Sudan University of Science and Technology

College of Graduate Studies

Impact of Rain in Single and Multiple Beam Wavelength Division Multiplexing Free Space Optical Systems

تأثير الأمطار في نظم الفضاء الحر البصرية ذات التبديل بتقسيم الطول الموجي وحيد الحزمة ومتعدد الحزمة

A Research Submitted In Partial fulfillment for the Requirements of the Degree of M.Sc. degree in Electronics Engineering (Communication)

Prepared By:

Nusaiba omer hassab elrasoul

Supervisor:

Dr. Fath Elrhman IsmaelKhalifa Ahmed

November 2018

الآية

قال تعالى :

بسم الله الرحمن الرحيم

﴿يرفع الله الذين آمنوا منكم والذين أوتوا العلم درجات

والله بما تعملون خبير﴾

سورة المجادلة

الآية (١١)

DEDICATION

This thesis is dedicated to:

The sake of Allah, my Creator and my Master,

My great teacher and messenger, Mohammed

(May Allah bless and grant him)

My great parents, who never stop giving of

Themselves in countless ways,

My beloved brothers and sisters,

My dearest husband, who stood by my side

And supported me materially and morally,

My beloved kid ISRAA whom I can't force myself to stop loving,

To all my family, the symbol of love and giving,

My friends who encourage and support me,

All the people in my life who touch my heart,

I dedicate this research.

AKNOWLEDGMENT

I would especially like to thank Dr. Fath Elrhman Ismael, who has done a great job managing the project and keeping me on track,and for his steadfast support during the preparation of this work,

Also grateful to thank Eng. Haifa AbuObaidaAbu AL Hassan who did her best to help me and stand by me during preparing this work,

Last, but not least i would like to thank Teachers at Sudan University Faculty of Engineering Department of Electronics,And all teachers at Omdurman Islamic University, and especially Faculty of Electrical and Electronics Engineering, who taught us throughout our college career.

Abstract

Free Space Optics (FSO) has received much attention in recent years as a cost – effective, licence free and wide-bandwidth access technique for high data rates applications.Attenuation due to different weather conditions plays a significant role in the performance of the Free Space Optical Communication (FSO).The hybrid WDM FSO network is proposed to provide a significant improvement in the link distance, received power and BER.Single beam FSO and Multiple beam FSO system is designed, analyzed and compared to produce the best system capable of tackling the effect of atmospheric weather conditions by using OptiSystem7.0 as simulation tool to simulate the link for the data-rate of 10 Gb/s with input power 40 dBm. It was realized that four-beam FSO system can operate successfully for a link distance of 8.5k m at BER of $10^{-6}$with a received optical power of -23.7 dBm for light rain and link distance of 6 km at BER of 10^{-6} with a received optical power of -23.2 dBm for medium rain,and link distance of 3 km at BER of 10^{-8} with a received optical power of –19.9 dBm for heavy rain providing the fact that multi beam FSO is sensitive even to very low optical power.

