PERFORMANCE ANALYSIS OF A SUBCARRIER MULTIPLEXED FREE SPACE OPTICAL MIMO TRANSMISSION LINK THROUGH ATMOSPHERIC TURBULENCE

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in

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By

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Approval

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Dedication

To all of my respected teachers

Acknowledgement

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Table of Contents

Chapter: 2: Free Space Optical Communication System

Chapter-3: Analysis of the Optical Communication System with Turbulence

Chapter-4: Results and Discussion

Chapter-5: Conclusion and Future Work

List of Abbreviations

BPSK	**Binary Phase Shift Keying**
BER	**Bit Error Rate**
FSO	**Free Space Optical**
IM/DD	**Intensity Modulation Direct Detection**
LED	**Light Emitting Diode**
LASER	**Light Amplification by Stimulated Emission of Radiation.**
MIMO	**Multiple Input Multiple Output**
MISO	**Multiple Input Single Output**
OFC	**Optical Fiber Communication**
OFS	**Optical Fiber System**
QPSK	**Quadrature Phase Shift Keying**
SISO	**Single Input Single Output**
SIMO	**Single Input Multiple Output**
SNR	**Signal to Noise Ratio**

List of Tables

Lists of Figures

Abstract

Free space optical communications is a line-of-sight (LOS) technology that transmits a modulated beam of visible or infrared light through the atmosphere. Now a days, Free Space Optical (FSO) communication is a very much promising technology for communication. But the main weakness is atmospheric turbulence which causes major transmission impairment for an open air optical communication system. To overcome the effect of atmospheric turbulence, Multiple Input Multiple Output (MIMO) communication system has become a very important topic of research over the past few years, due to its capability to greatly enhance spectral efficiencies. So, free space Multiple Input Multiple Output (MIMO) optical communication system through atmospheric turbulence is studied in this thesis.

The main objective of this thesis is to analyze the performance of Free Space optical (FSO) communication through atmospheric channel using QPSK Subcarrier Intensity Modulation. Here the performance analysis for a Subcarrier Multiplexed Intensity modulated OFS link with optical intensity modulation and direct detection considering single transmitter and single photo detector in the presence of atmospheric turbulence is carried out. Then the theoretical analysis is extended to a MIMO optical transmission link in the presence of the atmospheric turbulence effect considering Maximal Ratio Receive Combining (MRRC) technique. The performance of the FSO system is evaluated in the presence of atmospheric turbulence for both SISO and MIMO configurations. In this thesis, the performance results are evaluated and shown in terms of BER for several parameters and it is clearly found that BER performance is significantly improved for a Multiple Input Multiple Output (MIMO) system.

Chapter 1

Introduction

Chapter-1

Introduction

1.1 Introduction to Communication System

Communication is defined as the technology to transmit information from one place to another. The explanation of the word "telecommunication" adopted during the 1947 International Radiotelegraphic Conference held at Atlantic City (USA) is: *"any transmission, emission or reception of signs, signals, writings, images, sounds or information of any nature by wire, radio-electricity, optics or other electromagnetic systems."* The way of transmission must be electromagnetic in nature, which provides a very extensive scope, since, as Maxwell showed, electromagnetic waves include electricity and optics.

1.2 Brief History of Optical Communication

For several years ago, optical communication was news words to the general people. But people always use light to send message from a long time ago, that it is optical communication. So, optical communication is not new things to people. Fires were used for signaling in biblical times, smoke signals have been used for thousands of years and flashing lights have been used to communicate between warships at sea since the days of Lord Nelson.

The concept of using glass fiber to transmit an optical communication signal originated by Alexander Graham Bell. However this idea had to wait some 80 years for better glasses and low-cost electronics for it to become useful in practical situations.

Development and growth of fibers and devices for optical communications began in the early 1940s and continues robustly today. But the real revolutionize came in the 1980s. During this decade optical communication in pubic communication networks developed from the status of a curiosity into being the dominant technology.

Among the tens of thousands of developments and inventions that have contributed to this progress four stand out as milestones:

- The invention of the LASER (in the late 1950's)
- The development of low loss optical fiber (1970's)
- The invention of the optical fiber amplifier (1980's)
- The invention of the in-fiber Bragg grating (1990's)

The ongoing progress of semiconductor technology is quite essential for the development of optical communication but of course not specifically optical.

1.3 Types of Optical Communication

Optical communication can be classified into two types-

i) Optical fiber communication

ii) Free space optical communication

1.3.1 Fiber Optic Communication System

An optical fiber is a thin, flexible, transparent fiber that works as a waveguide, or "light pipe", to pass on light between the two ends of the fibre. Optical fiber typically consists of a crystal clear core surrounded by a transparent cladding material with a lower index of refraction. Light is kept in the core by total internal reflection. This causes the fiber to act as a waveguide. Fiber-optic communication is a technique of transmitting information from one place to another by sending pulses of light through an optical fiber. The light forms an electromagnetic carrier wave that is modulated to bring information. The development of low loss optical fiber (1970's) has revolutionized fiber-optic communication systems in the telecommunications industry and have played a most important role in the advent of the Information Age. Because of its advantages over electrical transmission, optical fibers have largely replaced copper wire communications in core networks in the developed world.

1.3.2 Free Space Optical Communication System

“Free space" means air, outer space, vacuum, or something similar. It is the opposite of a fiber optic cable or transmission line. Free Space Optics (FSO) is also an optical communication technology that uses light propagating in free space to send out information between two points. The technology is useful where the physical connections by the means of fibre optic cables are impractical due to high costs or other considerations. This system is useful to apply for the following circumstances:

- LAN-to-LAN connections on campuses at Fast Ethernet or Gigabit Ethernet speeds.
- LAN-to-LAN connections in a city. Example, Metropolitan area network.
- To cross a public road or other barriers which the sender and receiver do not own.
- Speedy service delivery of high-bandwidth access to optical fiber networks.
- Converged Voice-Data-Connection.
- Temporary network installation (for events or other purposes).
- Reestablish high-speed connection quickly (disaster recovery).
- As an alternative or upgrade add-on to existing wireless technologies.
- As a safety add-on for important fiber connections (redundancy).
- For communications between spacecraft, including elements of a satellite constellation.
- For inter- and intra-chip communication.

The advantages of the FSO system are as follows:

- Ease of deployment
- License-free long-range operation
- High bit rates
- Low bit error rates
- Immunity to electromagnetic interference
- Full duplex operation
- Very secure due to the high directionality and narrowness of the beam(s)

There are also some drawbacks of the FSO system-

- Pointing error due to building sway.
- The intensity fluctuation which is also known as scintillation is one of the most important factors that degrade the performance of a MIMO FSO communication link even under the clear sky condition.
- Atmospheric turbulence has strong effect on MIMO wireless system.

1.4 Review of Previous Work

- In reference [1] and [3] it is found that two primary challenges for FSO communication are pointing error and fading due to scattering and scintillation.
- FSO communication is less affected by snow and rain, but severely affected by the atmospheric turbulence and fog [2,4].
- Free space laser communication systems based on a single laser source and single detector suffers the effect of atmospheric turbulence much [1]. The

communication system based on the use of a Multiple Laser Multiple Detector (MLMD) architecture can considerably diminish the effect of this problem [1,[5].

- In reference [2], the author proposed the gamma-gamma distribution for the atmospheric turbulence across weak to strong regime while negative exponential turbulence model considering Rayleigh distribution is used in the limit of strong turbulence.
- Already different modulation schemes are examined for the FSO system through atmospheric turbulence [1], [2], [4], [6] & [8].
- In reference [6] it is discussed that subcarrier phase shift keying (PSK) intensity modulation is superior to on-off keying in the presence of atmospheric turbulence .

1.5 Objective with Specific Aims and Possible Outcome

The main objective of this thesis is to analyze the performance of FSO communication through atmospheric channel using Subcarrier QPSK modulation. The main purpose of this thesis is:

(i) To develop the performance analysis for a Subcarrier Multiplexed Intensity Modulated OFS link with optical intensity modulation and direct detection considering single transmitter and single photo detector in the presence of atmospheric turbulence. In this thesis, QPSK modulation is considered in the Subcarrier Multiplexing.

(ii) To extend the theoretical analysis to a MIMO optical transmission link in the presence of the atmospheric turbulence effect considering Maximal Ratio Receive Combining (MRRC) technique.

(iii) To evaluate the performance of the FSO system in the presence of atmospheric turbulence for both SISO and MIMO configurations.

(iv) To determine the effectiveness of Subcarrier QPSK modulated MIMO FSO system in the presence of atmospheric effect compared to Intensity Modulated Direct Detection (IM/DD) system.

1.6 Outline of Methodology/ Experimental Design

Analysis has been carried out for a multiplexed subcarrier QPSK modulated optical intensity modulated free space link over a turbulence atmospheric channel. The received optical signal is detected by a direct detection receiver and coherent sub carrier demodulator. The analysis is carried out to find the signal and noise at the receiver output with fading due to atmospheric turbulence. The analysis has been extended to an optical MIMO link transmit and receive diversity. The expression for the BER is derived for different number of subcarriers and MIMO configurations.

1.7 Organization of this Thesis

This thesis consists of five chapters. Chapter-1 is concentrated on the purpose and present state of FSO communication system and importance of FSO communication.

In chapter-2, a brief overview of the different components of the FSO communication system and the impact of atmospheric condition on FSO communication link is discussed.

In chapter-3, the techniques and technological details of subcarrier multiplexed QPSK modulation scheme through atmospheric turbulence channel is discussed analytically.

In chapter-4, numerical results are presented for different conditions which are theoretically analyzed in chapter-3.

Finally, conclusions and some proposals for future work are given in chapter-5.

Chapter 2

Free Space Optical Communication System

Chapter: 2

Free Space Optical Communication System

2.1 Introduction

In this chapter, the free space optical communication is briefly described. As FSO uses a directed beam of light radiation between two end points to transfer information (data, voice or even video), this is similar to OFC (optical fiber cable) networks, except that light pulses are sent through free air instead of OFC cores. The transmitted optical beam passing through the atmosphere can be absorbed, scattered or displaced depending on the atmospheric condition. In this chapter, different FSO system and atmospheric turbulence are discussed.

2.2 Importance of FSO in Present Day Communication

At present we are faced with a growing demand for high bandwidth and differentiated data services. Network traffic doubles every 9-12 months. It compels the bandwidth or data storing capacity to raise and keep pare with this increase. The right solution for the pressing demand is the untapped bandwidth potential of optical communications. Optical communications are in the process of evolving Giga bits/sec to terabits/sec and eventually to pentabits/sec. Free space optical communications (FSO) is a promising technology capable of offering full-duplex gigabit rate throughput (data, voice, and video simultaneously) in certain applications and environment [2]. FSO offers an enormous license-free frequency spectrum using a single wavelength, immunity to electromagnetic interference together with co/adjacent channel, and high security [2]. FSO defeats the last mile access blockage by sending high bitrates signals through the air using laser transmission. So, presently Optical communication systems are becoming more and more popular as the interest and requirement in high capacity and long distance space communications grow.

2.3 Block Diagram of FSO Communication System

A block diagram of QPSK subcarrier intensity modulated FSO link is as follows:

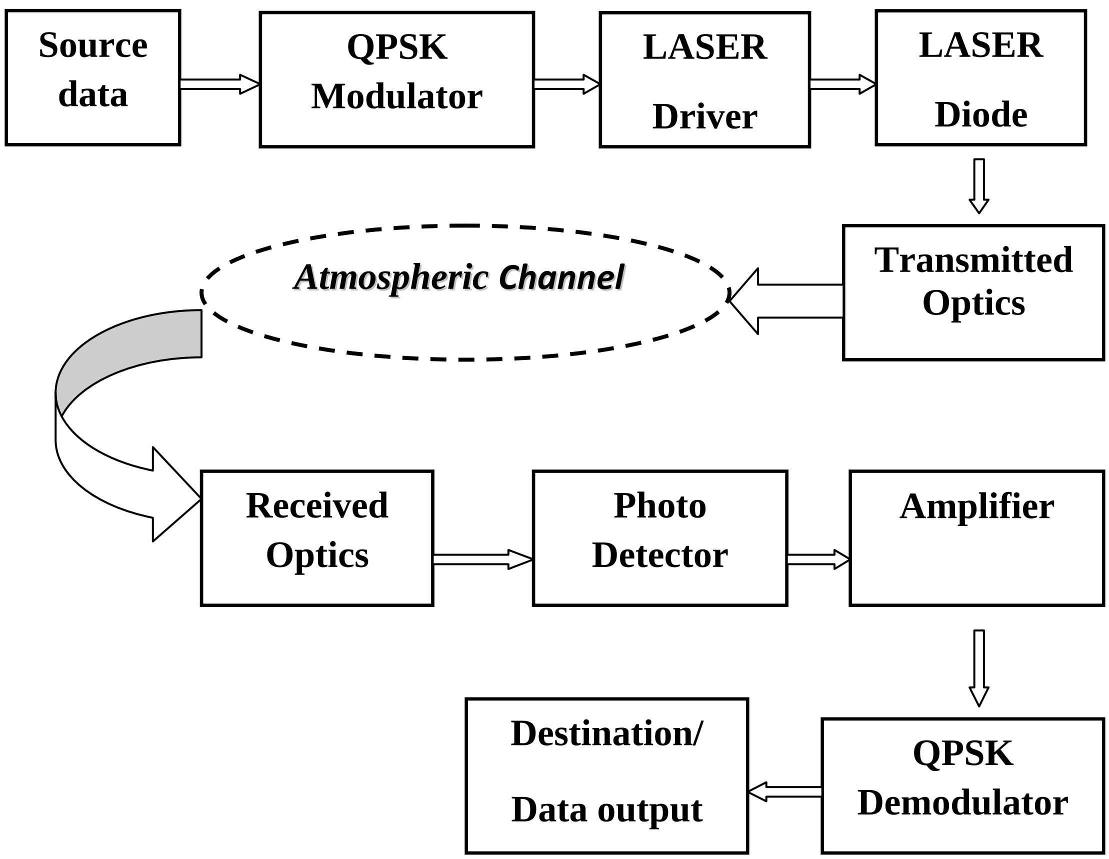

Fig. 2.1: FSO system block diagram

2.3.1 The Transmitter

In this thesis, within the transmitter QPSK Modulator, laser driver and laser diode is used to convert the source data into transmitted optical signal which then propagate through the atmosphere.

There are different types of light sources are used in free space optics. They are briefly described as follows:

- **LED**

A light-emitting diode (LED) is a semiconductor light source. When a light-emitting diode is forward biased (switched on), electrons are able to recombine with electron holes within the device, releasing energy in the form of photons. This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor.

LED-based systems have a number of advantages, the most obvious being expenditure and dimension. Not only is the optical sub-system design far less expensive, but the driving electronics are also more simplified. The result is that system cost per milliwatt for an LED based system is much lower, than for a laser diode design. The problem is the emitted light by LED is incoherent and unfocused.

- **Laser Diode**

Laser diodes are electrically pumped semiconductor lasers in which the gain is generated by an electrical current flowing through a p–n junction or (more frequently) a p–i–n structure. In such a heterostructure, electrons and holes can recombine, releasing the energy portions as photons. This process can be spontaneous, but can also be stimulated by incident photons, in effect leading to optical amplification, and with optical feedback in a laser resonator to laser oscillation. Laser diodes are small in size and power efficient.

Long range, very high speed (gigabit or more) point-to-point FSO systems require laser diodes. The wavelength of the laser diodes chosen for FSO system is 850 nm or 1550 nm. The 1550 nm light source is chosen for longer distance communication. The 1550 is also chosen as more photons per watt power arrive for longer wavelengths and therefore more photo current is produced per watt of incident power for same efficient devices.

2.3.2 The Receiver

Once the transmitter passes the signal through the atmosphere, it must be collected by the receiver. The light signal collected from the air is firstly converted into electrical signal by the photo detector. Then it is amplified and passes to the QPSK demodulator. Both coherent and non-coherent detection schemes are possible in the receiver end. But considering the complexity and cost, non-coherent or direct detection scheme is preferred. For this thesis Intensity Modulated Direct Detection (IM/DD) system is considered. The quality of reception is measured by the probability of error, expressed in terms of bit error rate (BER).

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-carriers, in a well-designed photo detector, the probability of an incident photon causing the free carrier is high.

For the optical communication, the most popular photo detectors are p-i-n photodiode and avalanche photodiode. They are briefly discussed below-

➢ P-i-N Photodiodes

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

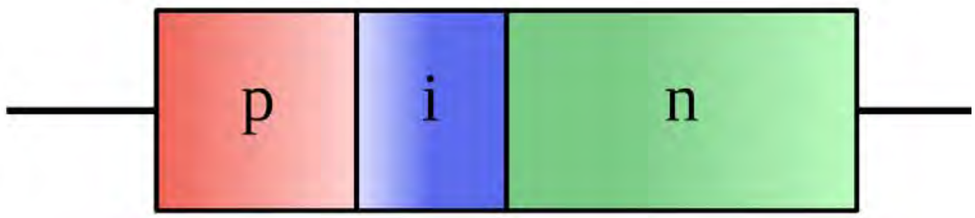

Fig. 2.2: P-i-N Photodiode

A PIN diode functions under high-level injection. In other words, the intrinsic "i" region is flooded with charge carriers from the "p" and "n" regions. When the diode is forward biased, the injected carrier concentration is typically several orders of magnitude higher than the intrinsic level carrier concentration. Due to this high level injection, which in turn is due to the depletion process, the electric field extends deeply (almost the entire length) into the region. This electric field helps in speeding up of the transport of charge carriers from P to N region, which results in faster operation of the diode, making it a suitable device for high frequency operations.

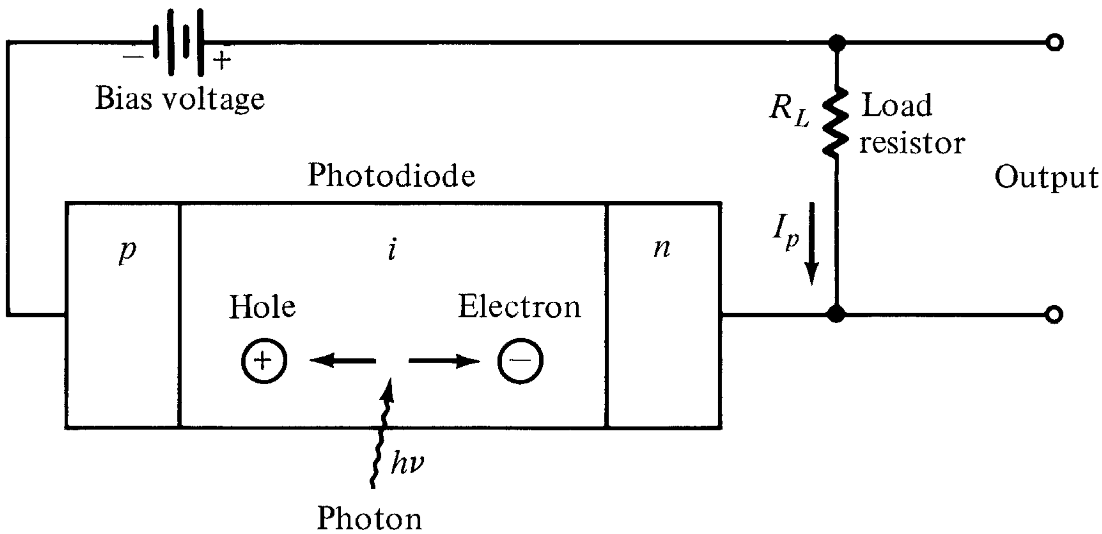

Fig 2.3: Basic *pin* photodiode circuit

Incident photons trigger a photocurrent I_p in the external circuitry by pumping energy Photocurrent which is proportional to the incident Optical Power.

➢ Avalanche Photodiodes

An avalanche photodiode (APD) is a highly sensitive semiconductor electronic device that exploits the photoelectric effect to convert light to electricity. APDs can be thought of as photodetectors that provide a built-in first stage of gain through avalanche multiplication. 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 APD’s are costly and need high reverse bias voltage.

2.4 FSO Transmitting Medium

In FSO communication, the transmitter and the receiver are separated by the propagation channel, which is the atmosphere. Free-Space Optical (FSO) links involve the transmission, absorption and scattering of light by the Earth’s atmosphere. The atmosphere interacts with light due to the composition of the atmosphere. Under normal conditions, the atmosphere consists of a variety of different molecules and small suspended particles called aerosols. This interaction produces a wide variety of optical phenomena as follows:

i) Selective attenuation of radiation that propagates in the atmosphere.

ii) Absorption at specific optical wavelengths due to the molecules.

iii) Generation by scattering (the sky blue color, the red sunset, etc.) or by radioactive emission of an optical beam comparable to noise at the source of perception contrasts loss. This loss is all the more important since the distance is large.

iv) Scintillation due to the variation of the air’s refractive index under the effect of Temperature.

