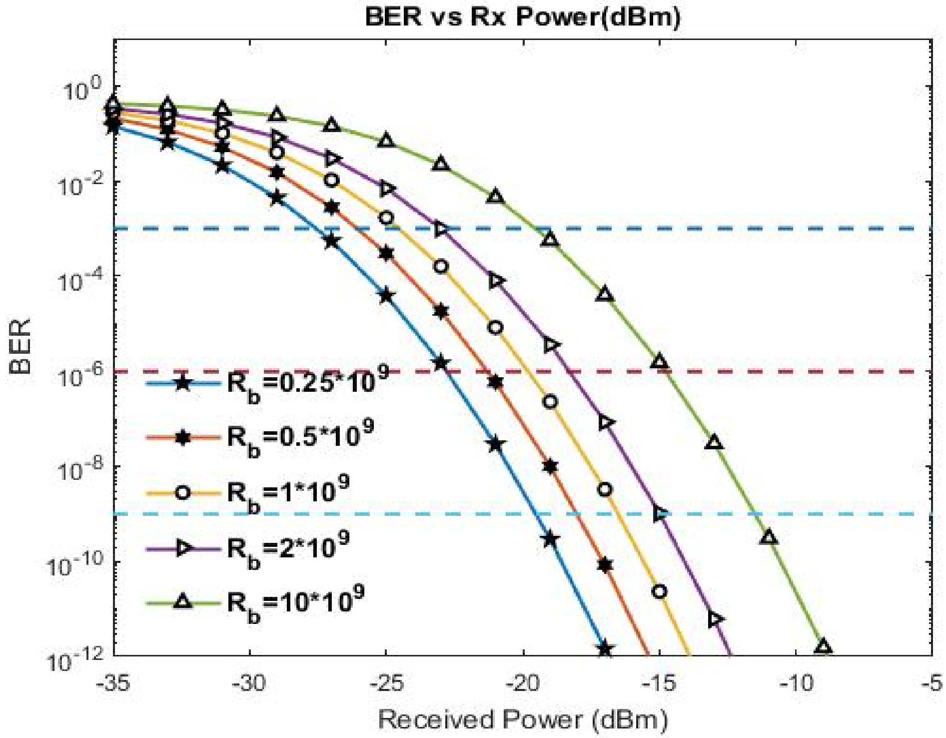


Figure 7.3: BER vs Received Optical Power (dBm) with various Bit Rate, R_b.

In Fig. 7.3 BER is plotted vs Received power taking Bit Rate, taking R_b as parameter. It is found that for same Receiver Sensitivity with the increase in R_b BER also increases. We found it by varying cut off bandwidth, B=R_b of LPF in receiver.

It is found that if Bit Rate is doubled then required optical power for detection keeping a certain BER is about 2dB. For example in order to achieve a BER of $10{-}9$ required receiver power for R_b = 250 Mbps, 500 Mbps, 1 Gbps, 2 Gbps the required optical power at the receiver are about -19.9 dBm, -17.8 dBm, 16.2 dBm, -14 dBm,

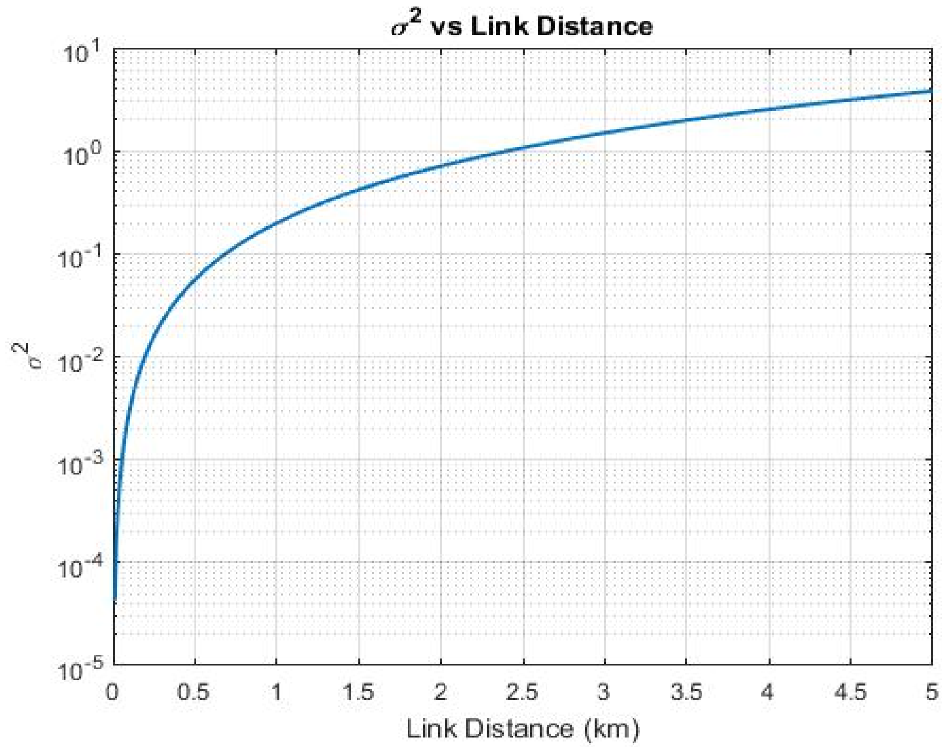


Figure 7.4: σ^2 vs Link Distance (km).