المستخلص

حظيت اتصالات الفضاء الحر باهتمام كبير في السنوات الأخيرة باعتبارها تقنية فعالة من حيث التكلفة وعدم الحاجة للترخيص بالاضافة لعرض النطاق الترددي العريض لتطبيقات معدلات البيانات العالية. يلعب التوهين بسبب الظروف الجوية المختلفة دوراً هاماً في أداء الاتصالات الضوئية في الفضاء الحر.في هذه الأطروحةيتم اقتراح شبكة هجين منمزج الإرسال بتقسيم طول الموجة واتصالات الفضاء الحر لتوفير تحسن كبير في مسافة الوصلة والطاقة المستقبَلة و معدل خطأ البيانات،حيث يتم تصميم الحزمة الأحادية والحزمة المتعددة وتحليلها ومقارنتها لإنتاج أفضل نظام قادر على معالجة تأثير الظروف المناخية الجوية باستخدام برنامج محاكاة لمحاكاة الارتباط لمعدل بيانات ١٠ جيجابت / ثانية مع طاقة مرسلة قدرها ٤٠ ديسيبل. تبين أن نظام الحزمة المتعددة بأربعة حزم يمكن أن يعمل بنجاح من أجل مسافة وصلة قدرها ٨.٥ كم بمعدل خطأ $١٠^{-٦}$ مع قدرة ضوئية مستقبلة تبلغ -٢٣.٧ ديسيبل لكل متر للمطر الخفيف،ومسافة وصلة تبلغ ٦ كمبمعدل خطأ $١٠^{-٦}$ مع قدرة ضوئية مستقبلة تبلغ -٢٣.٢ ديسيبل لكل متر للأمطار المتوسطة ، ومسافة وصلة قدرها ٣كمبمعدل خطأ $١٠^{-٨}$ مع قدرة ضوئية مستقبلة تبلغ -١٩.٩ ديسيبل لكل مترللأمطار الغزيرة مما يؤكد حقيقة أن الحزم المتعددة حساسة حتى بالنسبة إلى القدرة الضوئية المنخفضة جداً.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

APD	Avalanche photo diode
BER	Bit error rate
CW	Continuous Wave
DEMUX	Demultiplexer
DSL	Deep space links
EUs	End users
FSO	Free space optic
HAPs	High-altitude platforms
IOL	Inter orbital links
IR	Infrared
ISL	Inter satellite links
LOS	Line of sight
MUX	Multiplexer
NRZ	None return to zero
OS	Optical Splitter
OWC	Optical wireless communication
PRBS	Pseudo Random Bit Sequence
Q-Factor	Quality factor
UAVs	Unmanned aerial vehicles
UV	Ultraviolet
WDM	Wavelength Division Multiplexing

Chapter One

Introduction

1.1 Preface

Optical wireless communication (OWC) refers to transmission in unguided propagation media through the use of optical carriers, i.e., visible, infrared (IR) and ultraviolet (UV) band. This research, focus on outdoor terrestrial OWC links which operate in near IR band, These are widely referred to as free space optical (FSO) communication. FSO systems are used for high rate communication between two fixed points over distances up to several kilometers, the FSO link has a very high optical bandwidth available, allowing much higher data rates . FSO systems use very narrow laser beams. This spatial confinement provides a high reuse factor, an inherent security, and robustness to electromagnetic interference. the frequency in use by the FSO technology is above 300 GHz which is unlicensed worldwide. Therefore, FSO systems do not require license fees. FSO systems are also easily deployable and can be reinstalled without the cost of dedicated fiber optic connections [12].

Wavelength Division Multiplexing (WDM) is a multiplexing technique in which multiple optical signals are multiplexed on a single medium using different wavelengths. It is a technique to carry more than one optical signal with dissimilar wavelengths. Although the FSO system is a well-studied topic, the appearance of the WDM technique and the high demand for broadband communications has become a new study in communication area [3].

In a Wavelength Division Multiplexing (WDM) based access, the demand for bandwidth has increased in an extremely fast and is a promising solution for data transport in future all-optical wide area networks. At the same time, the cost of transporting information bit per km also needs to be reduced [13]. WDM it is technique in which more than one signals are multiplexed together and transmitted as one signal. So, in WDM-FSO, multiple modulating signals modulate different optical carriers (channels) which are then multiplexed and sent through a single laser beam. WDM systems best utilize the channel capacity ameliorating the data transfer ability of FSO systems. These systems are flexible as channels can be added or removed at any point in the link using add/drop multiplexers [14].

The attenuation for different type of rain is 6.2, 9.2, and 19.3 dB/km for light, medium, and heavy rain, respectively. 1550nm wavelength is best for both rain and haze as there is less attenuation than any other wavelength. The priority for optimization of parameters is required to be done for the better performance of system [15].