The construction of an opto-electronic arrangement, made up of a transmitter and a receiver in free atmosphere, requires a good quality of knowledge of specific optical properties of the atmosphere. To describe the effects of the atmosphere on light propagation, it is first necessary to define the following optical phenomena-

2.4.1 Atmospheric Absorption

Atmospheric absorption results from the interaction between the photons of the radiation and the atoms or molecules of the medium. Due to atmospheric absorption the incident photon is disappeared. Let us consider a light beam of wavelength λ which passes through an absorbing medium of thickness dx.

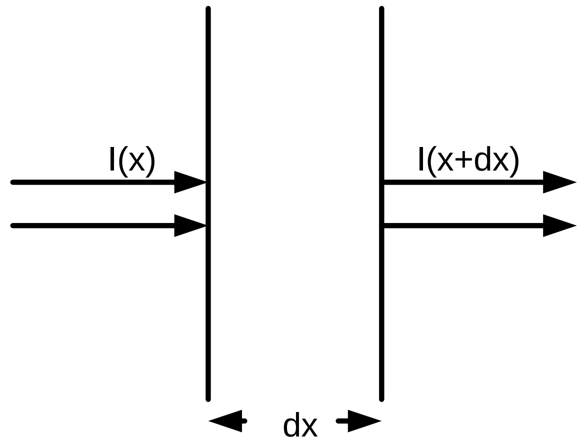

Fig. 2.4: Light absorption by atmosphere for a thickness of dx.

Due to absorptions of the medium, the number of photons in the radiation is reduced throughout the length of its path. The intensity of the radiation, measured at $x + dx$ (Figure 2.2), in relation to the intensity measured at x , is written as [10]:

$$I(\lambda,x+dx)= I(\lambda,x)- dI_a(\lambda,x) \qquad (2.1)$$

The quantity $dI_a(\lambda, x)$ corresponds to the intensity of the light absorbed by the absorbing medium, this latter being proportional to the incident intensity $I(\lambda, x)$, to dx and to a spectral parameter which represents the absorption of the medium $\alpha(\lambda, x)$ at this wavelength-

$$dI_a(\lambda,x)= \alpha(\lambda,x)\, I(\lambda,x)dx \qquad (2.2)$$

2.4.2 Atmospheric Scattering

Atmospheric scattering results from the contact of a part of the light with the atoms and/or the molecules in the propagation medium, which causes an angular redistribution of this part of the radiation with or without modification of the wavelength.

To calculate the transmission of a scattering medium we can write [10]:

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

Where $\beta(\lambda, x)$ is the specific spectral scattering coefficient. In the case of scattering, the scattered light does not disappear locally as with absorption.

2.4.3 Atmospheric Turbulence due to Aerosols

Aerosols are extremely fine particles (solid or liquid) suspended in the atmosphere with a very low fall speed caused by gravity. Their size generally lies between 0.01 µm and 100 µm. Due to the action of terrestrial gravity, the biggest sized particles ($r > 0.2$ µm) are in the vicinity of the ground. Fog and mist are liquid aerosols, salt crystals and sand grains are solid aerosols. The presence of aerosols may cause severe disturbance to the propagation of optical and infrared waves, since their dimensions are very close to the wavelengths of these frequencies. It is not the same in the range for instance of centimeter and millimeter waves where the wavelength is much longer than the size of the aerosols.

Although rain and snow can hamper light propagation, the most harmful environmental conditions are fog and haze. This is due to their high concentration of scattering particles with radii on the same order of magnitude as the laser wavelength.

The following figure shows the atmospheric effect on the transmitted signal-

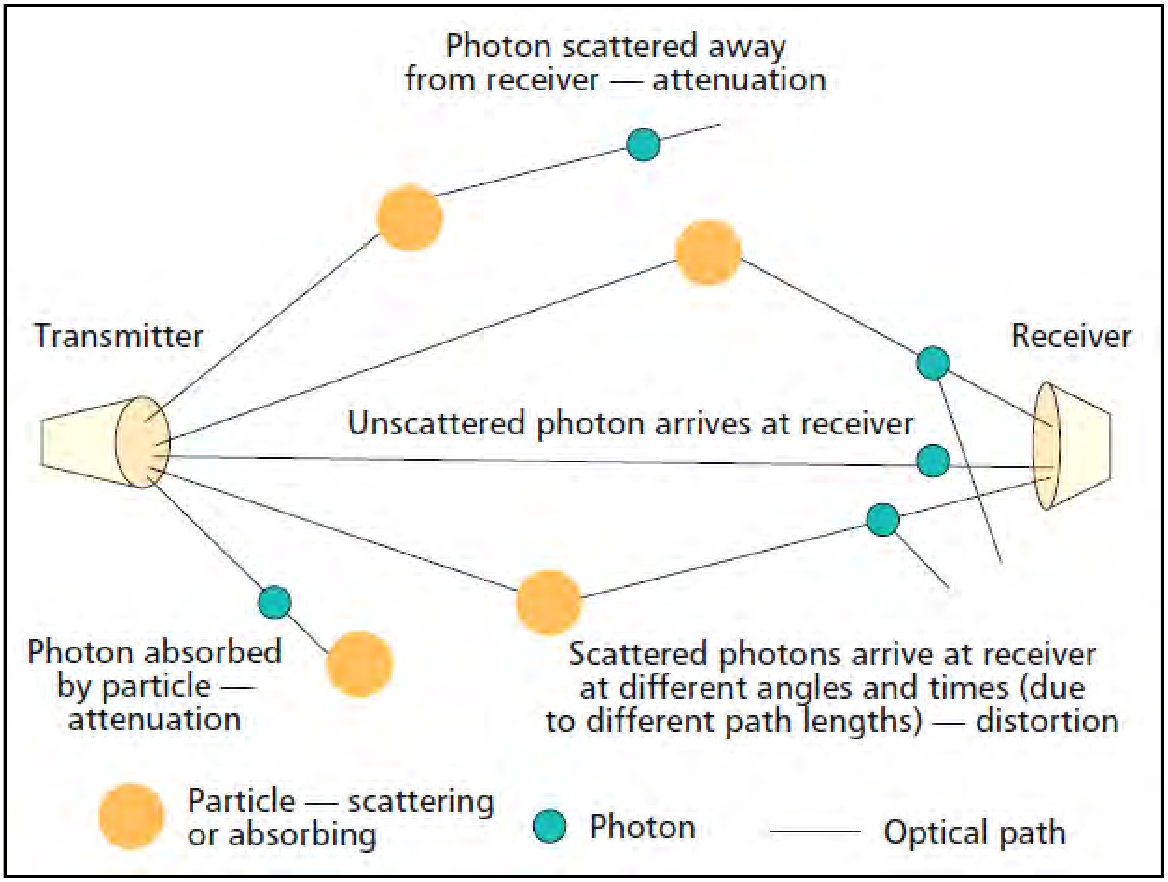

Fig. 2.5: Multiple scattering showing spatial and angular spreading and variations in path length. Absorption of a photon by a particle is also shown.

In the above discussion it is observed that the transmitted optical beam passing through the atmosphere can be absorbed, scattered or displaced depending on the atmospheric condition. This is the fundamental limits of FSO systems. Compared with the RF system, FSO is less affected by snow and rain, but can be severely affected by the atmospheric turbulence and fog [2].

2.5 Atmospheric Turbulence Models

Atmospheric turbulence is well studied and various models exist to describe it. Generally three types of atmospheric models are used. They are-

i) Log Normal Distribution

ii) Gamma-Gamma Model and

iii) Negative Exponential Model

It is observed that Log normal distribution is suitable for weak turbulence regime and The atmospheric turbulence across weak to strong regime is represented using the gamma-gamma distribution[2]. During strong turbulence negative exponential model is suitable [2]. The turbulence models are described below---

2.5.1 Log Normal Distribution

In wireless communication, the attenuation caused by shadowing or slow fading from random objects is often assumed to be log-normally distributed. A log-normal distribution is a probability distribution of a random variable whose logarithm is normally distributed. If X is a random variable with a normal distribution, then $Y = \exp(X)$ has a log-normal distribution; likewise, if Y is log-normally distributed, then $X = \log(Y)$ is normally distributed. The probability density function of a log-normal distribution is:

$$f_X(x;\mu,\sigma) = \frac{1}{x\sigma\sqrt{2\pi}}\, e^{-\frac{(\ln x-\mu)^2}{2\sigma^2}}, \quad x > 0 \tag{2.4}$$

In a log-normal distribution, the parameters denoted μ and σ, are the mean and standard deviation, respectively.

2.5.2 Gamma-Gamma Model

The gamma-gamma turbulence model is based on the modulation process where the fluctuation of light radiation traversing turbulent atmosphere is assume to consist of small scale (scattering) and large scale (refraction) effects [2]. The gamma-gamma model for the probability density function (pdf) of received irradiance fluctuation which is based on the assumption that both the large and small scale effects are governed by the gamma distribution. It is therefore derived as-

$$\mathbf{P(I)}=\frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \qquad (2.5)$$

Where $K_n(.)$ is the modified Bessel function of the 2nd kind of order n , and $\Gamma(.)$ represents the Gamma function. If the optical radiation is assumed to be a plane wave, the two parameters and that characterize the irradiance fluctuation pdf are related to the atmospheric conditions by-

$$\alpha=\left[exp\left(\frac{0.49\sigma_l^2}{\left(1+1.11\sigma_l^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right)-1\right]^{-1} \qquad (2.6)$$

$$\beta==\left[exp\left(\frac{0.51\sigma_l^2}{\left(1+0.69\sigma_l^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right)-1\right]^{-1} \qquad (2.7)$$

Here $\sigma_l^2=1.23C_n^2\, k^{7/6}\, L^{11/6}$ is the log irradiance variance, L is the link range, $k=2\pi/\lambda$, and the refractive index structure parameter which is constant for an horizontal link is assumed the value $Cn^2=5.10^{-13}m^{-2/3}$.

The pdf of irradiance fluctuation of the Gamma-Gamma model is valid for all turbulence scenarios from weak to strong.

2.5.3 Negative Exponential Model

Negative Exponential model is suitable in the limit of strong irradiance fluctuations (i.e., in saturation regime and beyond) where the link length spans several kilometers [2]. the number of independent scatterings becomes large. Negative Exponential model consider the fact of Rayleigh distribution implying negative exponential statistics for the irradiance. The pdf is as follows-

$$P(I)=\frac{1}{I_o}exp(\frac{-I}{I_o}) \qquad \text{where, } I_o>0. \qquad (2.8)$$

I_o is said as the mean irradiance or noise turbulence variance which is often normalized to unity.

2.6 FSO Communication with Diversity

The possible solution to mitigate the atmospheric effect is to use Optical communication with diversity where multiple antennas at both the transmitter and receiver side are used. It significantly improves the communication performance. The performance of Optical communication with diversity is examined in this thesis and found considerable improvements in the communication system.

Optical communication may have different type of diversity which depends on the no. of antennas at the transmitter and receiver end. The following figure shows different type of diversity-

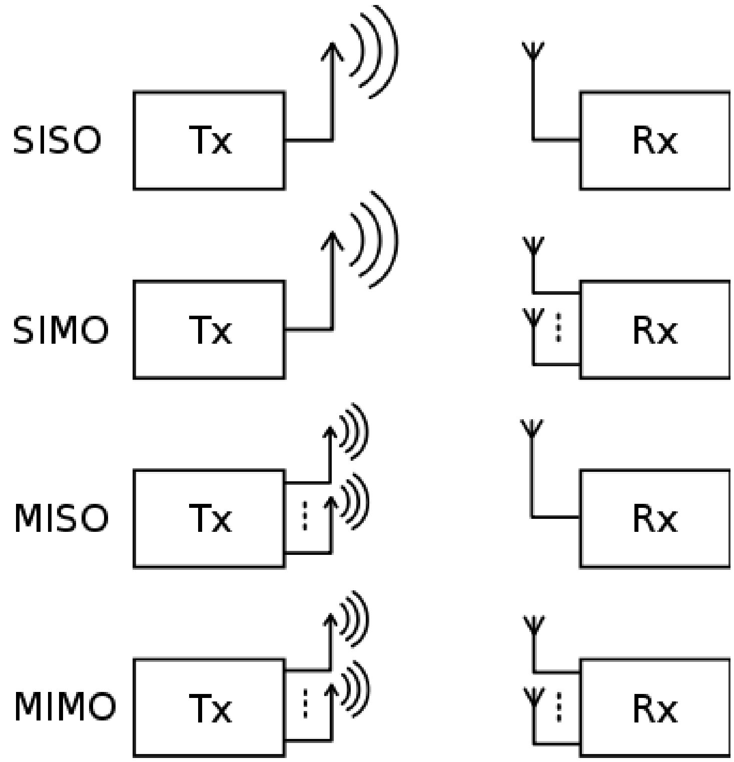

Fig. 2.6: Configuration of SISO, SIMO, MISO and MIMO where the terms input and output refer to the radio channel carrying the signal, not to the devices having antennas.

2.6.1 SISO

In the Single Input Single Output (SISO) system, single channel is used at the both transmitting and receiving side. SISO systems are typically less complex than Multiple-Input Multiple-Output (MIMO) systems but it system does not perform well when strong turbulence is present.

2.6.2 SIMO

In the Single Input Multiple Output (SIMO) system, single channel is used at the transmitting side and multiple channels are used in the receiving side.

2.6.3 MISO

In the Multiple Input Single Output (MISO) system, multiple channels are used at the transmitting side and single channel is used in the receiving side.

2.6.4 MIMO

Multiple-input and multiple-output, or MIMO is the use of multiple antennas at both the transmitter and receiver to improve communication performance. It is one of several forms of smart antenna technology.

In MIMO, the transmit antennas and receive antennas are jointly combined in such a way that the quality (Bit Error Rate) or the rate (Bit/Sec) of the communication is improved. At the system level, careful design of MIMO signal processing and coding algorithms can help to increase the capacity and coverage significantly and thus can improve the economics of network deployment for operators. Today, MIMO wireless is widely recognized as one of three or four key technologies in the forthcoming high-speed high-spectrum efficiency wireless networks (4G, and to some extent 3G). Applications also be present in fixed wireless and wireless LAN networks.

The following figure is a free space optical MIMO system model.

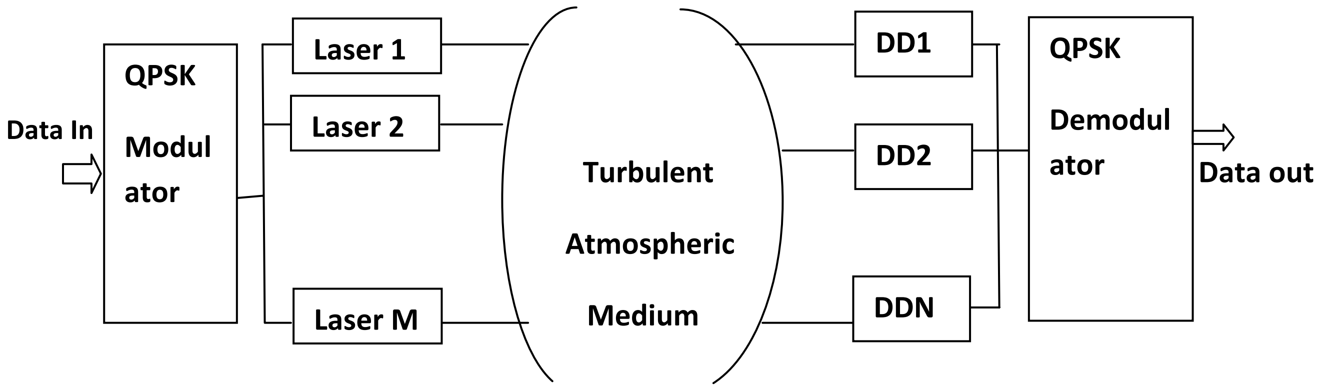

Fig. 2.7: free space Optical MIMO system model

2.7 Importance of MIMO Technology

MIMO system in FSO communication has the following advantages-

- Powerful performance-enhancing capabilities.
- Linear increase in data rate.
- Reduce the bit error rate of the system.
- Low impact installation
- Unlicensed use

2.8 Drawbacks of MIMO Technology

MIMO system in FSO communication has the following disadvantages-

- Pointing miss alignment error.

- Strong effect in Fogy weather.
- Strong wind flow may reduce the performance.
- The intensity fluctuation which is also known as scintillation is one of the most important factors that degrade the performance of a MIMO FSO communication link even under the clear sky condition.
- Atmospheric turbulence have strong effect on MIMO wireless system and increase the Bit Error rate (BER).

2.9 Intensity Modulated Direct Detection (IM/DD) System

In optical communications, intensity modulation (IM) is a form of modulation in which the optical power output of a source is varied in accordance with some characteristic of the modulating signal. The recovery of the modulating signal is done by direct detection, not heterodyning. In the free-space, optical intensity-modulated direct detection (IM/DD) is frequently used. Most practical wireless optical channels use light emitting diodes as transmitters and photodiodes as detectors, as shown below. These devices modulate and detect solely the intensity of the carrier, not its phase, which implies that all transmitted signal intensities are nonnegative.

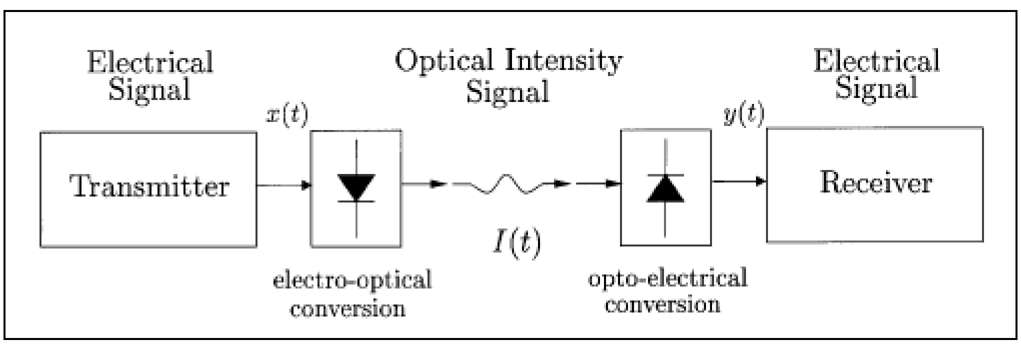

Fig. 2.8 A simplified block diagram of an optical intensity direct detection communications system.

2.10 Signal to Noise Ratio (SNR)

SNR is defined as follows-

$$SNR = \frac{\text{Signal power from photocurrent}}{\text{Detector Noise + Amplifier Noise}}$$

To achieve high SNR, the Photo detector must have large quantum efficiency to generate large signal current. Also Detector and amplifier noise must be low. One important thing is SNR can not be improved by amplification.

2.11 Bit Error Rate (BER)

BER is the ratio of erroneous bits to correct bit. Estimate of BER often needed to estimate the performance of a communication link. BER depends on the signal and noise power i.e. Signal to Noise Ratio (SNR).

2.12 Summary

This chapter concentrates on the Free Space Optical Communication System and shows the effect of atmospheric turbulence and turbulence model on the FSO communication link. To mitigate the effect of atmospheric turbulence different communication models are also discussed here.

Chapter 3

Analysis of the Optical Communication System with Turbulence

Chapter-3

Analysis of the Optical Communication System with Turbulence

3.1 Introduction

In this chapter the techniques and technical details of subcarrier multiplexed QPSK modulation scheme through atmospheric turbulence channel is discussed analytically. In this thesis the objective is to transmit FSO signal for a longer distance where strong turbulence is present. So, the Negative Exponential turbulence Model is used throughout the thesis.

3.2 QPSK Modulation

There are different modulation schemes that can be used to modulate the data:- namely BPSK, QPSK, m-QAM, FSK etc. In space communication power is severely limited. FSK is not generally used as it would require very high bandwidth to modulate our data resulting in very low bandwidth efficiency. Higher constellation QAM also can’t be used in our case as that would require very high C/N ratio. The choice is between QPSK and BPSK. The advantage of BPSK is that it requires the lowest C/N ratio. The drawback is that the data rate achieved using BPSK is very low. QPSK is basically two BPSK links operating on the same radio channel with their carriers in phase quadrature with respect to each other. Therefore the BER of a QPSK remains the same as BPSK. At the same time the data rate is doubled. The only penalty we pay is in terms of C/N ratio. QPSK requires 3 dB more C/N ratio than BPSK.

The Quadrature Phase Shift Keying (QPSK) is a 4-ary PSK signal. The QPSK is a modulation scheme widely used in Satellite Communications. As we mentioned earlier, PSK signals are considered one of the linear modulation techniques, which are well known of their bandwidth efficiency. The phase of the carrier in the QPSK takes 1 of 4 equally spaced shifts, such as 0, π/2, π, 3π/2, where each value of phase corresponds to a unique pair of message bits. The QPSK transmitted signal is defined by:

$$S_i = \sqrt{\frac{E_b}{T_b}} \cos\left(2\pi f_c t + (i-1)\frac{\pi}{2}\right) \qquad (3.1)$$

Where, $0 \leq t \leq T_b$ and i=1, 2, 3, 4

The following table shows the the Binary Dibit and its corresponding phase for a QPSK signal-

		Coordinates of message point	
Input Dibit ($0 \leq t \leq T$)	**Phase of QPSK Signal (radians)**	S_{i1}	S_{i2}
10	**π/4**	$+\sqrt{\frac{E}{2}}$	$-\sqrt{\frac{E}{2}}$
00	**3π/4**	$-\sqrt{\frac{E}{2}}$	$-\sqrt{\frac{E}{2}}$
01	**5π/4**	$-\sqrt{\frac{E}{2}}$	$+\sqrt{\frac{E}{2}}$
11	**7π/4**	$+\sqrt{\frac{E}{2}}$	$+\sqrt{\frac{E}{2}}$

Table. 3.1: The Binary Dibit and its corresponding phase.