Fig. 7.4 shows the relation between variance and link distance with a particular refractive index structure parameter. From the figure we found that the variance is proportionate to the link distance but after a certain distance (3km) the effectiveness of the variance with link distance became comparatively less.

It is found that for about 4 km the effect of turbulence, σ_x^2 is about 1.2 and it is also found that upto 0.5 km the effect of turbulence increases very drastically then as aforementioned this effect of atmospheric turbulence variance does not increase much.

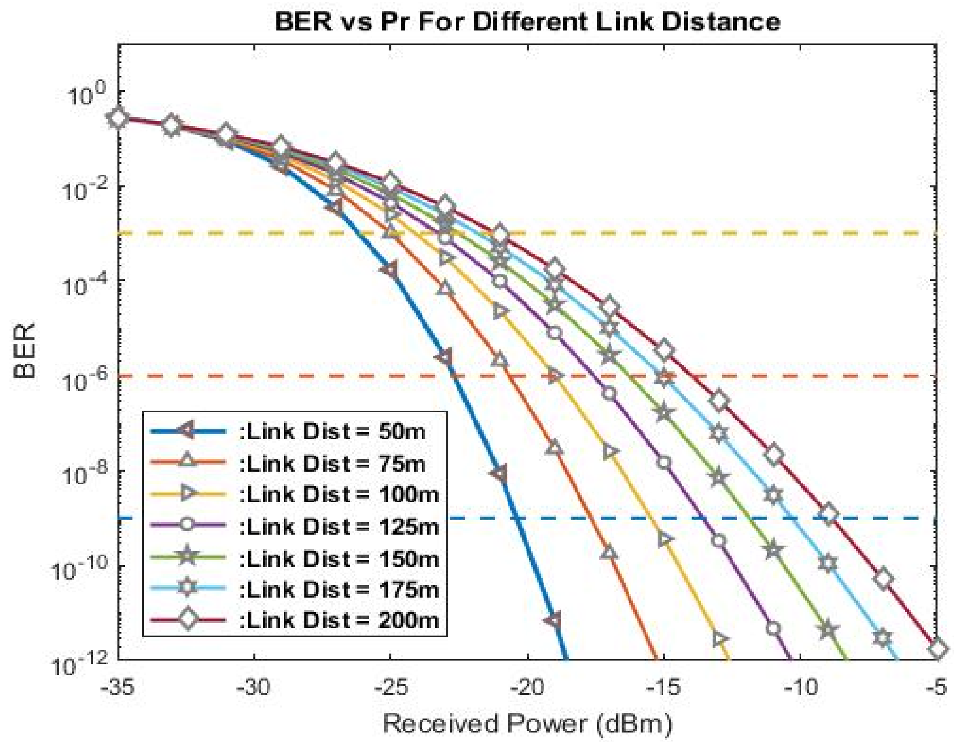


Figure 7.5: BER vs Received Optical Power (dBm) with various Link Distance (km).

BER vs Received Power is plotted in Fig. 7.5 taking Link Distance as parameter where the dependence on the link distance L is illustrated for Optical On-Off-Keying or Intensity Modulation. It is further assumed the operating wavelength is λ = 1550 nm, $C_n^2 = 1 \times 10^{-13} m^{-2/3}$. As expected, the BER increases with the increase in link distance. For example in order to achieve a BER of 10^{-9} for link distance 50m, 75m, 100m, 125m, 150m, 175m, 200m the required received optical power is needed to be -20.9dBm, -17.5dBm, -14.7dBm, -12.5dBm, -11.1dBm, -9.7dBm, -6dBm accordingly. So it is understandable that when link distance increases the atmospheric turbulence induced variance also increases and accordingly the value of PDF decreases. So the performance degrades and requires more power to recover the signal.