3.3 QPSK Transmitter

As for the QPSK modulator (transmitter), the basic block diagram is shown in the following figure-

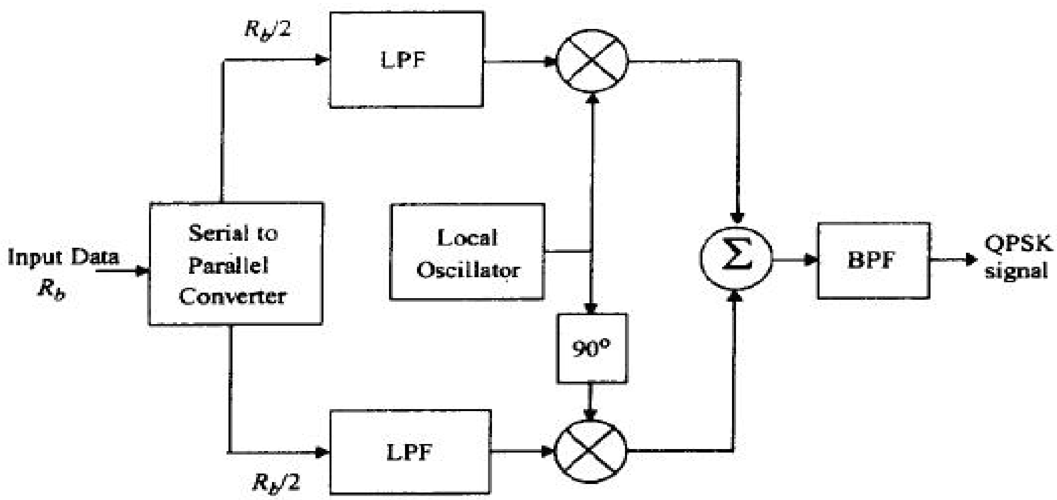

Fig. 3.1 QPSK Modulator Block Diagram

The QPSK modulator consists of two streams of BPSK modulators, one is fed with the odd data sequence and the other with the even sequence. Also one stream is modulated with a cosine wave and the other with a sine wave to have 90 degree phase difference. The bandwidth efficiency of QPSK is twice that of BPSK since we are transmitting two bits per signal.

The Average probability of bit error of the QPSK signaling is:

$$P_e = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \qquad (3.2)$$

Surprisingly, the average probability of bit error of the QPSK is the same as that of the BPSK in AWGN channel, while as much data can be sent in the same bandwidth. Thus compared to BPSK, QPSK provides twice the spectral efficiency with exactly the same energy efficiency.

3.4 QPSK Receiver

For the QPSK Demodulator, the basic block diagram is shown in the following figure-

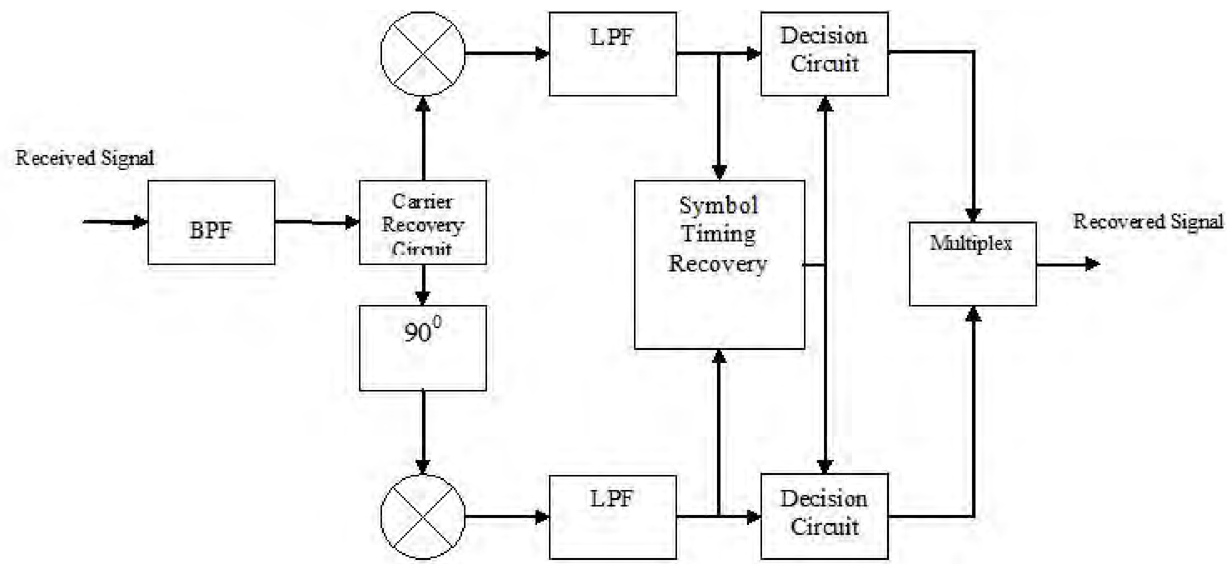

Fig. 3.2 QPSK Demodulator Block Diagram

As shown in the block diagram, the input QPSK stream is applied to two sinusoidal modulators that are 90 apart. The outputs from the multipliers are then applied to perform both filtering. After that the decision device determines the received level. The outputs from the decision devices are applied to a multiplexer that performs parallel to serial data conversion, thus reconstructing the final output data stream.

3.5 QPSK Subcarrier Intensity Modulation

In optical SIM links, an RF subcarrier signal pre-modulated with the source data d(t), is used to modulate the intensity of the optical carrier by a continuous wave laser diode shown in the following Fig.

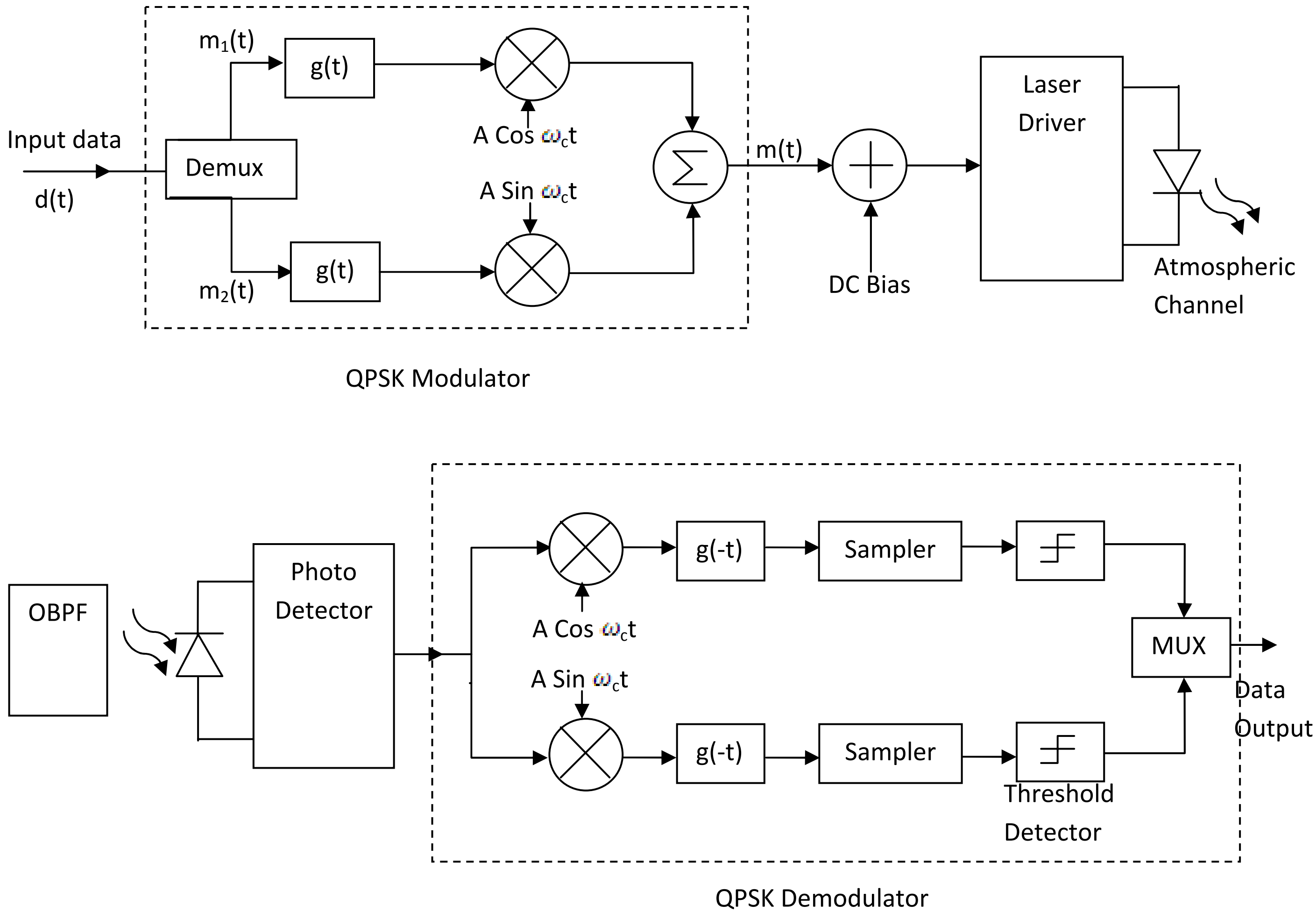

Fig. 3.3: Block diagram of QPSK subcarrier intensity modulated FSO link.

The above figure shows the system model of a subcarrier intensity modulated FSO link. Prior to modulating the laser irradiance, is modulated onto the RF subcarrier signal using QPSK in which four dibits are represented by four different phases 90 degree apart from one another. In the QPSK modulator, the transmitted signal m(t) can be expressed as,

$$m(t)=A_c g(t)\varepsilon[m_1(t)\cos(\omega_c t+\theta)+m_2(t)\sin(\omega_c t+\theta)] \quad (3.3)$$

where, A_c is the channel carrier amplitude, ε is the channel modulation index, ω_c is the channel angular frequency and g(t) is the rectangular pulse shaping function. This modulated signal is added to the dc bias current of a semiconductor laser in order to directly intensity modulate it.

The transmitted optical signal by the laser is-

$$S(t)=\sqrt{P_o[1+m(t)]} \quad (3.4)$$

Where P_o is the output power at the bias level for the semiconductor laser. The radiated optical signal is proportional to m(t).

At the receiver end, the incoming optical radiation is passed through an optical band pass filter (OBPF) before being converted into an electrical signal by the photo detector. The OBPF is used to limit the amount of background radiation noise detected by the photodetector. Now the total power received at the input of the photo diode detector can be written as-

$$P_r= P_o[1+m(t)] \quad (3.5)$$

Now this optical signal is converted into the corresponding electrical signal through Direct Detection by using the photo diode detector. At the receiver end, the received photo current is [2]-

$$i_r=RI(1+m(t))+n(t) \quad (3.6)$$

where,

R= Photodetector responsivity,

I=Optical intensity.

m(t)=Subcarrier Signal= $A_c g(t)\varepsilon[m_1(t)\cos(\omega_c t+\theta)+m_2(t)\sin(\omega_c t+\theta)]$

n(t)=AWGN (Additive white Gaussian Noise)

n(t)= Thermal Noise+ Background radiation shot noise.

Now from equation (3.5.4) we can write down-

$$i_r=RI(1+A_c g(t)\varepsilon[m_1(t)\cos(\omega_c t+\theta)+m_2(t)\sin(\omega_c t+\theta)])+n(t)$$

$$= RI + RI\, A_c g(t)\varepsilon[m_1(t)\cos(\omega_c t + \theta) + m_2(t)\sin(\omega_c t + \theta)] + n(t) \qquad (3.7)$$

RI is a DC component which is filtered out by the QPSK demodulator. So, equation (3.7) can be written as-

$$i_r = RI\, A_c g(t)\varepsilon[m_1(t)\cos(\omega_c t + \theta) + m_2(t)\sin(\omega_c t + \theta)] + n(t) \qquad (3.8)$$

The additive white Gaussian noise n(t) consists of both the thermal noise and the background radiation shot noise.

The shot noise,

$$\sigma^2_{shot} = 2qB.i_{sho} \qquad (3.9)$$

And the background noise is

$$\sigma^2_{bg} = 2qB_{el.}i_{bg} \qquad (3.10)$$

Here ,

B_{el} =Post detection electrical filter bandwidth.

.i_{bg} =Background current=R.I_{Bg} ;

Considering I_{Bg}= background radiation irradiance.

Now, (3.10) can be written as-

$$\sigma^2_{bg} = 2qB_{el.}\, R.I_{Bg} \qquad (3.11)$$

Here the thermal noise,

$$\sigma^2_{th} = 4kTB_{el}/RL \qquad (3.12)$$

Where, k=Boltzman const.=$1.38*10^{-23}$

R_L= Receiver circuit load resistance

T=temperature

Now, considering the background noise and thermal noise power from equations (3.11) and (3.12), total noise power is-

$$\sigma^2 = \sigma^2_{bg} + \sigma^2_{th}$$

$$= 2qB_{el.} R.I_{Bg} + 4kTB_{el}/R_L$$

$$= 2 B_{el.}(qR.I_{Bg} + 2kT/R_L) \quad (3.13)$$

Now the post detection SNR of the photo detector is-

$$SNR = \frac{(IR\varepsilon)^2 Pm}{2 B_{el.}(qR.I_{Bg} + 2kT/R_L)} \quad (3.14)$$

Where P_m is the subcarrier signal power and $P_m = \frac{1}{T}\int_T m_x^2(t)dt$

And, $m_x = A_c g(t)[m_1(t)\cos(\omega_c t + \theta) + m_2(t)\sin(\omega_c t + \theta)]$

Now, the detected baseband signal for the QPSK coherent detection, is [2]-

$$I_d(t) = d_j RI\varepsilon(A_c/2) + n_d(t) \quad (3.15)$$

Where, d_j represents the signal level for the j'th data.

3.6 BER without Turbulence

Without diversity for a single transmitter and single detector the BER for the QPSK detector without atmospheric turbulence will be as follows [2]-

$$BER = \int_0^{\infty} Q\left(\frac{IRA\varepsilon}{\sqrt{2}\sigma}\right)dI \quad (3.16)$$

3.7 BER with Turbulence

Without diversity for a single transmitter and single detector the BER for the QPSK detector considering atmospheric turbulence will be as follows -

$$\text{BER}=\int_0^{\infty} Q\left(\frac{IRAs}{\sqrt{2}\sigma}\right)\text{P(I)dI} \qquad (3.17)$$

Where, P(I) indicates the pdf of atmospheric turbulence model. In this thesis, Negative Exponential Model is used considering that the turbulence is strong.

For a negative exponential model,

$$\text{P(I)}=\frac{1}{I_0}\exp\left(\frac{-I}{I_0}\right)$$

So, the unconditional BER will be-

$$\text{BER}=\int_0^{\infty} Q\left(\frac{IRAs}{\sqrt{2}\sigma}\right).\frac{1}{I_0}\exp\left(\frac{-I}{I_0}\right)dI \ . \qquad (3.18)$$

3.8 FSO Communication with Spatial Diversity

To further improve the error performance, the turbulence induced irradiance fluctuation is mitigated by employing multiple transmitters and receivers. Diversity improves transmission performance by making use of more than one independently faded version of the transmitted signal. This significantly improves transmission accuracy as transmission errors are most likely to happen when instantaneous SNR is low for strong turbulence of the atmosphere. Diversity should be considered in the FSO communication system for the following reasons-

- The degradation of the transmission quality due to turbulence of the medium cannot be simply overcome by increasing the transmitted power.
- In wireless communications, power is severely limited by the battery capacity. With diversity the required transmitted power can be significantly reduced.
- Diversity reduced BER and improve the system performance. It also improves the system capacity.

3.8.1 Diversity Combining

Due to diversity, after obtaining independently faded signal components at the output of the demodulators, the next step is to combine these signal components for transmitted signal detection. Various methods are used to combine the signals. They are-

- Maximal-ratio combining
- Equal gain combining
- Selection combining
- Switched combining

In this thesis, Maximal Ratio Combining technique has been considered at the detector end for the diversity condition.

3.8.2 Diversity Reception with Maximal Ratio Combining

Let, the transmission of digital modulating signal x(t) over a flat slow Rayleigh fading channels using coherent demodulation with L-th order diversity at the receiver end. The received signal component of l-th diversity is given by-

$$r_1 (t) = \alpha_1(t)\exp[j\theta_1(t)]x(t) + w_1(t), \quad (3.19)$$

where, 1=1,2.......L

Here, it is assumed that,

(i) The channel fading process is mutually and statistically independent.

(ii) The additive white Gaussian noise processes are mutually statistically independent.

(iii) The channel fading processes and additive white Gaussian noise processes are free from each other.

For a slow fading channel, the complex channel gain can be assumed to be complex constant over each symbol interval. The demodulator in each channel is optimum for AWGN channel. The output of the demodulator of the l-th branch at the end of the k-th symbol interval is [9]-

$$\alpha_{1k} exp\ (j\theta_{1k}) x_k + n_{lk} \tag{3.20}$$

Where, $\alpha_{1k}\ exp(j\theta 1k)$ = Complex channel gain of l-th channel over the k-th symbol interval.

x_k = Vector representation of the transmitted signal over k-th symbol interval in the N-Th dimensional signal space and is also demodulator output over AWGN channel.

$n_{lk} = (n_{lk,1}, n_{lk,2} \ldots \ldots \ldots \ldots n_{lk,N})$ = Vector representation of the noise component of the demodulator output due to $w_1(t)$.

It can be shown that, $||x_k||^2 = E$ (Symbol energy), and each component in $\mathbf{n_{lk}}$ is a Gaussian random variable with zero mean and variance $N_o/2$ which is independent of any other noise component in the same or different diversity channels.

Let us consider the maximal ratio combining, as shown in the following figure-

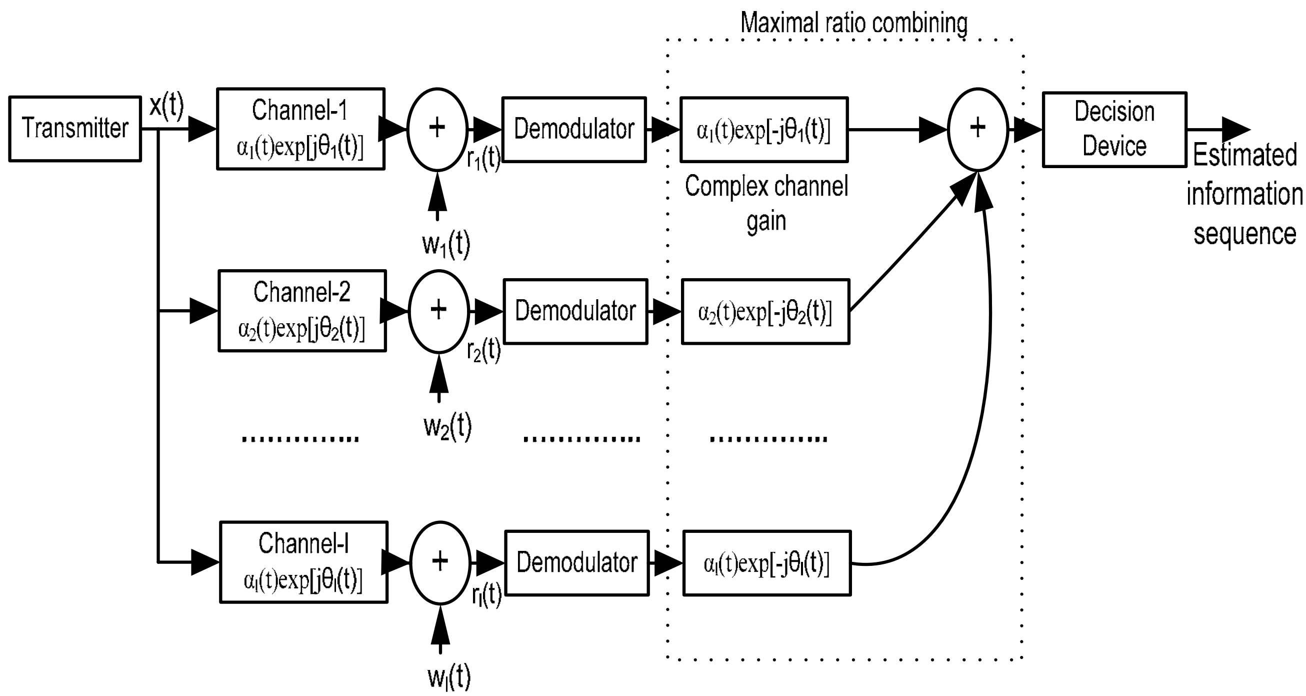

Fig. 3.4 Diversity reception with Maximal Ratio Combining

The decision variable for the k-th transmitted symbol interval can be represented as [9],

$$\mathbf{r_k} = \sum_{l=1}^{L} \alpha_{lk} \exp(-j\theta_{lk}) \left[\alpha_{lk} \exp(j\theta_{lk})\, \mathbf{x_k} + \mathbf{n_{lk}}\right]$$

$$= \sum_{l=1}^{L} \alpha_{lk}^2 \boldsymbol{x_k} + \sum_{l=1}^{L} \alpha_{lk} \exp(-j\theta_{lk})\, \mathbf{n_{lk}}]$$

$$= \mathbf{g_k}\, \mathbf{x_k} + \mathbf{n_k} \qquad (3.21)$$

Where,

$$\mathbf{g_k} = \sum_{l=1}^{L} \alpha_{lk}^2$$

$$\mathbf{n_k} = \sum_{l=1}^{L} \alpha_{lk} \exp(-j\theta_{lk}) n_{lk}$$

For the noise vector $n_k = (n_{k,1}, n_{k,2} \ldots \ldots \ldots \ldots \ldots n_{k,n})$, each component is,

$$n_{k,n}=\sum_{l=1}^{L} \alpha_{lk} \exp(-j\theta_{lk}) n_{lk,n} \tag{3.22}$$

Where, n=1, 2, 3, ……….., N.