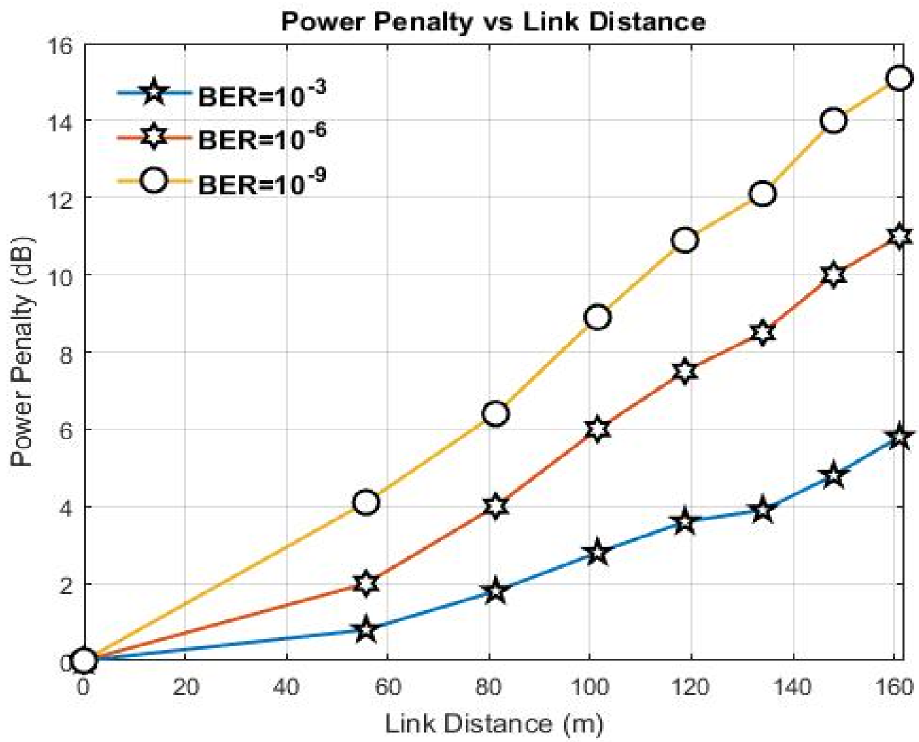


Figure 7.6: Power Penalty vs σ^2 for various Required BER Value.

Form Fig. 7.5 Power Penalty is derived and plotted in Fig. 7.6 vs Link Distance and it is Found that for a particular Bit Rate with the increase in Link distance power Penalty also increases to get a certain BER of 10^{-3}, 10^{-6} or 10^{-9}

7.2 Results from Analysis Considering Multiple Hop

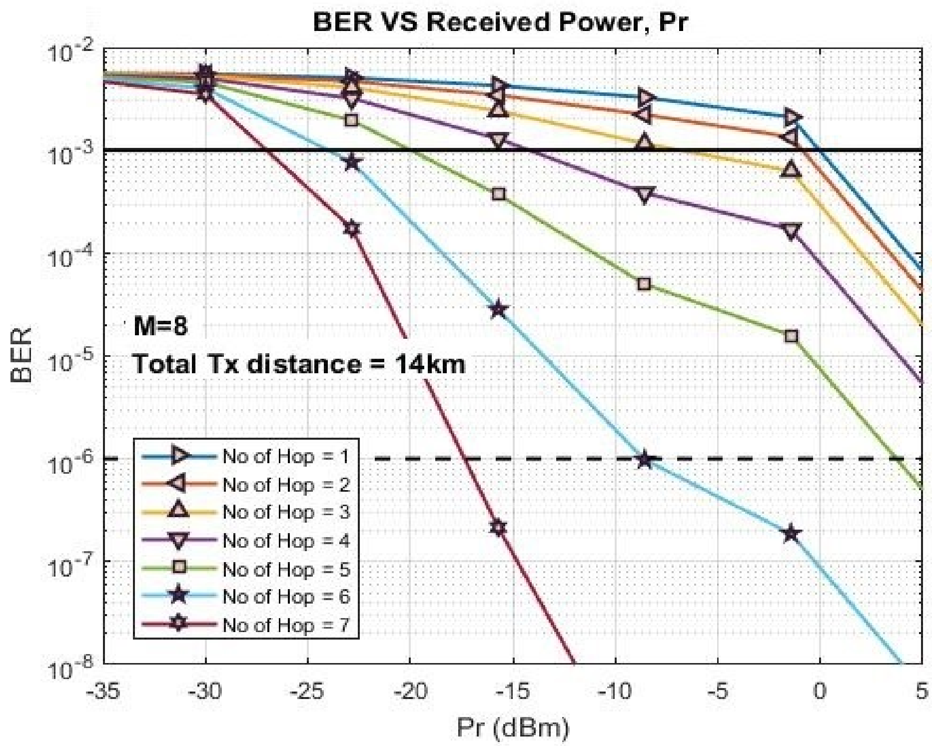


Figure 7.7: BER vs Rx Optical Power with various no. of Hops.

For multiple hop FSO system performance acquired should be developed than the performance acquired from single hop transmission. In multiple hop Free Space Optical Communication system in each node signal is received and then it is amplified and then retransmitted to next hop and thus the transmission is continued upto the receiver node. Our findings also supports this hypothesis.