Therefore given the weighting vector gain $\alpha_{lk}\exp(-j\theta lk)$, 1=1,2 .... L, each noise component $n_{k,n}$ is a Gaussian random variable with zero mean and variance,

$$\sigma^2_{k,n}=\frac{No}{2} \sum_{l=1}^{L} \alpha_{lk}^2 \tag{3.23}$$

The vectors $\mathbf{r_k}$,$\mathbf{x_k}$ and $\mathbf{n_k}$ can be represented by the corresponding scalar variables r_k, x_k, n_k respectively. The decision variable for k-th transmitted symbol is,

$$r_k=g_k x_k+n_k$$

Where, $x_k = \sqrt{Eb}$ for symbol "1" and $x_k = -\sqrt{Eb}$ for symbol "0". The SNR per bit at the output of the combiner for the k-th symbol is then [9],

$$\gamma_k=\frac{(g_k x_k)^2}{2\sigma_{k,n}^2} = \frac{\left[\sum_{l=1}^{L} \alpha_{lk}^2 x_k\right]^2}{No \sum_{l=1}^{L} \alpha_{lk}^2} = \frac{E_b}{N_o} \sum_{l=1}^{L} \alpha_{lk}^2 \tag{3.24}$$

Where E_b/N_o is the SNR value for the AWGN channel with α_{lk}=1 and L=1.

In a Rayleigh fading environment, the α_{lk}'s are the Rayleigh random variables with parameter σ^2_α. Therefore γ_k follows a chi-square distribution with 2L degrees of freedom. Its pdf is given by,

$$f_\gamma(X)=\frac{X^{L-1} exp\left(-x/_{\Gamma_c}\right)}{(L-1)!\Gamma_c^L} \tag{3.25}$$

Where r_c is the average SNR per bit in each diversity channel and that is-

$$r_c=2\sigma_\alpha^2 \frac{E_b}{N_o} \tag{3.26}$$

The mean SNR per bit after the combining is-

$$\Gamma_b=E[\gamma_k]=L_{\Gamma c} \quad (3.27)$$

Maximal ratio combining makes use the signal components in all the diversity channels and the mean SNR per bit increases linearly with L. The analysis of the probability of error over a Rayleigh fading channel can be extended to case of diversity as,

$$P_b=\int_0^{\infty} P_{e|\gamma}(X) f_\gamma(X)\,dx \quad (3.28)$$

Where $P_{e|\gamma}(X)$ is the conditional probability of bit error given that the received SNR per bit is γ = x. For coherent QPSK, we have,

$$P_{e|\gamma}(x) = Q(\sqrt{2x}) \quad (3.29)$$

Substituting equation (3.8.10) and (3.8.7) into equation (3.8.9) we get,

$$P_b=\left(0.5(1-\mu)\right)^L \sum_{l=0}^{L-1} \binom{L-1+l}{l} [0.5(1+\mu)]^L \quad (3.30)$$

Where,

$$\mu=\sqrt{\frac{\Gamma_c}{1+\Gamma_c}} \quad (3.31)$$

For Γc >>1, we have, 0.5 (1+μ)≈1 and 0.5(1-μ)≈1/4 Γc. Furthermore,

$$\sum_{l=0}^{L=1} \binom{L-1+l}{l} = \binom{2L-l}{L} \quad (3.32)$$

As a result, for Γc >> 1 the probability of error can be approximated as,

$$P_b \approx \left(\frac{1}{4\Gamma_c}\right) \binom{2L-l}{L} \quad (3.33)$$

Equations (3.30) or (3.33) are obtained where number of transmitting antenna is 1 and the number is receiving is L. So the system is SIMO in Rayleigh fading environment over uncorrelated channel where each transmitting antenna transmits digital signals at the same time and in the same bandwidth using the same symbol period.

Maximal Ratio Combing can be used to find out probability of bit error for MIMO system. If there are N transmitting antenna and L receiving antenna, signal from the first transmitting antenna will go to L receiving antenna. So the diversity channel will be L for the first antenna. The probability of bit error for after combining L diversity channel at the receiving side will follow equation (3.30)-

$$P_{b(1,L)}=\left(0.5(1-\mu)\right)^{L}\sum_{l=0}^{L-1}\binom{L-1+l}{l}\left[0.5(1+\mu)\right]^{L} \qquad (3.34)$$

For the other transmitting antenna same thing will happen. So, the probability of bit error for N transmitting antenna will be-

$$P_{b(N,L)}=\left\{\left(0.5(1-\mu)\right)^{L}\sum_{l=0}^{L-1}\binom{L-1+l}{l}\left[0.5(1+\mu)\right]^{L}\right\}^{N} \qquad (3.35)$$

Where,

$$\mu=\sqrt{\frac{\Gamma_c}{1+\Gamma_c}} \qquad (3.36)$$

and Γ_c is the average SNR per bit of each channel. Using subcarrier multiplexed QPSK modulation scheme, the considered SNR is-

$$\Gamma_c=\frac{(IRs)^2 Pm}{2\,B_e\cdot(qRI_{Bg}+2kT/R_L)} \qquad (3.37)$$

3.9 Summary

In this chapter theoretical analysis on FSO MIMO communication system based on QPSK subcarrier intensity modulation has been discussed. The performance analysis has been done in terms of bit error rate (BER).

Chapter 4

Results and Discussion

Chapter-4

Results and Discussion

4.1 Introduction

The analytical results are presented and discussed in this chapter. Here the performance has been shown in terms of bit error rate (BER) for a SISO, SIMO, MISO and MIMO system.

4.2 Results and Discussion

In this thesis the performance of FSO communication through atmospheric channel using Subcarrier multiplexed QPSK modulation has been analyzed. The performance for a Subcarrier Multiplexed Intensity modulated OFS link with optical intensity modulation and direct detection in the presence of atmospheric turbulence is observed. QPSK modulation is considered in the Subcarrier Multiplexing. If the length of a FSO medium i.e. air is increased, then the effect of atmospheric turbulence will be significant. Negative Exponential Model has been used to represent the atmospheric effect during strong turbulence.

First the BER has been observed varying different parameters for a single transmitter and single detector. Then for multiple transmitters and multiple detectors the BER has been presented and it is clearly found that the performance is considerably improved i.e. the BER is significantly decreased for multiple transmitters and multiple receivers.

In this thesis, the numerical computation and graphical representation have been done by using MatLab software. Different parameters used for computation in this chapter are shown in the following table-

Parameter Name	**Value**
Bit Rate	1 Gbps
Modulation Index	1.0
Responsivity of the Detector	0.85
Modulation	Subcarrier Multiplexed QPSK
Channel Type	Negative Exponential
Turbulence Varience	0.8
Load resistance	50Ω
Temperature	300K

Table 4.1: Nominal parameters used in FSO communication link

4.3 Performance Analysis of a SISO FSO System without Turbulence

4.3.1 Observation of SNR Vs Subcarrier Signal Power

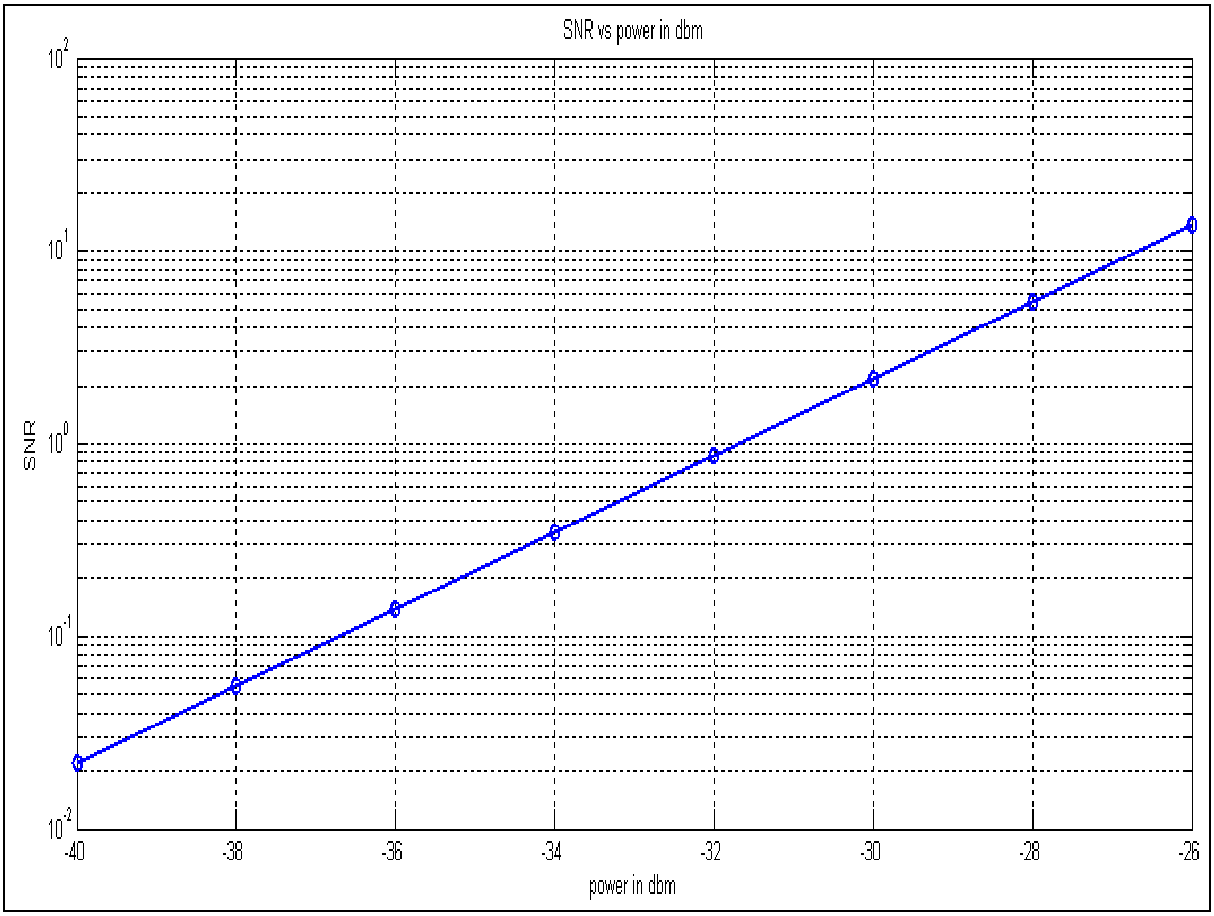

Figure 4.1: SNR vs Subcarrier Power of a FSO link without Turbulence

Fig. 4.1 shows the plot of SNR vs. subcarrier power for a SISO FSO link considering no atmospheric turbulence.

In the above figure, it is clearly seen that the snr of the FSO signal is increased with subcarrier power. The numerical analysis is given in the side table**.**

Power in dbm	SNR
-40	0.02181
-36	0.1376
-32	0.8635
-28	5.48
-26	13.76

Table 4.2: Numerical analysis of SNR vs subcarrier power in dbm

4.3.2: Observation of Bit Error Rate vs. Subcarrier Power

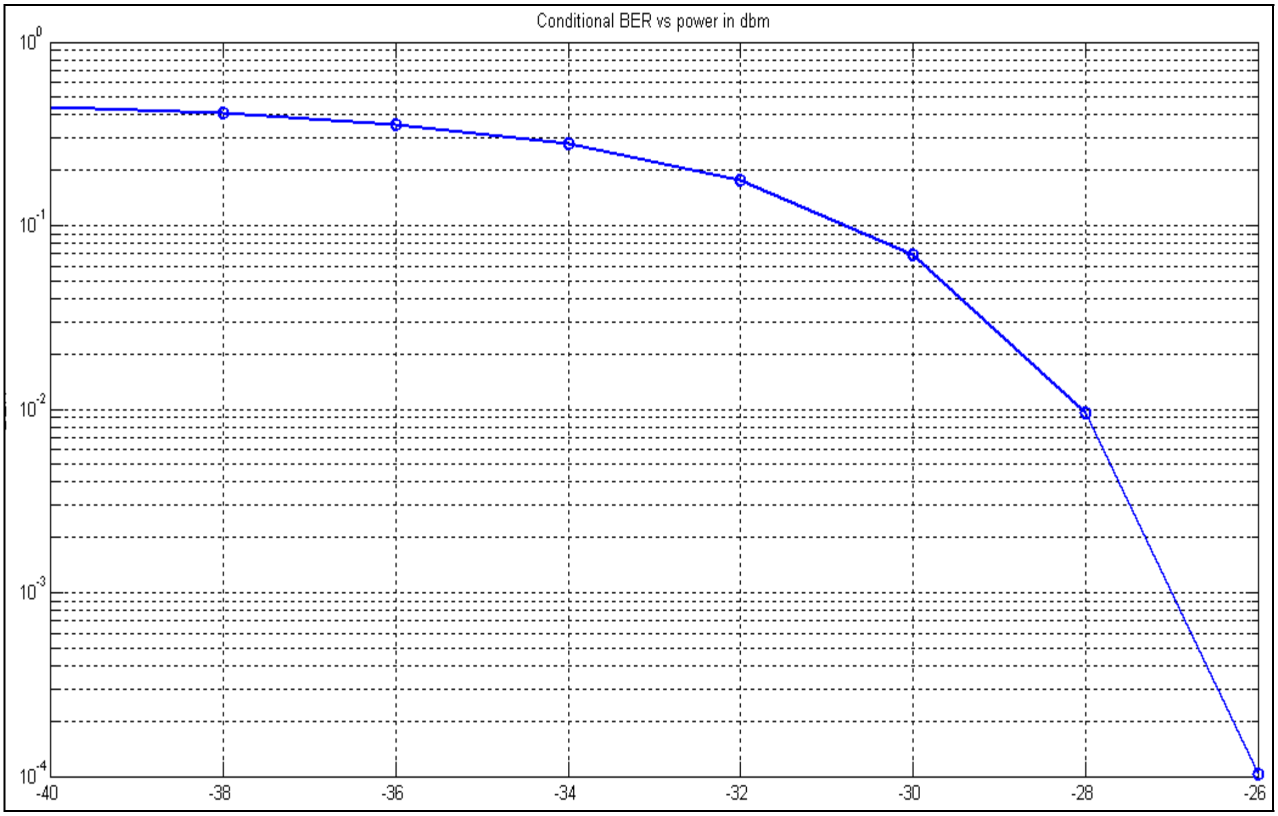

Figure 4.2: BER Vs subcarrier power for a FSO link without turbulence.

In fig. 4.2 BER vs. subcarrier power for a FSO link is shown without turbulence. It is observed in fig. 4.1 that with the signal power, the SNR is increased. It clearly indicates that the BER should be decreased with the signal power which is clearly seen in figure 4.2.

Power in dbm	BER
-40	0.4413
-36	0.3553
-30	0.06984
-26	0.0001036

Table 4.3: BER with various Signal Power

4.4 Performance Analysis of a SISO FSO System with Turbulence

4.4.1: BER of a FSO Link with and without Turbulence

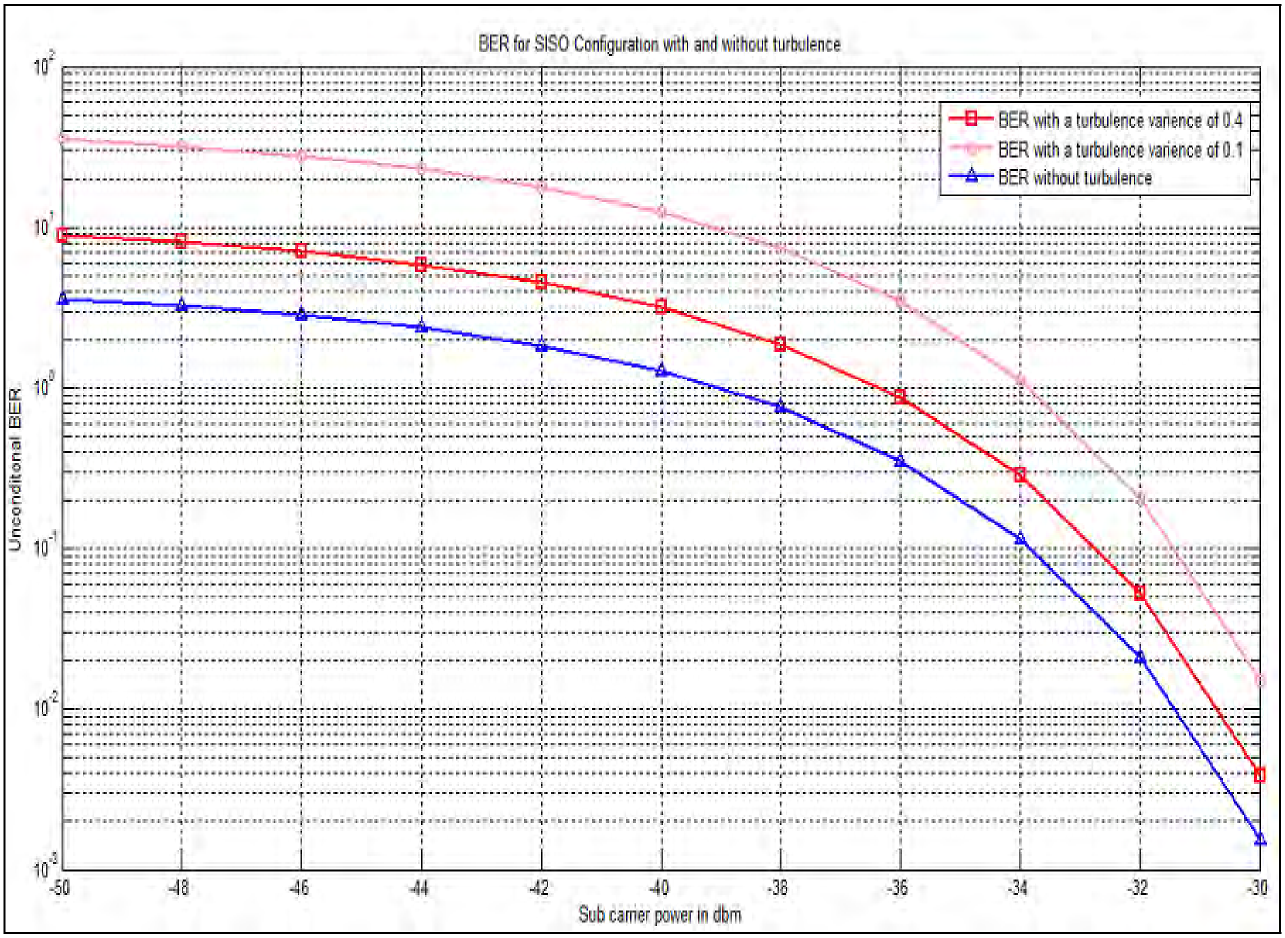

Figure 4.3: BER of a FSO link with and without Turbulence

Fig. 4.3 shows the effect of BER vs. subcarrier power in the presence of atmospheric turbulence. Due to turbulence the FSO link faces obstacle to transmit signal which results more BER. This is observed in the above figure clearly where BER is higher in the presence of atmospheric turbulence.

Power in dbm	BER without turbulence	BER with turbulence variance 0.4	BER with turbulence variance 0.1
-32	$2x10^{-2}$	$5.2x10^{-2}$	$2.03x10^{-1}$
-30	$1.56x10^{-3}$	$3.9x10^{-3}$	$1.52x10^{-2}$

Table 4.4: BER of a FSO link with and without Turbulence with various power.