In Fig. 7.7 the bit error rate (BER) performance vs Received optical power for various number of hops is portrayed. It is found that, if the number of hop increases, then the BER decreases (i.e. the BER curve shifts to left) considerably for transmission distance 14 km with PPM modulation order 8. For maximum number of hops the best performance is found which is showed in this figure. It can be also found that in order to attain BER 10^{-6} keeping required optical power less than 5 dBm, minimum number of hops required is 5.

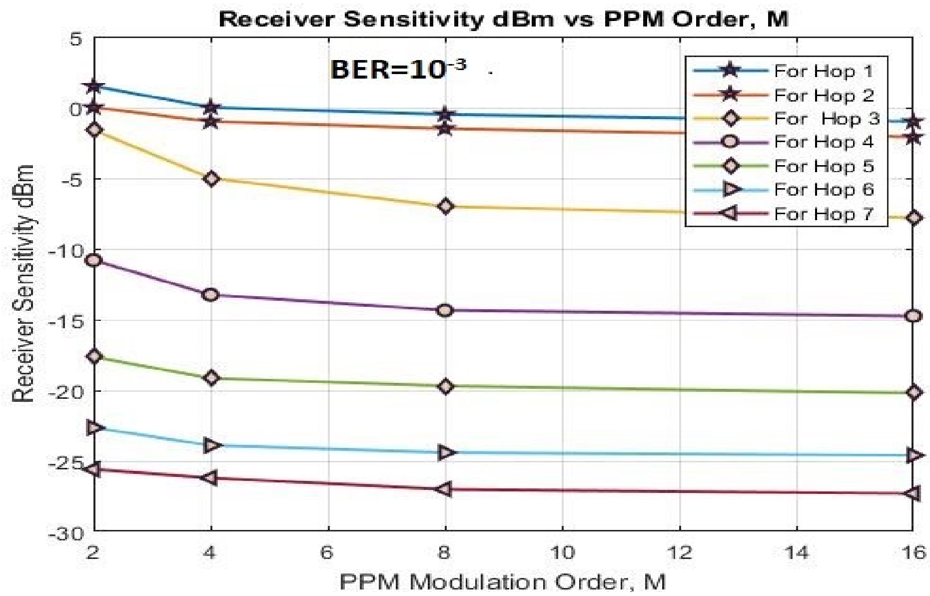


Figure 7.8: Receiver Sensitivity vs Order of PPM Modulation of BER 10^{-3}.

From Fig. 7.7 we can derive the required receiver sensitivity for a fixed BER value. We have derived receiver sensitivity for BER = 10^{-3} and also for BER = 10^{-6} depicted in Fig. 7.8 and Fig. 7.9. In Fig. 7.8 and Fig. 7.9 it is found that for lower

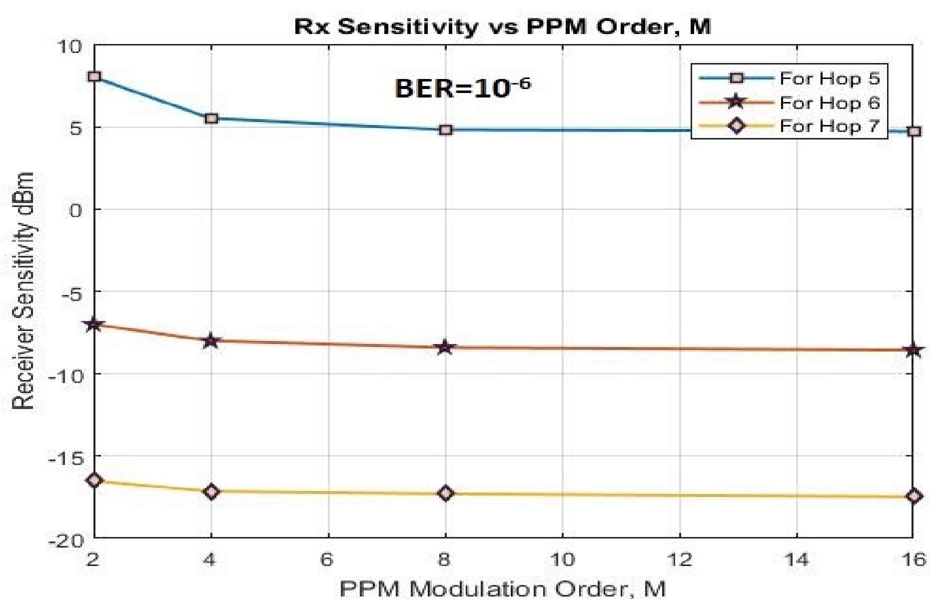


Figure 7.9: Receiver Sensitivity vs Order of PPM Modulation for BER 10^{-6}.