4.4.2: Observation of BER of a FSO link with Variable Responsivity of the Detector in the Presence of Atmospheric Turbulence

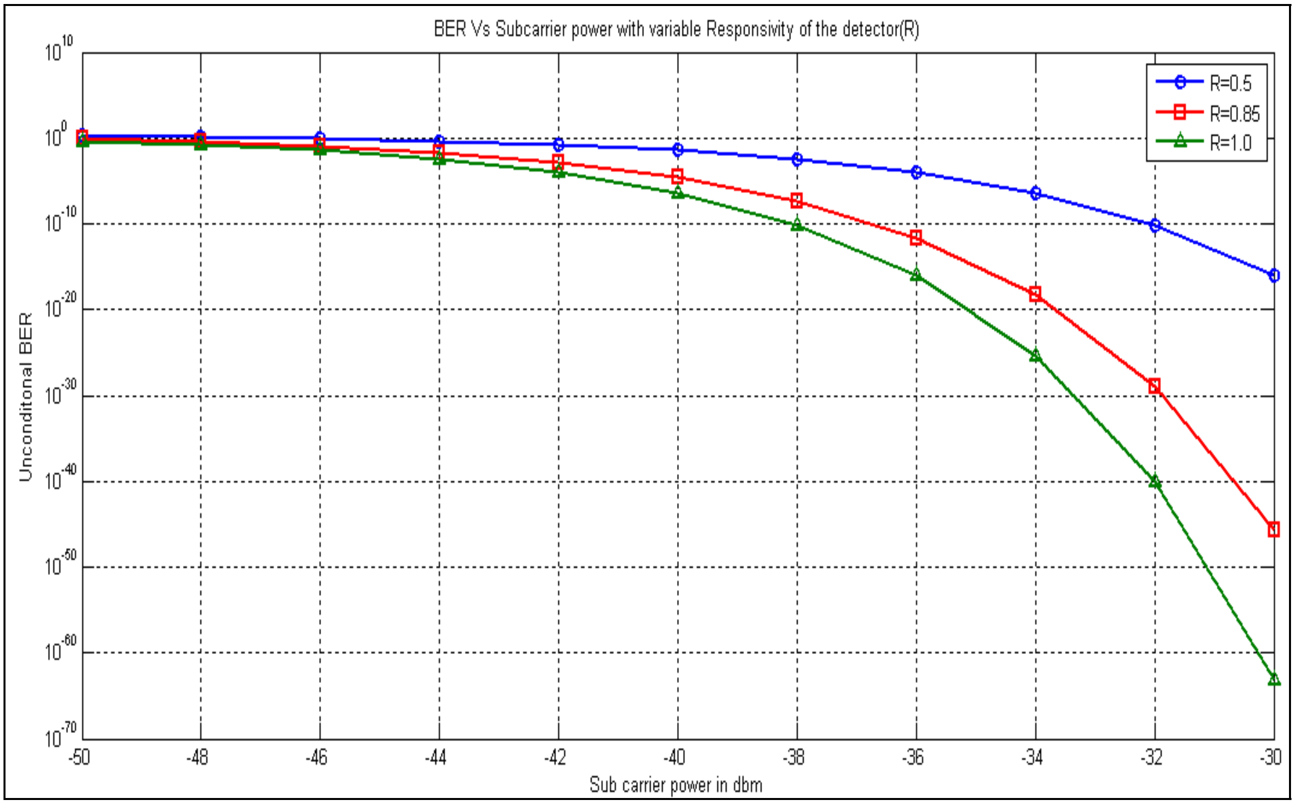

Figure 4.4: BER of a FSO link with variable Responsivity(R) of the detector in the presence of Turbulence

Fig. 4.4 shows BER vs. subcarrier power with the variation of detector responsivity. In the mathematical analysis, it is observed that with the increase of the detector responsivity, the SNR is increased and consequently BER should be decreased which is clearly seen in the above figure.

Signal power in dbm	BER in the presence of turbulence with variable Responsivity (R)		
	R=0.5	***R=0.85***	***R=1.0***
-44	0.4476	0.0198	0.003511
-38	0.003615	$4.624 x 10^{-8}$	$7.043 x 10^{-11}$
-30	$1.072 x 10 -_{16}$	$1.819 x 10^{-46}$	$6.896 x 10^{-64}$

Table 4.5: BER in the presence of turbulence with variable Responsivity (R) and various signal power

4.4.3: Observation of BER of a FSO Link with Variable Modulation Index (m) in the Presence of Atmospheric Turbulence

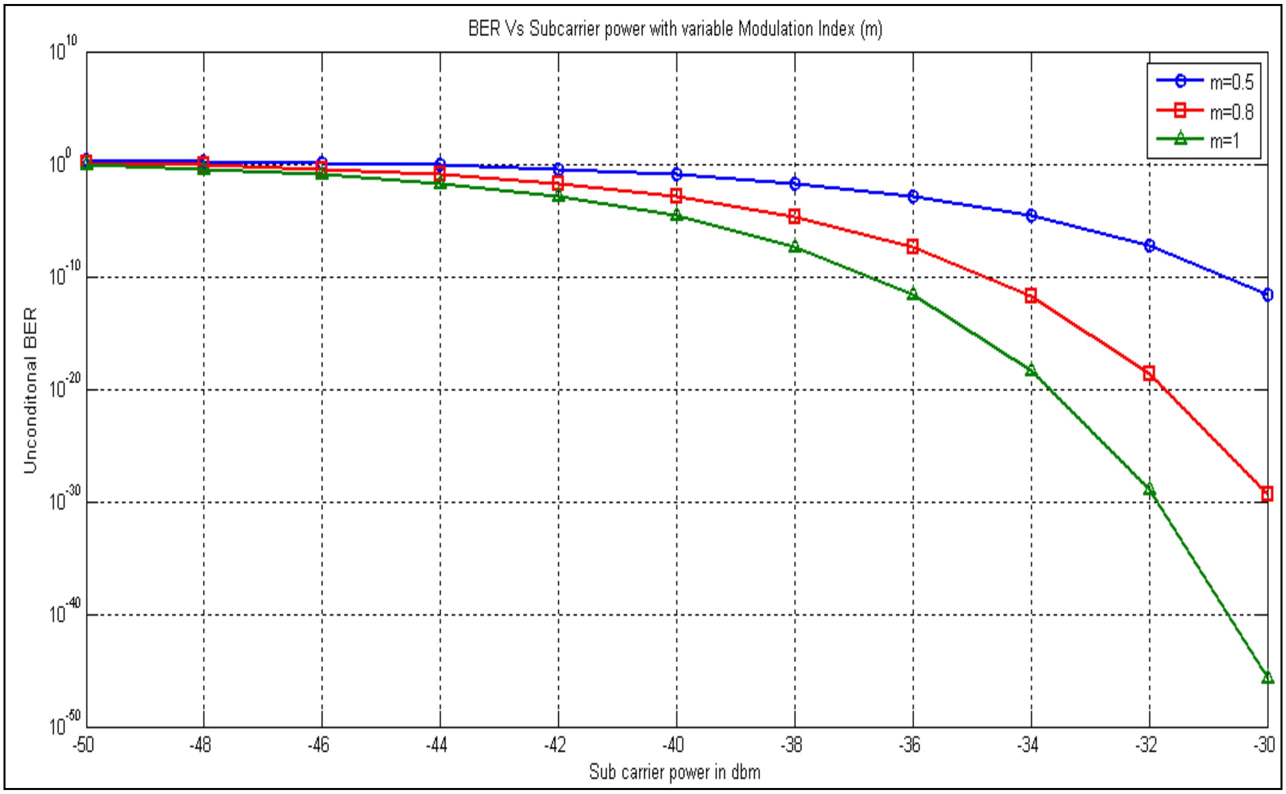

Figure 4.5: BER of a FSO link with variable Modulation Index (m) in the presence of Turbulence

Fig. 4.5 shows the BER vs. subcarrier power with the variation of modulation index in the presence of atmospheric turbulence. In the arithmetical analysis, it is observed that with the increase of modulation index (m) the SNR is increased and thus BER should be decreased which is clearly seen in the above figure.

Signal power in dbm	**BER in the presence of turbulence with variable modulation index(m)**		
	m=0.5	***m=0.8***	***m=1.0***
-44	0.7428	0.1054	0.0198
-38	0.02024	2.154×10^{-5}	4.624×10^{-8}
-30	2.731×10^{-12}	4.156×10^{-30}	1.819×10^{-46}

Table 4.6: BER of a FSO link with variable Modulation Index (m) in the presence of Turbulence with various signal power.

4.4.4: Observation of BER of a FSO Link with Variable Turbulence Variance (I_o)

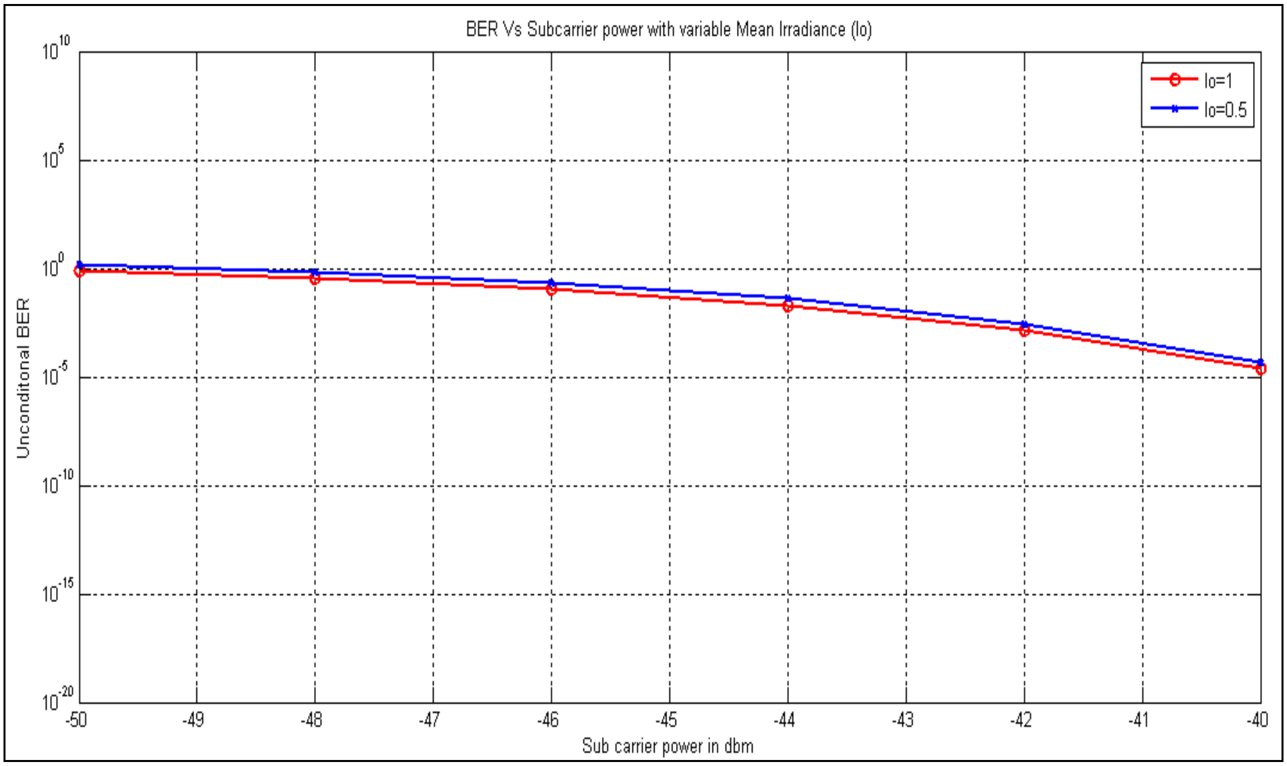

Figure 4.6: BER of a FSO link with variable Turbulence Variance (Io)

In fig. 4.6 BER vs. subcarrier power with the variation of turbulence variance is presented. It is observed that with the increase of turbulence variance the BER is reduced with various signal power.

Signal power in dbm	BER with variable turbulence variance (I_o)	
	I_o=0.5	I_o=1.0
-48	0.6799	0.3433
-44	0.03922	0.0198
-40	4.984x10^{-5}	2.517x10^{-5}

Table 4.7: BER of a FSO link with variable Turbulence Variance (Io) with various signal power.

4.4.5: Observation of BER of a FSO Link With Variable Bit Rate (R_b) in the Presence of Atmospheric Turbulence

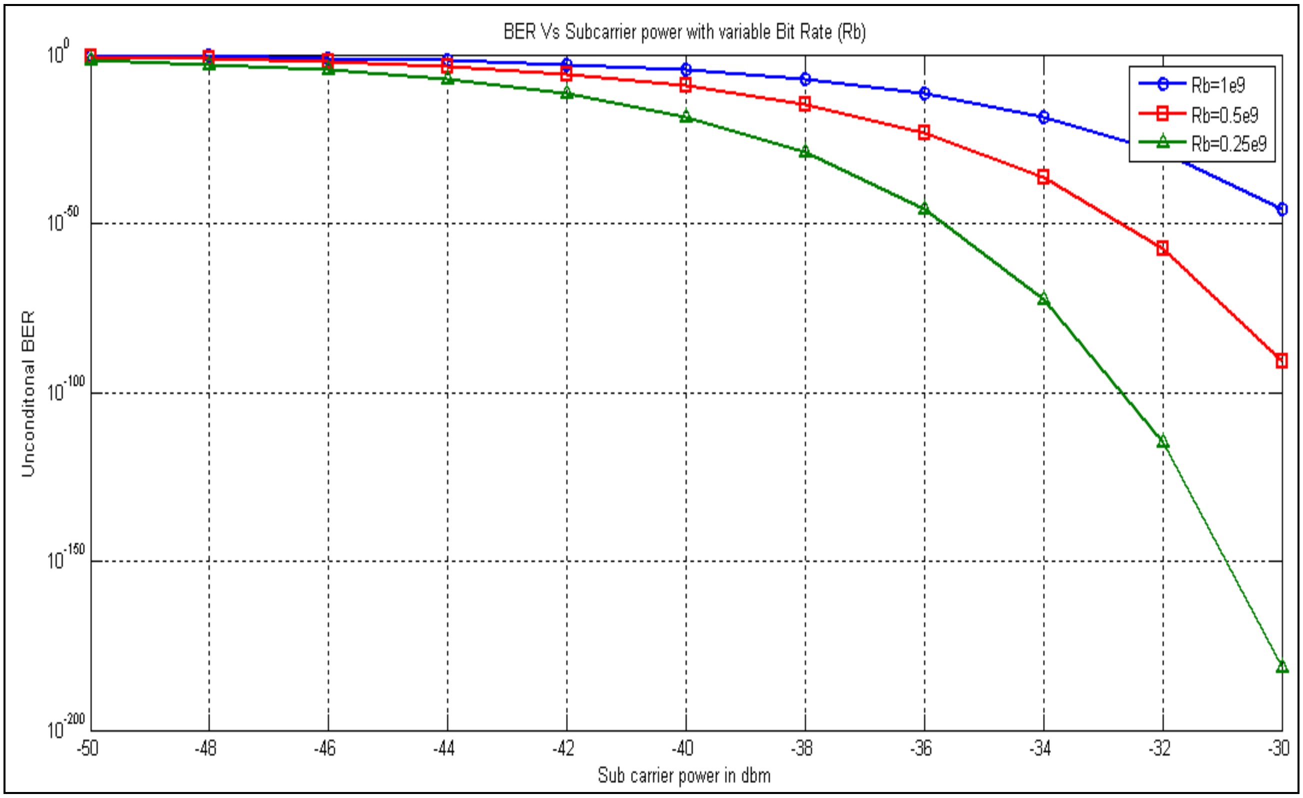

Figure 4.7: BER of a FSO link with variable Bit Rate (R_b) in the presence of atmospheric Turbulence

In fig. 4.7 BER vs. subcarrier power with different bit rate is shown. In the above figure it is observed that with the increase of Bit Rate (R_b) the BER is increased with various signal power. It is seen that the BER is significantly reduced at a lower bit rate.

Signal power in dbm	**BER in the presence of turbulence with variable Bit Rate (R_b)**		
	R_b=0.25 Gbps	***R_b=0.5 Gbps***	***R_b=1.0 Gbps***
-44	4.266×10^{-8}	0.0002326	0.0198
-38	7.828×10^{-30}	2.294×10^{-15}	4.624×10^{-8}
-30	2.717×10^{-182}	8.607×10^{-92}	1.819×10^{-46}

Table 4.8: BER of a FSO link with variable Bit Rate (Rb) in the presence of atmospheric Turbulence with various signal power.

4.4.6: Observation of BER of a FSO link with Variable Band Width (B) in the Presence of Atmospheric Turbulence

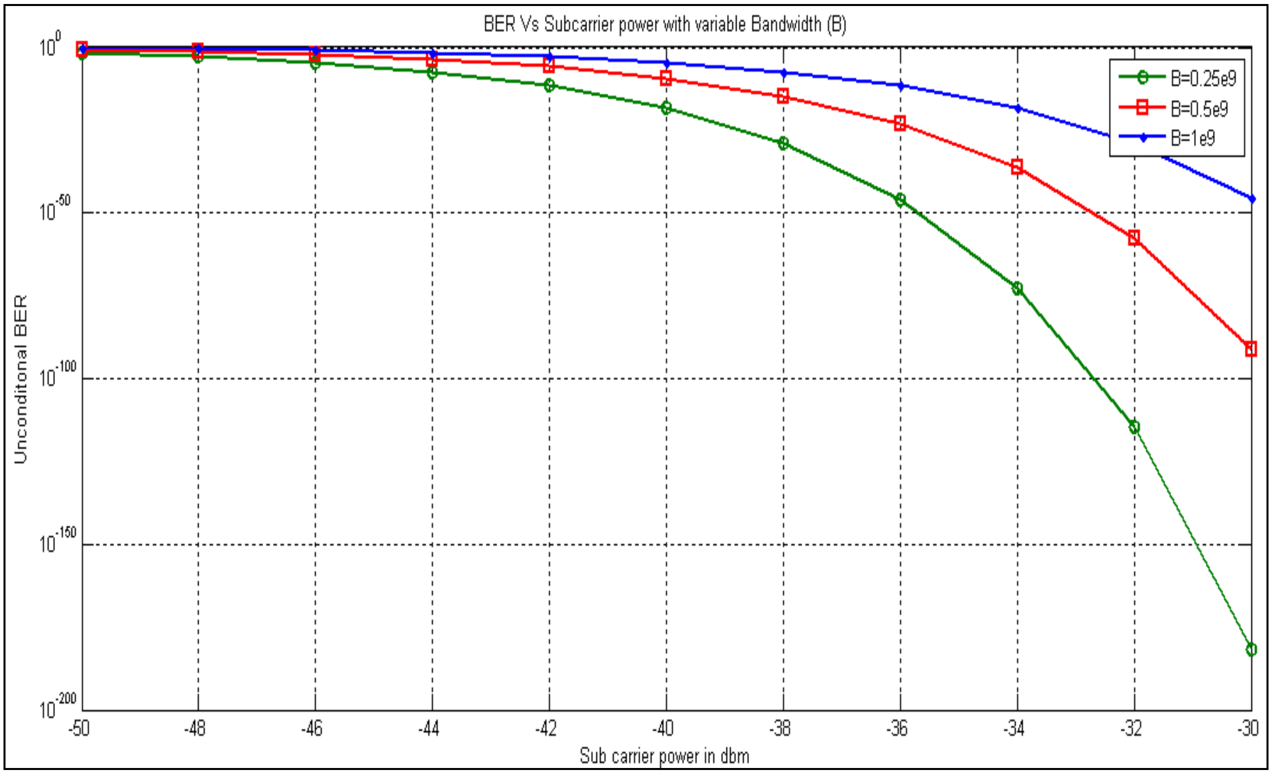

Figure 4.8: of BER of a FSO link with variable Band width (B) in the presence of atmospheric Turbulence

Fig. 4.8 shows the BER vs. subcarrier power of a FSO link with variable Band width (B) in the presence of atmospheric Turbulence. With the increase of the bandwidth(B), effect of noise is increased. So, the BER should be increased which is found in the above figure. For a particular power, BER is increased with the increase of bandwidth(B).

Signal power in dbm	BER in the presence of turbulence with variable Bandwidth (B)		
	B=0.25 Gbps	*B=0.5 Gbps*	*B=1.0 Gbps*
-44	4.266×10^{-8}	0.0002326	0.0198
-38	7.828×10^{-30}	2.294×10^{-15}	4.624×10^{-8}
-30	2.717×10^{-182}	8.627×10^{-92}	1.819×10^{-46}

Table 4.9: BER of a FSO link with variable Band width (B) in the presence of atmospheric Turbulence with various power

4.5 Performance Analysis of a SIMO FSO System with Turbulence

4.5.1 Observation of BER of a SIMO FSO Link with Variable Turbulence Variance (I_o)

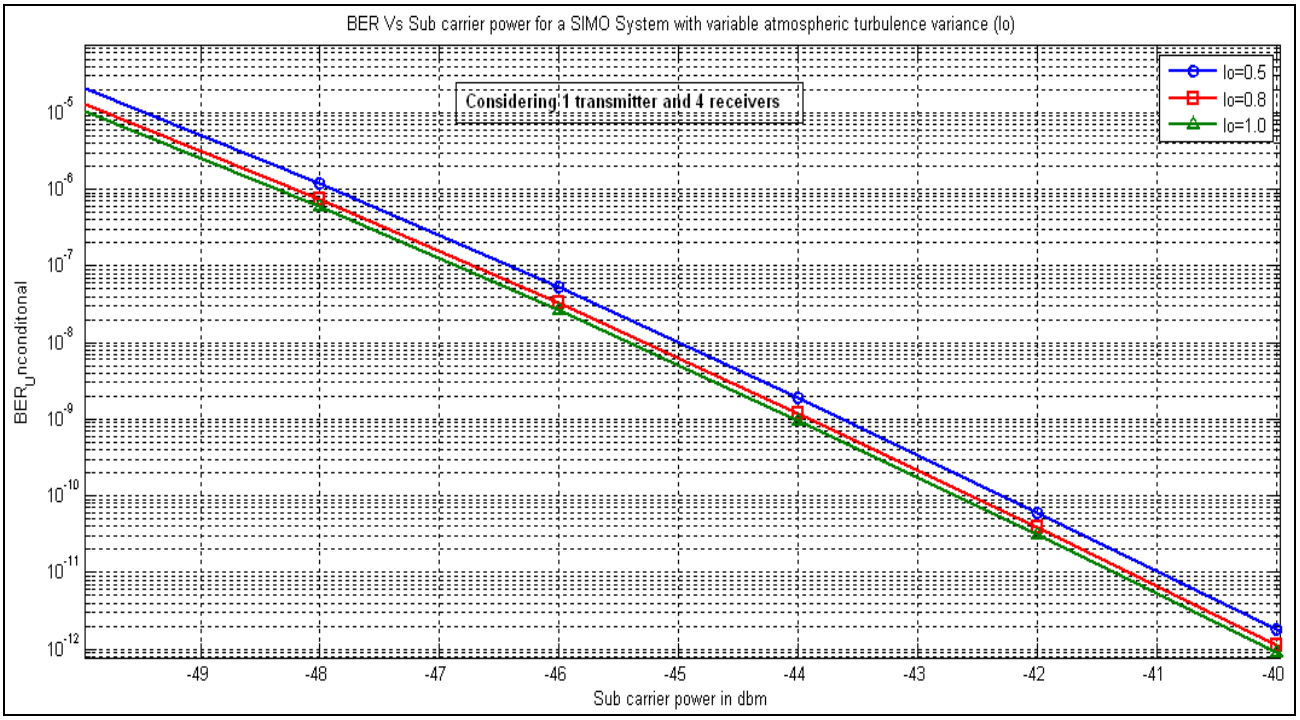

Figure 4.9: BER of a SIMO FSO link with variable Turbulence Variance (Io)

Fig. 4.9 shows the BER vs. subcarrier power with variable turbulence variance considering one transmitter and four receivers. In the above figure it is observed that with the increase of turbulence variance the BER is reduced with various signal power for a SIMO FSO link where one transmitter and four receivers are used. For a SIMO system the BER is less with respect to a SISO FSO link.

Signal power in dbm	BER of a SIMO FSO link with variable Turbulence Variance (I_o)		
	I_o=0.5	I_o=0.8	I_o=1.0
-48	1.202×10^{-6}	7.565×10^{-7}	6.067×10^{-7}
-44	1.902×10^{-9}	1.197×10^{-9}	90603×10^{-10}
-40	1.799×10^{-12}	1.133×10^{-12}	9.084×10^{-13}

Table 4.10: BER of a SIMO FSO link with variable Turbulence Variance (Io) with various power

4.5.2 Observation of BER of a FSO Link with one Transmitter and Variable Receivers at a Bit Rate of 1 Gbps

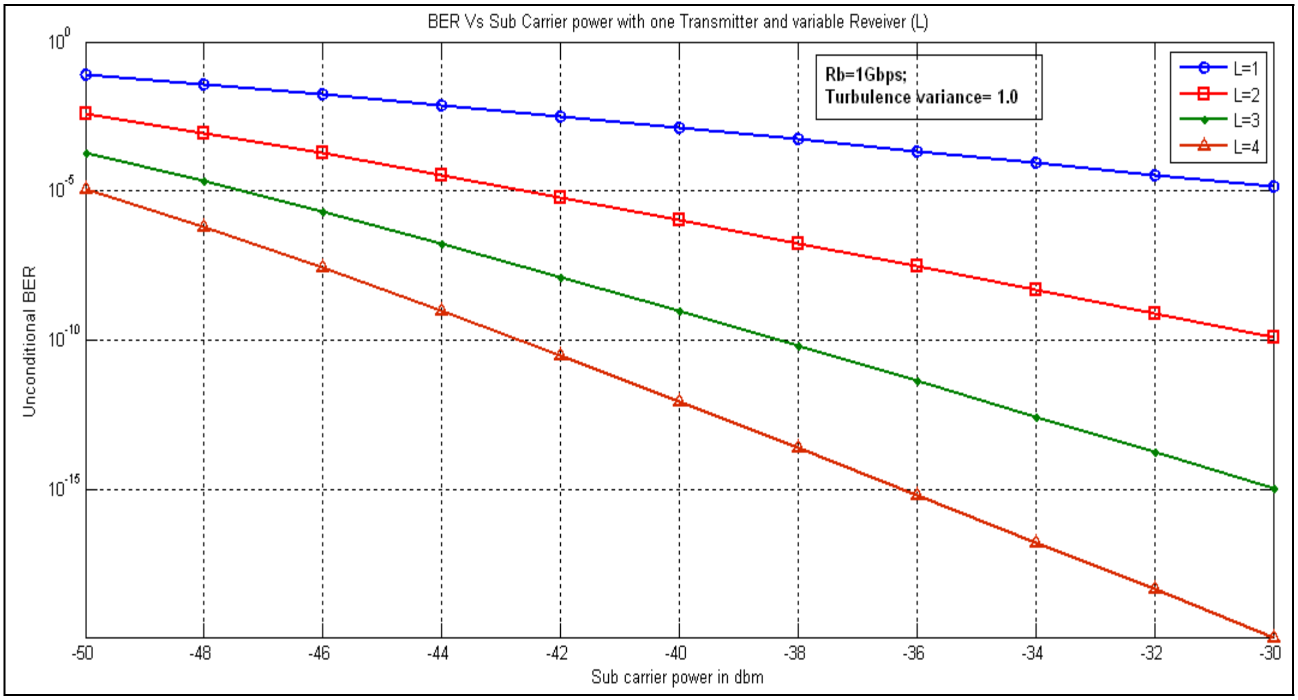

Figure 4.10: BER of a FSO link with one Transmitter and variable receivers at a bit rate of 1 Gbps

BER vs. subcarrier power with one transmitter and variable receivers at a bit rate of 1 Gbps is shown in fig. 4.10. In the above figure it is clearly seen that the BER is reduced with the increase of the number of receivers for a bit rate of 1 Gbps. In the table below, it is found that the amount of BER is appreciably reduced with the increase of the receivers at a particular power level.

Signal power in dbm	BER of a FSO link with one Transmitter and variable receivers(L) at a bit rate of 1 Gbps			
	L=1	***L=2***	***L=3***	***L=4***
-50	0.07853	0.00374	0.0001979	$1.1x10^{-5}$
-40	0.001331	$1.075x10^{-6}$	$9.643x10^{-10}$	$9.084x10^{-13}$
-30	$1.418*10^{-5}$	$1.22x10^{-10}$	$1.166x10^{-15}$	$1.173x10^{-20}$

Table 4.11: BER of a FSO link with one Transmitter and variable receivers(L) at a bit rate of 1 Gbps with various power.

4.5.3 Observation of BER of a FSO Link with One Transmitter and Variable Receivers at a Bit Rate of 2.5 Gbps

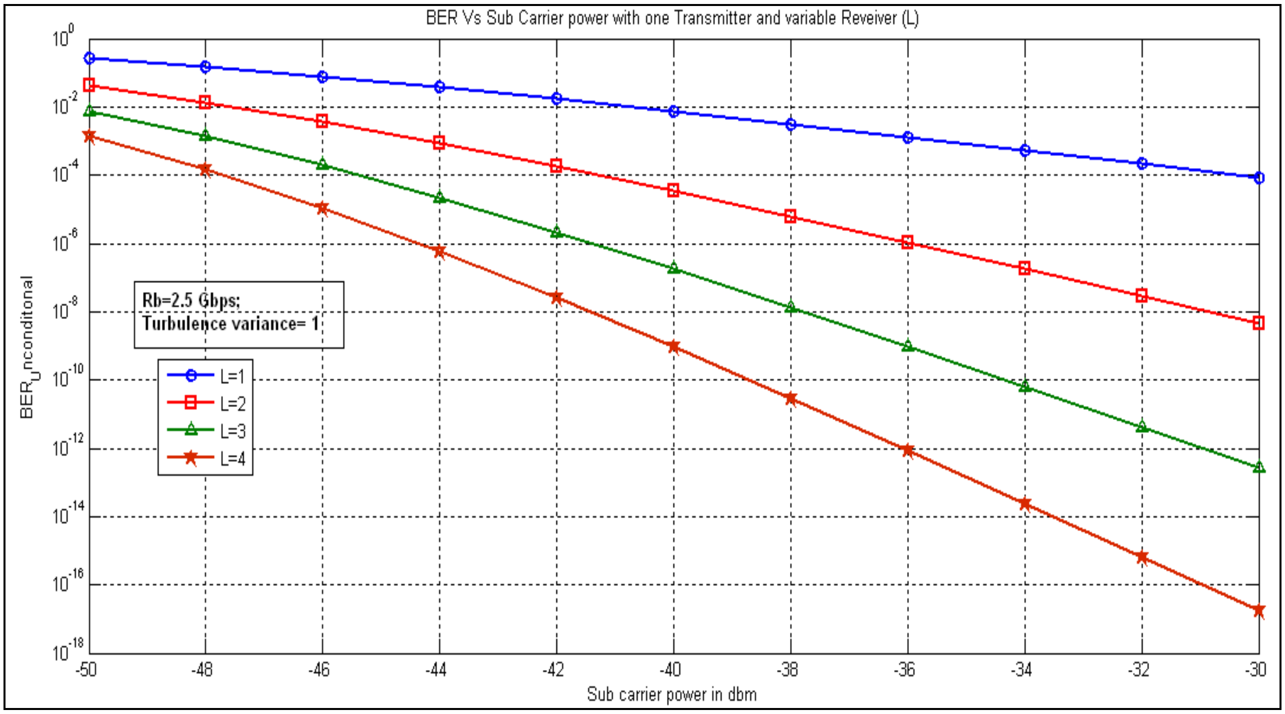

Figure 4.11: BER of a FSO link with one Transmitter and variable receivers at a bit rate of 2.5 Gbps.

Fig. 4.11 shows BER vs. subcarrier power with one transmitter and variable receivers at a bit rate of 2.5 Gbps considering turbulence variance 1.0. In the above figure it is noticeably seen that the BER is reduced with the increase of the number of receivers for a bit rate of 2.5 Gbps. In the following table, it is found that the amount of BER is appreciably reduced with the increase of the receivers at a particular power level.

Signal power in dbm	BER of a FSO link with one Transmitter and variable receivers(L) at a bit rate of 2.5 Gbps			
	L=1	*L=2*	*L=3*	*L=4*
-50	0.2629	0.04193	0.00743	0.001382
-40	0.007525	3.435×10^{-5}	1.742×10^{-7}	9.274×10^{-10}
-30	8.77×10^{-5}	4.665×10^{-9}	2.757×10^{-13}	1.711×10^{-17}

Table 4.12: BER of a FSO link with one Transmitter and variable receivers(L) at a bit rate of 2.5 Gbps with various power.

4.5.4 Observation of BER of a FSO Link with One Transmitter and Variable Receivers at a Bit Rate of 10 Gbps

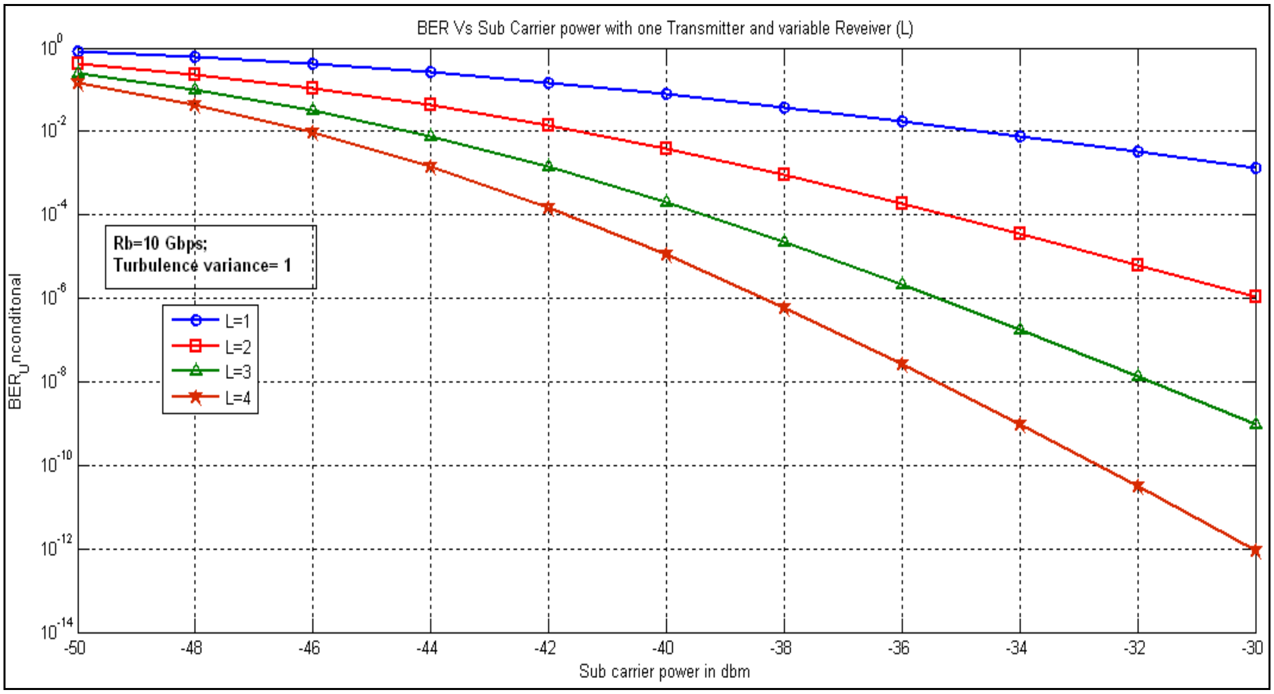

Figure 4.12: BER of a FSO link with one Transmitter and variable receivers at a bit rate of 10 Gbps.

Fig. 4.12 shows BER vs. subcarrier power with one transmitter and variable receivers at a bit rate of 10 Gbps considering turbulence variance 1.0. In the above figure it is seen that the BER is reduced significantly with the increase of the number of receivers for a bit rate of 10 Gbps. In the subsequent table, it is also established that the amount of BER is noticeably reduced with the increase of the receivers at a particular power level.

Signal power in dbm	BER of a FSO link with one Transmitter and variable receivers(L) at a bit rate of 10 Gbps			
	L=1	*L=2*	*L=3*	*L=4*
-50	0.8465	0.4345	0.2479	0.1485
-40	0.07853	0.00374	0.0001979	$1.1x10^{-5}$
-30	0.001331	$1.075x10^{-5}$	$9.644x10^{-10}$	$9.084x10^{-13}$

Table 4.13: BER of a FSO link with one Transmitter and variable receivers(L) at a bit rate of 10 Gbps with various power.

4.5.5 Observation of Required Subcarrier Power in dbm vs No. of Receiver for SIMO System for Different Bit Rate with a Particular Bit Error Rate

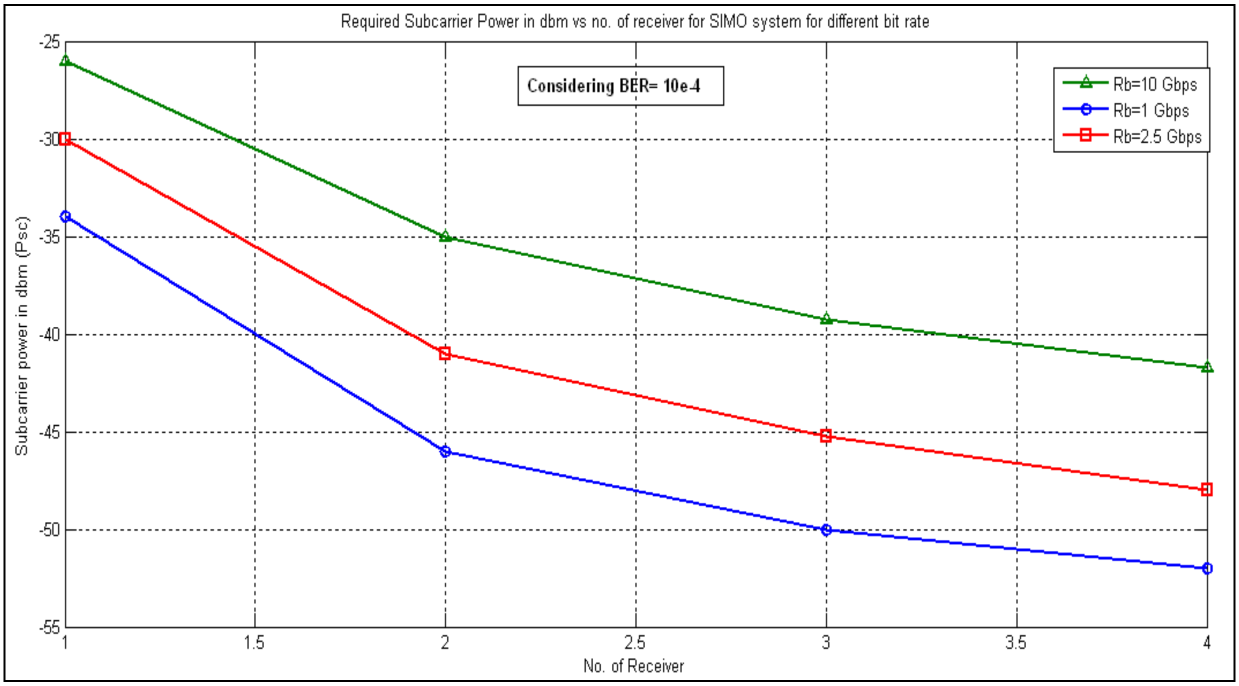

Figure 4.13: Required Subcarrier Power in dbm vs no. of receiver for a SIMO system for a bit error rate (BER) of 10^{-4}.

Fig. 4.13 shows the required subcarrier power vs. number of receivers for one transmitter considering a fixed BER of 10^{-4}. In the above figure it is clearly seen that BER is increased with the bit rate which is also seen earlier. To achieve a fixed BER and if the no. of receiver is fixed, then it is found that to transmit the FSO signal at a lower bit rate requires less subcarrier power than to transmit higher bit rate signal.

No. of receiver	Required Subcarrier Power for different no. of receivers		
	R_b=1 Gbps	***R_b=2.5 Gbps***	***R_b=10 Gbps***
2	-46	-41	-35
3	-50	-45.25	-39.25
4	-52	-48	-41.75

Table 4.14: Required Subcarrier Power in dbm vs no. of receiver for a SIMO system for a bit error rate (BER) of 10^{-4}.

4.6 Performance Analysis of a MISO FSO System with Turbulence

4.6.1 Observation of BER of a SIMO FSO Link with Variable Turbulence Variance (I_o)

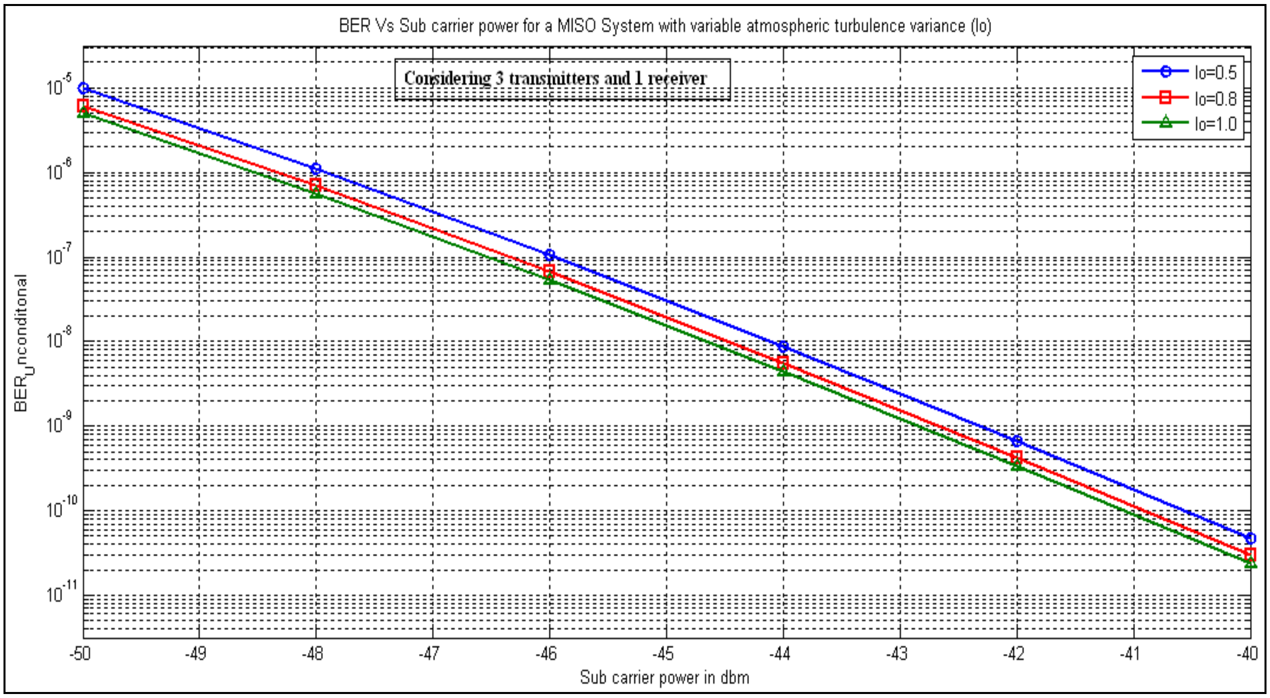

Figure 4.14: BER of a MISO FSO link with variable Turbulence Variance (Io)

Fig. 4.14 shows the BER vs. subcarrier power with variable turbulence variance considering three transmitters and one receiver. In the above figure it is observed that with the increase of turbulence variance the BER is reduced with various signal power for a MISO FSO link where three transmitters and one receiver are used. For a MISO system the BER is less with respect to a SISO FSO link.