PPM oder higher receiver sensitivity is required. In case of acquiring BER =10^{-3} considering PPM order 4, required receiver sensitivity 0 dBm, -1 dBm, -5 dBm and

-26.57 dBm for single hop,double hop,third hop and seventh hop accordingly.Thus, the required receiver sensitivity for other PPM modulation order can be found from the Fig.5.8 for BER= 10^{-3}.Similarly from Fig. 7.9, It is found that in order to acquire BER =10^{-6} required receiver sensitivity is 5 dBm, -7.66 dBm and -16.89 dBm for fifth and sixth hop and seventh hop respectively. We also calculated the energy over a

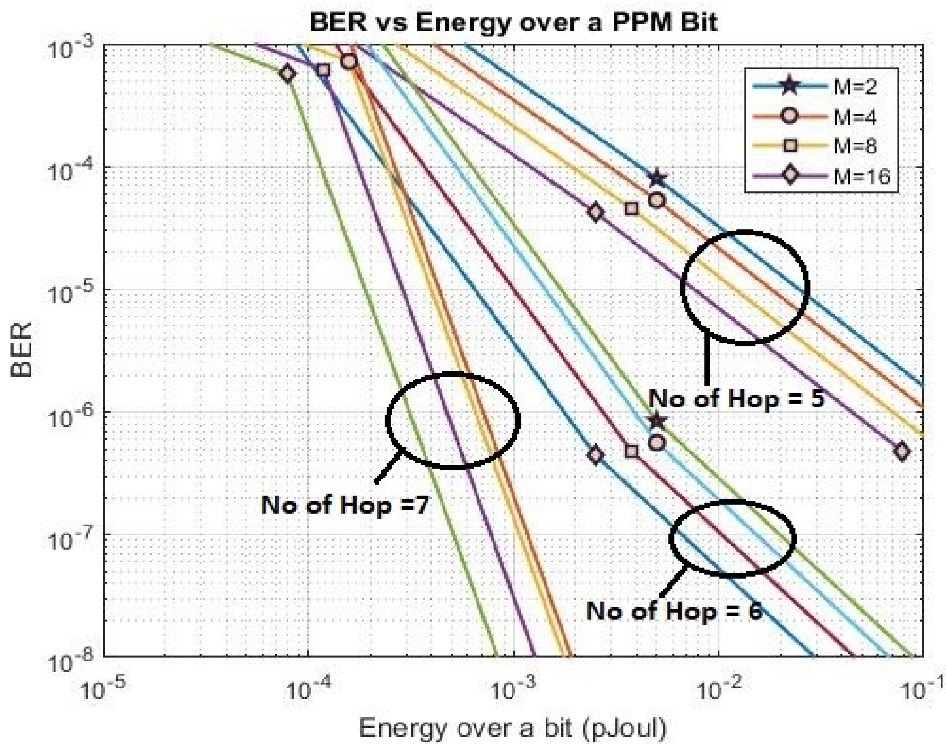


Figure 7.10: BER vs Energy over a PPM bit.

PPM bit which is depicted in Fig. 7.10 which shows the plot of BER vs Energy over a PPM bit. It is found that, for any hop with the increase in PPM order BER curve shifts left and BER decreases. It is also shown from Fig. 7.10 that for a lower BER, the required energy over a bit is high.

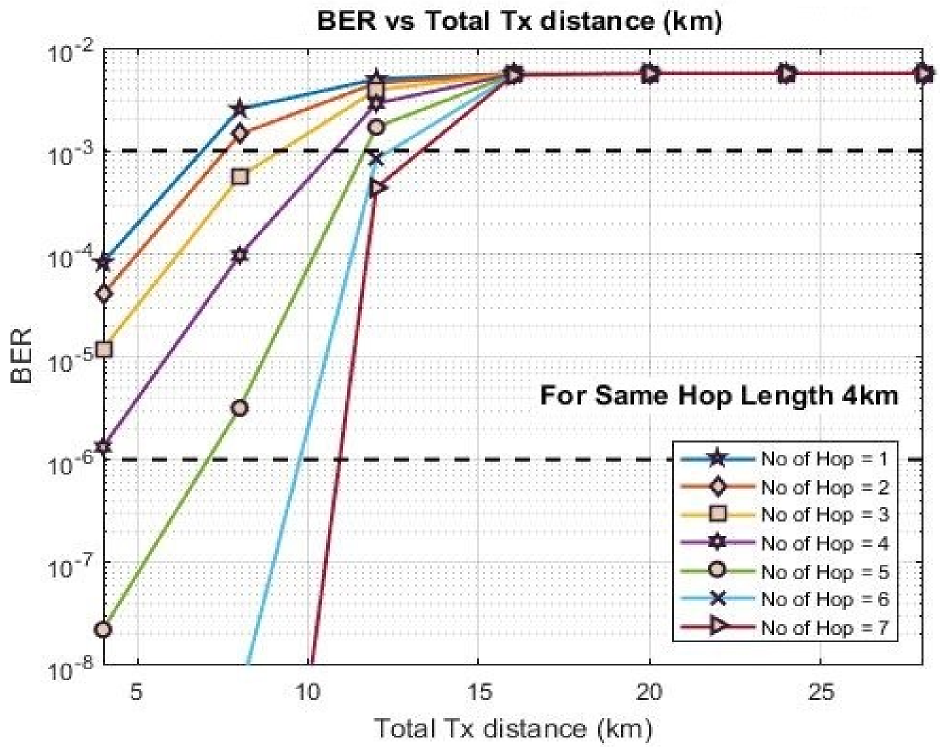


Figure 7.11: BER vs Total Tx distance (km).