Signal power in dbm	BER of a SIMO FSO link with variable Turbulence Variance (I_o)		
	I_o=0.5	***I_o=0.8***	***I_o=1.0***
-48	1.116×10^{-6}	7.024×10^{-7}	5.633×10^{-7}
-44	8.853×10^{-9}	5.574×10^{-9}	4.47×10^{-9}
-40	4.775×10^{-11}	3.007×10^{-11}	2.411×10^{-11}

Table 4.15: BER of a MISO FSO link with variable Turbulence Variance (Io) with various power.

4.6.2 Observation of BER of a FSO Link with Variable Transmitters and One Receiver at a Bit Rate of 1Gbps

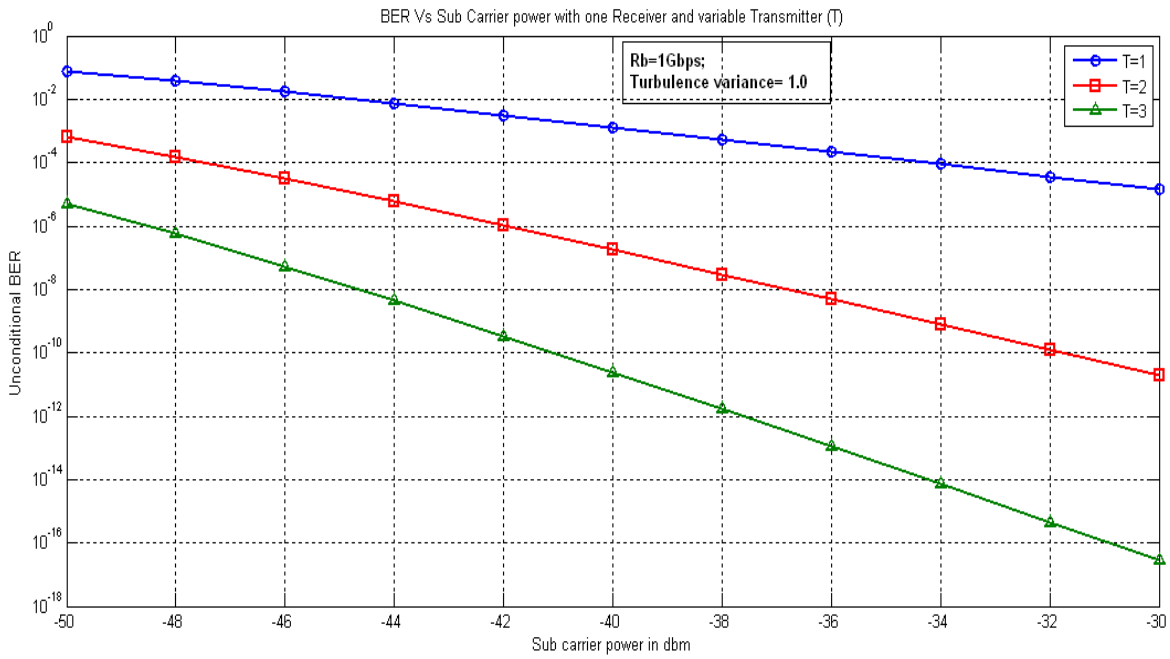

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Figure 4.15: BER of a FSO link with variable Transmitters and one receiver at a bit rate of 1 Gbps

Fig. 4.15 shows BER vs. subcarrier power with variable transmitters and one receiver at a bit rate of 1 Gbps considering turbulence variance 1.0. In the above figure it is clearly seen that the BER is reduced with the increase of the number of transmitters for a bit rate of 1 Gbps. In the table below, it is found that the amount of BER is significantly reduced with the increase of the transmitters at a particular power level.

Signal power in dbm	BER of a FSO link with variable Transmitters(T) and one receiver at a bit rate of 1 Gbps		
	T=1	***T=2***	***T=3***
-50	0.07853	0.0006234	$4.949\text{x}10^{-6}$
-40	0.001331	$1.791\text{x}10^{-7}$	$2.411\text{x}10^{-11}$
-30	$1.418\text{x}10^{-5}$	$2.034\text{x}10^{-11}$	$2.916\text{x}10^{-17}$

Table 4.16: BER of a FSO link with variable Transmitters and one receiver at a bit rate of 1 Gbps with various power.

4.6.3 Observation of BER of a FSO Link with Variable Transmitters(T) and One Receiver at a Bit Rate of 2.5 Gbps

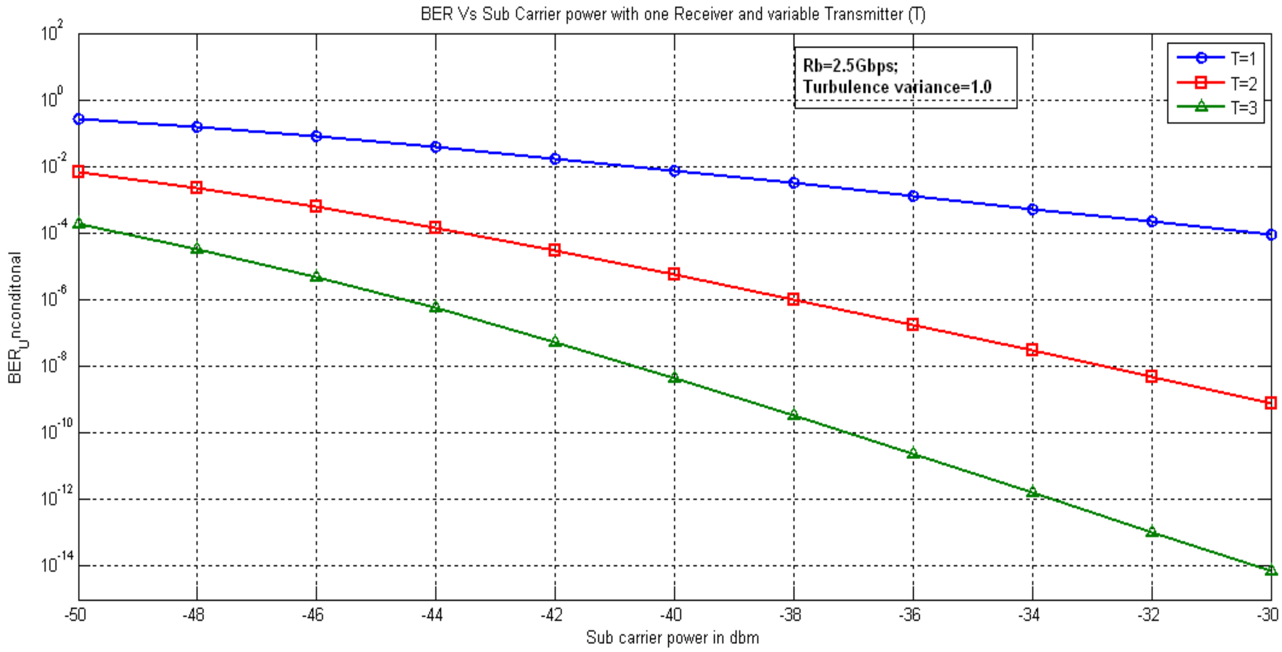

Figure 4.16: BER of a FSO link with variable Transmitters(T) and one Receiver at a bit rate of 2.5 Gbps.

Fig. 4.16 shows BER vs. subcarrier power with variable transmitters and one receiver at a bit rate of 2.5 Gbps considering turbulence variance 1.0. In the above figure it is noticeably observed that the BER is reduced with the increase of the number of transmitters for a bit rate of 2.5 Gbps. In the table below, it is found that the amount of BER is significantly reduced with the increase of the transmitters at a particular power level.

Signal power in dbm	BER of a FSO link with variable Transmitters(T) and one receiver at a bit rate of 2.5 Gbps		
	T=1	***T=2***	***T=3***
-50	0.2629	0.006989	0.0001858
-40	0.007525	$5.724\text{x}10^{-6}$	$3.354\text{x}10^{-9}$
-30	$8.77\text{x}10^{-5}$	$7.775\text{x}10^{-5}$	$6.892\text{x}10^{-15}$

Table 4.17: BER of a FSO link with variable Transmitters and one Receiver at a bit rate of 2.5 Gbps with various power.

4.6.4 Observation of BER of a FSO Link with Variable Transmitters(T) and One Receiver at a Bit Rate of 10 Gbps

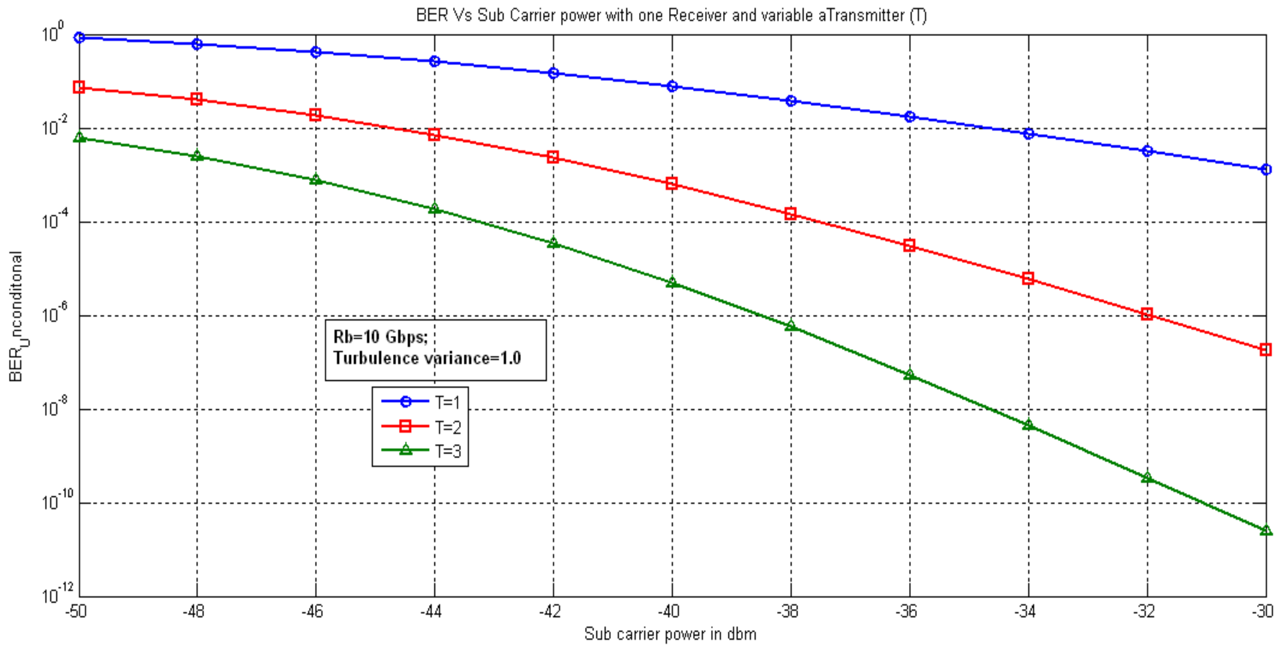

Figure 4.17: BER of a FSO link with variable Transmitters(T) and one Receiver at a bit rate of 10 Gbps.

Fig. 4.17 shows BER vs. subcarrier power with variable transmitters and one receiver at a bit rate of 10 Gbps considering turbulence variance 1.0.In the above figure it is noticeably observed that the BER is reduced with the increase of the number of transmitters for a bit rate of 10 Gbps. In the table below, it is initiated that the amount of BER is significantly reduced with the increase of the transmitters at a particular power level.

Signal power in dbm	BER of a FSO link with variable Transmitters(T) and one receiver at a bit rate of 2.5 Gbps		
	T=1	***T=2***	***T=3***
-50	0.8465	0.07242	0.006197
-40	0.07853	0.0006234	4.949×10^{-6}
-30	0.001331	1.791×10^{-7}	2.411×10^{-11}

Table 4.18: BER of a FSO link with variable Transmitters and one Receiver at a bit rate of 10 Gbps with various power.

4.6.5 Observation of Required Subcarrier Power in dbm vs. No. of Transmitters (T) for a MISO System for Different Bit Rate with a Particular Bit Error Rate of 10^{-4}

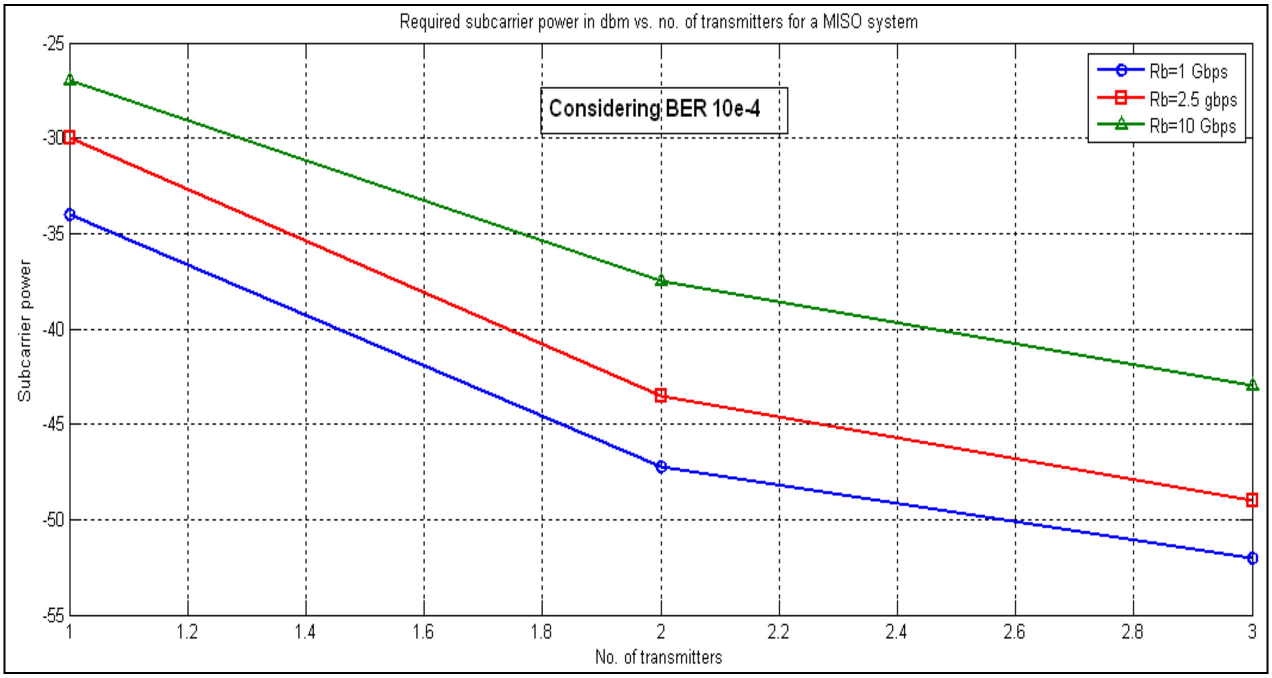

Figure 4.18: Required Subcarrier Power in dbm vs no. of Transmitters (T) for a MISO system at a bit error rate (BER) of 10^{-4}.

Fig. 4.18 shows the required subcarrier power vs. number of transmitters for one receiver considering a fixed BER of 10^{-4}. In the above figure it is clearly seen that BER is increased with the bit rate which is also seen earlier. To achieve a fixed BER and if the no. of transmitters are fixed, then it is found that to transmit the FSO signal at a lower bit rate requires less subcarrier power than to transmit higher bit rate signal.

No. of transmitters (T)	**Required Subcarrier Power for different no. of transmitters**		
	R_b=1 Gbps	***R_b=2.5 Gbps***	***R_b=10 Gbps***
1	-34	-30	-27
2	-47.25	-43.5	-37.5
3	-52	-49	-43

Table 4.19: Required Subcarrier Power in dbm vs no. of Transmitters (T) for a MISO system at a bit error rate (BER) of 10^{-4}.

4.7 Performance Analysis of a MIMO FSO System with Turbulence:

4.7.1 Observation of BER of a MIMO FSO Link with Variable Turbulence Variance (I_o)

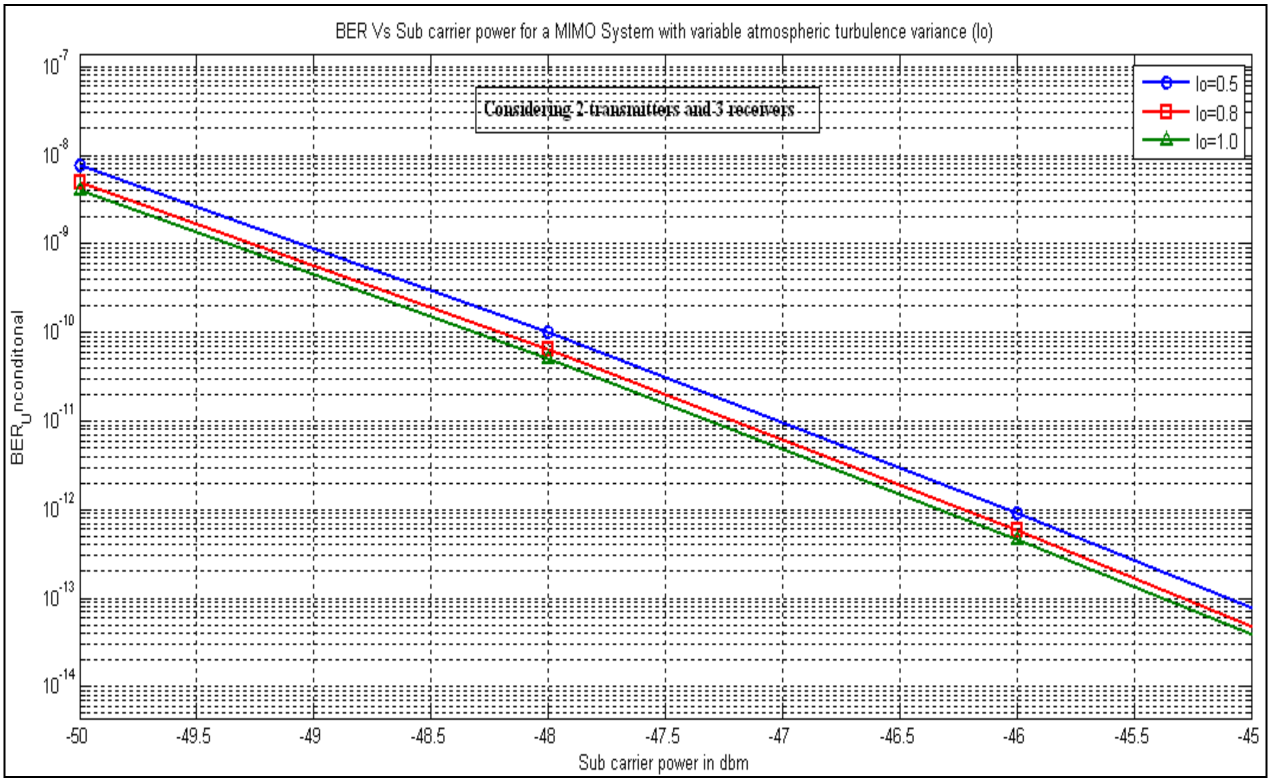

Figure 4.19: BER of a MIMO FSO link with variable Turbulence Variance (Io)

Fig. 4.19 shows the BER vs. subcarrier power with variable turbulence variance considering two transmitters and three receivers. In the above figure it is observed that with the increase of turbulence variance the BER is reduced with various signal power for a MIMO FSO link where two transmitters and three receivers are used.