Till now we have discussed about multi-hop transmission keeping the total Tx distance, fixed and number of hops were varied thus the performance was found to be improved. Now in Fig. 7.11, BER performance keeping the Hop distance, $d_{k-1,k}$ fixed to 4 km, the number of hop is varied and thus varying the total Tx distance is depicted and we can see that the BER increases with the increase in total Tx distance.

From this result one important point can be noted that, seeing this figure it can be found that in order to keep a constant BER of 10^{-6} using 5 hops maximum 7km can be transmitted where as using 6 or 7 hops the same BER performance can be achieved and at the same time maximum transmission distance can be increased to 9.8km and 11.8km accordingly while keeping the PPM order M=8.

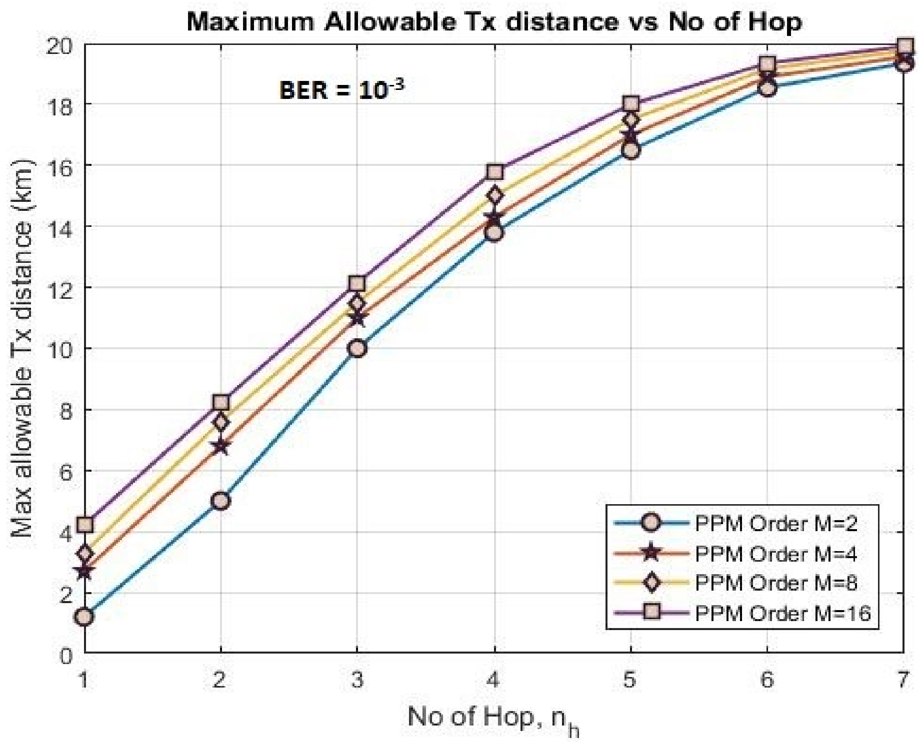


Figure 7.12: Max allowable Tx distance vs No of Hop for BER = 10^{-3}*.*

From these curves and for a fixed BER = 10^{-3} we have derived maximum transmission distance, depicted in Fig. 7.12, and found that with the increase in number of hops the maximum allowable Tx distance can be increased also results for various PPM orders are shown. When no. of hops n_h =4 and PPM order, M=2 for keeping BER= 10^{-3} max 14 km can be transmitted. If we increase PPM order 2 to 4,8,16 we can transmit maximum 14.76 km, 15.34 km and 16 km respectively for BER= 10^{-3}. Thus using seventh hop , we can transmit maximum 20 km for BER= 10^{-3} from our derived curves.

CHAPTER 8
CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

An analytical approach is presented to find the Bit Error Rate (BER) performance of a multiple-hop FSO link in presence of weak atmospheric turbulence and pointing errors, which is Log Normally distributed. The results show that better performance can be achieved by using more number of hops than no hop considering higher PPM order of modulation. The maximum allowable distance that reported in this paper and also other results can be used for designing multiple-hop FSO link.