Signal power in dbm	BER of a MIMO FSO link with variable Turbulence Variance (I_o)		
	I_o=0.5	I_o=0.8	I_o=1.0
-50	7.844x10^{-9}	1.939x10^{-9}	3.961x10^{-9}
-48	1.016x10^{-10}	6.398x10^{-11}	5.131x10^{-11}
-46	9.212x10^{-13}	5.8x10-^{13}	4.651x10^{-13}

Table 4.20: BER of a MISO FSO link with variable Turbulence Variance (Io) with various power.

4.7.2 Observation of BER of a FSO Link with Variable Transmitters and Variable Receivers at a Bit Rate of 1 Gbps

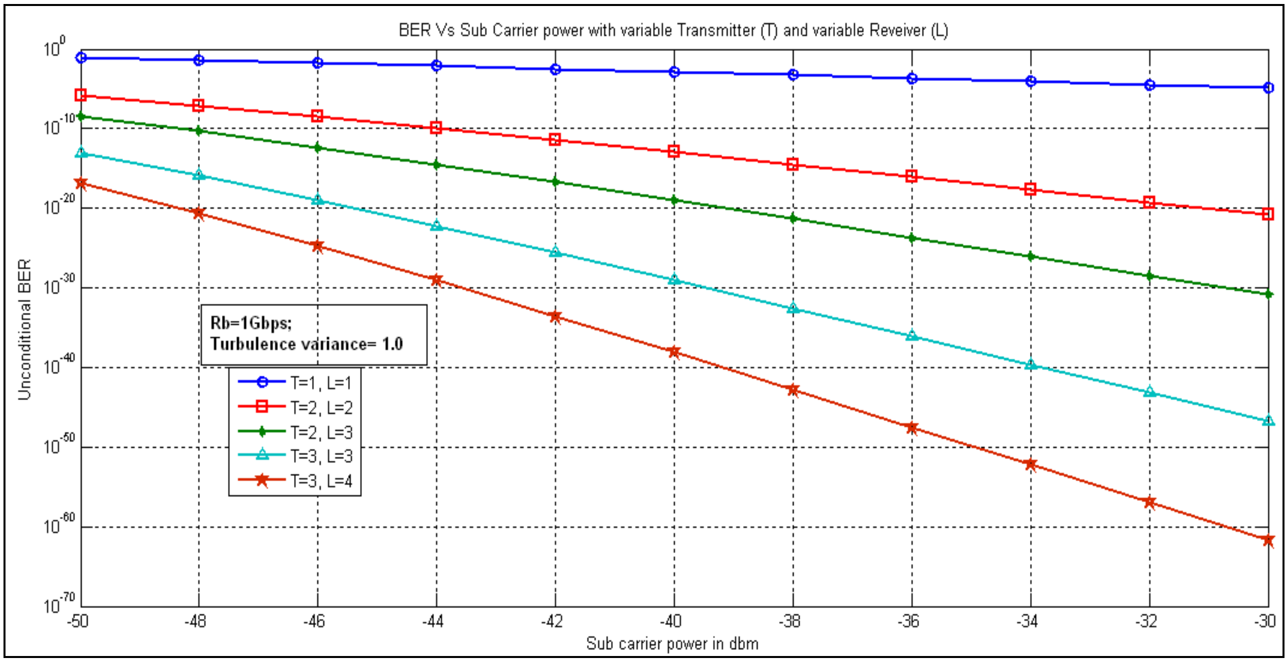

Figure 4.20: BER of a FSO link with variable Transmitters and variable Receivers at a bit rate of 1 Gbps

Fig. 4.20 shows BER vs. subcarrier power with variable transmitters and variable receivers at a bit rate of 1 Gbps considering turbulence variance 1.0. In the above figure it is clearly seen that the BER is reduced with the increase of the number of transmitters and receivers for a bit rate of 1 Gbps. In the table below, it is found that the amount of BER is significantly reduced with the increase of the transmitters and receivers at a particular power level.

Signal power in dbm	BER of a FSO link with variable Transmitters(T) and variable Receivers(L) at a bit rate of 1 Gbps			
	T=2,L=2	***T=2,L=3***	***T=3,L=3***	***T=3,L=4***
-50	1.414×10^{-6}	3.961×10^{-9}	7.925×10^{-14}	1.36×10^{-17}
-40	1.168×10^{-13}	9.399×10^{-20}	9.162×10^{-30}	7.658×10^{-39}
-30	1.505×10^{-21}	1.381x10-31	1.632×10^{-47}	1.65×10^{-62}

Table 4.21: BER of a FSO link with variable Transmitters and variable Receivers at a bit rate of 1 Gbps

4.7.3 Observation of BER of a FSO Link with Variable Transmitters and Variable Receivers at a Bit Rate of 2.5 Gbps

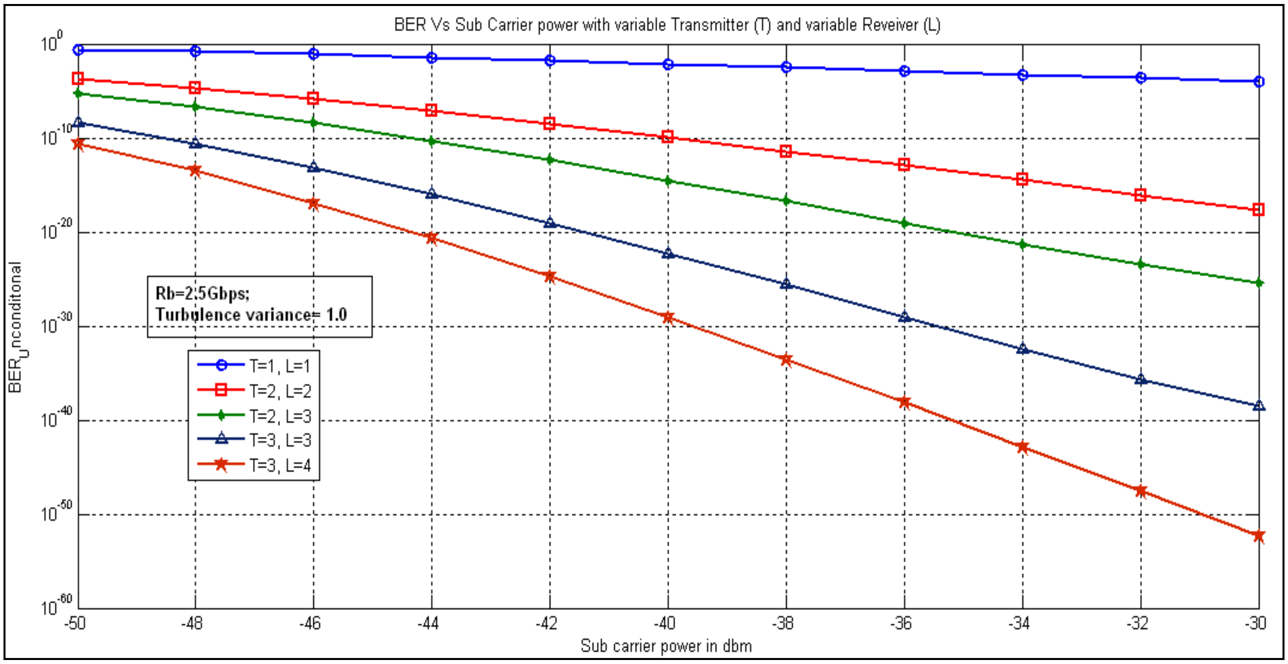

Figure 4.21: BER of a FSO link with variable Transmitters and variable Receivers at a bit rate of 2.5 Gbps

Fig. 4.21 shows BER vs. subcarrier power with variable transmitters and variable receivers at a bit rate of 2.5 Gbps considering turbulence variance 1.0. In the above figure it is clearly seen that the BER is reduced with the increase of the number of transmitters and receivers for a bit rate of 2.5 Gbps. In the following table, it is found that the amount of BER is significantly reduced with the increase of the transmitters and receivers at a particular power level.

Signal power in dbm	BER of a FSO link with variable Transmitters(T) and variable Receivers(L) at a bit rate of 2.5 Gbps			
	T=2,L=2	*T=2,L=3*	*T=3,L=3*	*T=3,L=4*
-50	0.0001777	5.58×10^{-6}	4.191×10^{-9}	2.699×10^{-11}
-40	1.193×10^{-10}	3.077×10^{-15}	5.426×10^{-23}	8.149×10^{-30}
-30	2.287×10^{-18}	4.323×10^{-26}	2.858×10^{-39}	5.116×10^{-53}

Table 4.22: BER of a FSO link with variable Transmitters and variable Receivers at a bit rate of 2.5 Gbps

4.7.4 Observation of BER of a FSO Link With Variable Transmitters and Variable Receivers at a Bit Rate of 10 Gbps

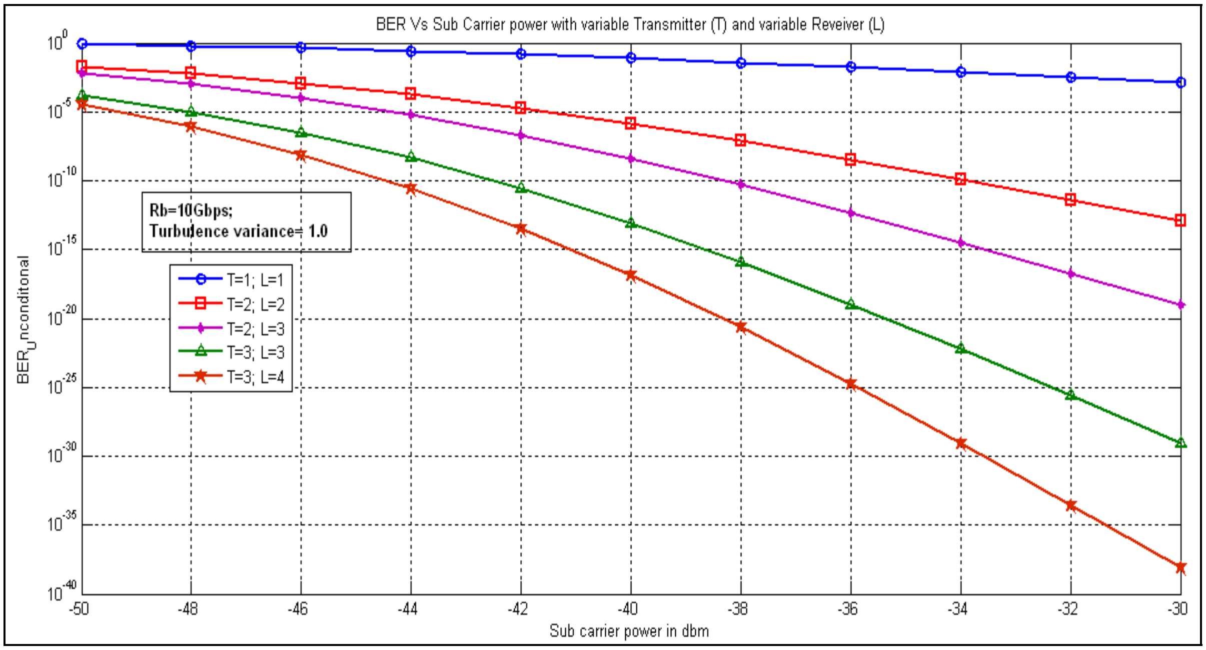

Figure 4.22: BER of a FSO link with variable Transmitters and variable Receivers at a bit rate of 10 Gbps

Fig. 4.22 shows BER vs. subcarrier power with variable transmitters and variable receivers at a bit rate of 10 Gbps considering turbulence variance 1.0. In the above figure it is clearly seen that the BER is reduced with the increase of the number of transmitters and receivers for a bit rate of 10 Gbps. In the following table, it is found that the amount of BER is significantly reduced with the increase of the transmitters and receivers at a particular power level.

Signal power in dbm	BER of a FSO link with variable Transmitters(T) and variable Receivers(L) at a bit rate of 10 Gbps			
	T=2,L=2	***T=2,L=3***	***T=3,L=3***	***T=3,L=4***
-50	0.01909	0.00621	0.0001556	3.343×10^{-5}
-40	1.414×10^{-6}	3.961×10^{-9}	7.925×10^{-14}	1.36×10^{-17}
-30	1.168×10^{-13}	9.399×10^{-20}	9.162×10^{-30}	7.658×10^{-39}

Table 4.23: BER of a FSO link with variable Transmitters and variable Receivers at a bit rate of 10 Gbps

4.7.5 Observation of Required Subcarrier Power in dbm vs Multiplication of the No. of Transmitters (T) and Receivers (L) for a MIMO System for Different Bit Rate with a Particular BER of 10^{-10}

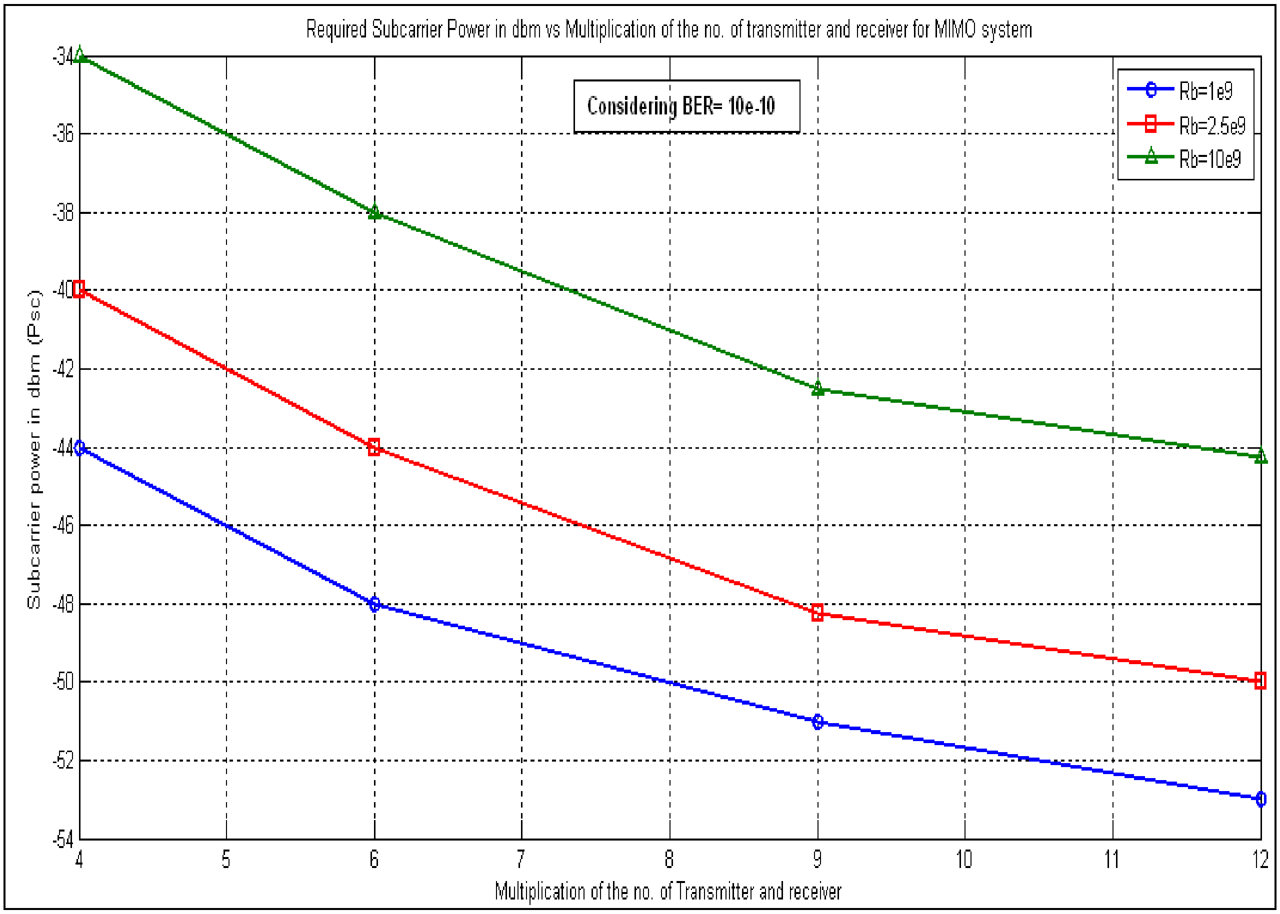

Figure 4.23: Required Subcarrier Power in dbm vs multiplication of the no. of Transmitters (T) and Receivers (L) for a MIMO system for different bit rate with a particular BER of 10^{-10}.

Fig. 4.23 shows subcarrier power vs. multiplication of the no. of Transmitters (T) and Receivers (L) for a MIMO system for different bit rate with a particular BER of 10^{-10}. In the above figure it is clearly seen that BER is increased with the bit rate which is also seen earlier. To achieve a fixed BER and if the no. of transmitters and receivers are fixed, then it is found that to transmit the FSO signal at a lower bit rate requires less subcarrier power than to transmit higher bit rate signal which is shown in the following table-

Multiplication of the no. of Transmitters (T) and Receivers (L)			Required Subcarrier Power for different no. of transmitters and receivers in a MIMO system		
T	***L***	***TxL***	***R_b=1 Gbps***	***R_b=2.5 Gbps***	***R_b=10 Gbps***
2	2	4	-44	-40	-34
2	3	6	-48	-44	-38
3	3	9	-51	-48.25	-42.5
3	4	12	-53	-50	-44.25

Table 4.24 Required Subcarrier Power for different no. of transmitters and receivers in a MIMO system at a bit error rate (BER) of 10^{-10}.

4.8 Summary

In this chapter analytical results are presented in the graphical and tabular format considering atmospheric turbulence. Negative Exponential model has been considered to represent the strong atmospheric turbulence. From the overall analysis it is clearly found that BER performance is much better for a MIMO system.

Chapter 5

Conclusion and Future Work

Chapter-5

Conclusion and Future Work

5.1 Conclusion

Now a days, Free Space Optical (FSO) communication is very much attractive for communication. But atmospheric effects play a major role and visibility conditions determine the data rate available on the link at that instant of time for a FSO link through the atmosphere. Factors like fog, rain, smog greatly influence the link availability and are being researched thoroughly by researchers all over the world. That is why, in this thesis the performance of the FSO system is evaluated in the presence of atmospheric turbulence for a SISO configurations in terms of BER for several parameters. Then to improve the scenario of the optical link, MIMO system is employed. Moreover in the FSO communication system, increasing the length of the transmission path is also very much challenging due to the impact of strong atmospheric turbulence. That is why, Negative Exponential Model has been chosen while considering atmospheric turbulence as this model is designed for strong turbulence.

In this thesis it is clearly found that MIMO system can significantly improve the BER performance and provide diversity gain over single input single output (SISO) system. Here analysis has been carried out for a multiplexed subcarrier QPSK modulated optical intensity modulated free space link over a turbulence atmospheric channel. The received optical signal is detected by a direct detection receiver and coherent sub carrier demodulator. The expression and graphical representation of the BER is shown for different MIMO configurations in this thesis. It is also observed that MIMO technology not only improve the transmitted signal quality, but also it can save signal power in comparison with the single input single output (SISO) system. However MIMO technology requires more cost for the extra arrangements in the transmission and receiving end.

The following table will give a very clear idea for a particular subcarrier power of -30dbm how the MIMO technology is improving the FSO signal through atmospheric turbulence which is a significant outcome of this thesis work-

Performance analysis of a FSO link for different transmitting and receiving diversity in terms of BER considering subcarrier power of -30dbm				
Atmospheric condition	**Applied technology**	**No. of transmitter**	**No. of receiver**	**Bit Error Rate (BER)**
Without turbulence	SISO	1	1	**1.55×10^{-3}**
With turbulence	SISO	1	1	**3.9×10^{-3}**
With turbulence	MISO	2	1	**2.03×10^{-11}**
With turbulence	MISO	3	1	**2.92×10^{-14}**
With turbulence	SIMO	1	2	**1.22×10^{-10}**
With turbulence	SIMO	1	3	**1.166×10^{-15}**
With turbulence	MIMO	2	2	**1.5×10^{-21}**
With turbulence	MIMO	2	3	**1.381×10^{-31}**
With turbulence	MIMO	3	3	**1.632×10^{-47}**
With turbulence	MIMO	3	4	**1.65×10^{-62}**

5.1: Performance analysis of a FSO link for different transmitting and receiving diversity in terms of BER considering subcarrier power of -30dbm

So, after doing this thesis work it is undoubtedly found that MIMO technology is improving the signal quality significantly at the receiver end.

5.2 Scope of Future Research Work

- In the free space optical communication, the length of communication channel is very much limited due to atmospheric turbulence in different atmospheric conditions. Still lots of research works should be carried out to increase the length of FSO channel.
- Here the effect of cloud is not considered. So, this work also can be extended considering the effect of cloud.
- This thesis work also can be studied by using Wavelength Division Multiplexing (WDM), LDPC (Low Density Parity Check Code) or STBC (Space Time Block Coding).
- Although, turbulence is very well studied and a number of models have been developed to explain it; however, most models do not deal with the turbulence across all regimes. So, there is a scope to design the turbulence model which can describe all the regimes.

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