So far all the outputs are showed and discussed about. It has been as mentioned in earlier chapters, two separate analyses have been carried out one is transmission of electronic signal optically through atmospheric turbulence induced channel and another is sending the same information through the same channel but this time between tx and rx multiple relay nodes are assumed to increase the performance of transmission. For each case we made some assumptions like we assumed in each case the light of wavelength 1550nm, we considered refractive index parameter as $10^{-13}m^{-2/3}$ and load resistance of detector is 100Ω etc. Again for analysis of typical single hop FSO link we considered On Off Keying as modulation scheme and for second case we considered Pulse Position Modulation as modulation scheme. So summarizing all the analyses it can be summarize that:

- Required received power is the least if there is no turbulence induced fading.
- Required received power increases if the turbulence induced fading increases and if the turbulence induced fading is less then the required received power is also less.
- Turbulence induced fading varies with link distance if the link distance increases

the turbulence variance also increases and if the link distance decreases, the turbulence variance also decreases.

- If the transmission bit rate is doubled then BER increases about by 2dB.
- It is also found that if the link distance between tx and rx is altered the BER also changes, if the link distance increases the BER increases due to the dependency of turbulence induced fading upon link distance.
- To mitigate this problem of BER dependency upon link distance and to increase transmission distance multi-hop FSO system is assumed and analyzed.
- Analyzing multi-hop FSO system it is found that better performance is achieved by using more number of hop in between transmitter and receiver.
- The dependency of Receiver Sensitivity with PPM order is also found out. It is found that for same BER less receiver sensitivity is required and also with the increase in PPM order The decrease in required receiver sensitivity is not too much.
- Keeping the hop distance an analysis is also found out from which an idea of maximum transmission distance (distance between source and destination) can be established, which is depicted in Fig. 6.11, where the figure portrays results for 8-array PPM

  .

In the wireless communication technology, FSO communication is very popular but an FSO link is greatly hampered due to atmospheric turbulence and pointing error. Keeping this in mind in our thesis work we carried out an analysis focusing on the Weak Atmospheric Turbulence and Pointing Error and our findings has been explained above, which can play an important role in designing an FSO link in practical world.

8.2 Scope of Future Research Work

In the free space optical communication, the atmospheric channel is prone to different atmospheric condition. So actual parameters need to be selected for maintaining desired specific bit error rate (BER). In future, adaptive transmitter can be used to improve the bit error rate whereas variable bit error rate can also be used. In receiver end, adaptive circuit can also be used for improving bit error performance

Also the modulation technique can be changed. Here we have considered OOK for signal hop and M-ary PPM modulation scheme. BPSK, QPSK and M-PSK or SIM modulation will result in different values for same range of SNR.

Extensive work can be carried out on different coding techniques like convolution code, turbo code, low density parity check code (LDPC), space time block code (STBC) can also be used to minimize the effect of atmospheric scintillation and spatial widening in the presence of atmospheric turbulence. Also the performance of the transmitted signal can be improved by using spatial diversity. In addition, considering the atmospheric turbulence along with cloud effect can be analyzed in future.

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APPENDIX A

BER CALCULATION FOR INTENSITY MODULATION (OOK) DIRECT DETECTION (IM/DD) SYSTEM

In the presence of noise the signal at receiver is not well defined although the transmitted signal consists of two well defined light levels.

I_i = Output Current for "1"

I_o = Output Current for "0"

n(t) = Thermal noise + Shot Noise = AWGN

when "1" is transmitted

$$i_1(t) = i_{j1}(t) + n_1(t) \tag{A.1}$$

when "0" is transmitted

$$i_0(t) = i_{j0}(t) + n_0(t) \tag{A.2}$$

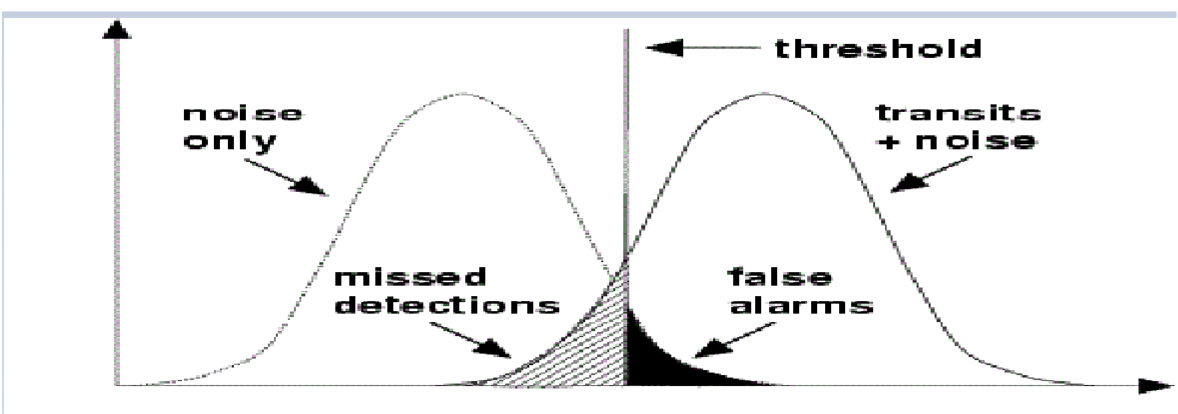

Figure A.1: Probability of detection and false alarm in IM/DD system.

$\sigma_1{}^2$ = output noise variance when 1 is received
= $2eBI_1 + 4kTB/R_L$
$\sigma_0{}^2$ = output noise variance when 0 is received
= $2eBI_0 + 4kTB/R_L$

Here $\sigma_0{}^2 \ll \sigma_1{}^2$

Let us consider $P_r\{1\}$ and $P_r\{0\}$ be the probabilities of transmission for binary ones and zeros. Also consider the probabilities that a signal is transmitted as 1 but received as 0 is $P_r\{0|1\}$. If a decision threshold i_{th} is set between the two signal states where signals greater than ith is registered as a one and those less than i_{th} is a zero.

BER = Probability of Bit Error
= $P_r\{1\}P_r\{0|1\} + P_r\{0\}P_r\{1|0\}$
= $0.5\,[P_r\{0|1\} + P_r\{1|0\}]$
= $0.5\,[P_r\{i<i_{th}|"1"\} + P_r\{i>i_{th}|"0"\}]$
P(n_o) = Gaussian $(0,\sigma_0{}^2)$
P(n_1) = Gaussian $(0,\sigma_1{}^2)$
P(i_o) = Gaussian $(I_o,\sigma_0{}^2)$

$$= \frac{1}{\sqrt{2\pi\sigma_0{}^2}}e^{-\frac{(i-I_O)}{2\sigma_o{}^2}}$$

P(i_1) = Gaussian $(I_1, \sigma_o{}^2)$

$$= \frac{1}{\sqrt{2\pi\sigma_1{}^2}}e^{-\frac{(i-I_1)}{2\sigma_1{}^2}}$$

$$P_r\{1|0\} = \int_{I_{th}}^{\infty} P(i_o)di = \int_{I_{th}}^{\infty}\left(\frac{1}{\sqrt{2\pi\sigma_0{}^2}}e^{-\frac{(i-I_O)}{2\sigma_o{}^2}}\right)di$$

$$= \frac{1}{\sqrt{\pi}}\int_{I_{th}}^{\infty} e^{-x^2}dx$$

$$P_r\{0|1\} = \int_{-\infty}^{I_{th}} P(i_o)di = \int_{-\infty}^{I_{th}}\left(\frac{1}{\sqrt{2\pi\sigma_1{}^2}}e^{-\frac{(i-I_1)}{2\sigma_1{}^2}}\right)di$$

$$= \frac{1}{\sqrt{\pi}}\int_{-\infty}^{I_{th}} e^{-y^2}dy$$

Where,

$x = \frac{i-I_o}{\sqrt{2}\sigma_o}$ and $dx = \frac{di}{\sqrt{2}\sigma_o}$

$y = \frac{i-I_1}{\sqrt{2}\sigma_1}$ and $dy = \frac{di}{\sqrt{2}\sigma_1}$

Similarly,

$$P_r\{1|0\} = \frac{1}{2}\frac{2}{\sqrt{\pi}}\int_{\frac{I_{th}-I_o}{\sqrt{2}\sigma_o}}^{\infty} e^{-x^2}dx$$

$$= \frac{1}{2}erfc(\frac{I_{th}-I_o}{\sqrt{2}\sigma_o})$$

For optimized threshold, I_{th} should be at middle.

$$P_r\{0|1\} = \frac{1}{2}erfc(\frac{I_1-I_{th}}{\sqrt{2}\sigma_1})$$

Now,

BER = $0.5[\frac{1}{2}erfc(\frac{I_{th}-I_o}{\sqrt{2}\sigma_o}) + \frac{1}{2}erfc(\frac{I_1-I_{th}}{\sqrt{2}\sigma_1})]$

The BER will be minimum when $P_r\{0|1\}$ = $P_r\{1|0\}$

So, $\frac{I_{th}-I_o}{\sqrt{2}\sigma_o}$ = $\frac{I_1-I_{th}}{\sqrt{2}\sigma_1}$

where, I_{th} = $\frac{I_1\sigma_o+I_o\sigma_1}{\sigma_o+\sigma_1}$

If it is considered that $\sigma_o = \sigma_1$ i.e. shot noise is negligible and thermal noies is dominated then $I_{th} = \frac{I_1+I_o}{2}$

BER = $\frac{1}{2}erfc(\frac{I_1-Io}{2\sqrt{2}(\sigma_o+\sigma_1)})$

And so,

$$BER = \frac{1}{2}erfc(\frac{\sqrt{SNR}}{2\sqrt{2}}) \quad (A.3)$$

So calculating the SNR we can find out the BER performance of IM/DD system.