1.2 Problem Statement

Attenuation due to different weather conditions plays a significant role in the performance of the Free Space Optical Communication (FSO). Rain is the weather condition of tropical region ,which is the major attenuation factor in environment for light ray that's why FSO link is very much affected.

1.3 Proposed Solution

The hybrid WDM FSO network is proposed to provide a significant improvement in the link distance, received power and BER. WDM has higher capacity so high data rate with longer link distance is possible.

Implementing Hybrid WDM multi-beam FSO system combines the advantages of WDM and spatial diversity to increase the system capacity and link reliability.

1.4 Aim and Objectives

The aim of the project is performance evaluation of A hybrid WDM-FSO with Multi beam system to overcome the challenge of FSO signal degradation due to atmospheric attenuation.

The objectives of the project is to:

- Make Comparison between single beam and multi beam system under different rain condition using parameters: received optical power (dBm), BER and Q-factor.
- Make a comparison for light, medium and heavy rain to determine maximum achievable link range for every rain condition.

1.5 Methodology

The hybrid WDM- FSO network is proposed to provide a significant improvement in the link distance, received power and BER. Here, the performance evaluation and applicability of single beam and multi beam FSO system, in light, medium and heavy rainy condition is further explored and investigated using WDM multiplexing by Implementing two systems: System I consist of 16 channels WDM-FSO without multi-beam and System II consist of 16 channels Hybrid WDM –FSO with multi-beam using OptiSystem7.0 as simulation tool to simulate the link for the data-rate of 10 Gb/s with input power 40 dBm.

1.6 Thesis Outlines

This thesis composed of five chapters their outlines are as follow:

Chapter One provides short Introduction; discuss Problem statement, proposed solution, and Objectives. While, Chapter Two review of free space optical communication, Degrading Factors of an FSO link, and Applications of FSO system. Chapter Three explain Wavelength Division Multiplexing, Multi beam Technique, Hybrid WDM/multi-beam FSO system, system model and explain Simulating overall system Using Opti System v7 layout and Design Parameters. Chapter Four include Results and Discussions. Finally, Chapter Five contain Conclusion and Recommendations.

Chapter Two

Literature Review

2.1 Background

Wireless Optical Communication (WOC) is considered as the next frontier for high-speed broadband connection due to its unique features: extremely high bandwidth, ease of deployment, tariff-free bandwidth allocation, low power, less mass, small size, and improved channel security. It has emerged a good commercial alternative to existing radio-frequency communication as it supports larger data rates and provides high gain due to its narrow beam divergence. It is capable of transmitting data up to 10 Gbps and voice and video communication through the atmosphere/free space [1].

WOC have two broad categories, namely, indoor and outdoor wireless optical communications. Indoor WOC is classified into four generic system configurations, i.e., directed line-of-sight (LOS), non-directed LOS, diffused, and quasi diffused. Outdoor wireless optical communication is also termed as free-space optical (FSO) communication. The FSO communication systems are also classified into terrestrial and space systems. Figure 2.1 shows the classification of WOC systems[1].

Over the last few years, massive expansion in WOC technology has been observed due to huge advances in optoelectronic components and tremendous growth in the market offering wireless optical devices. It seems to be one of the promising technologies for addressing the problem of huge bandwidth requirements and “last mile bottleneck.” There are many commercial applications of WOC technology which includes ground-to-LEO, LEO-to-GEO/LEO-to-ground, GEO to- ground, LEO/GEO-to-aircraft, deep space probes, ground stations, unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs), etc. It also finds applications in the area of remote sensing, radio astronomy, space radio communication, military, etc. When WOC technology is used over very short distances, it is termed as FSO interconnects (FSOI), and it finds applications in chip-to chip or board-to-board interconnections.

FSOI has gained popularity these days as it potentially addresses complex communication requirement in optoelectronic devices. This technology offers the potential to build interconnection networks with higher speed, lower power dissipation, and more compact packages than possible with electronic very large-scale integration (VLSI) technology.

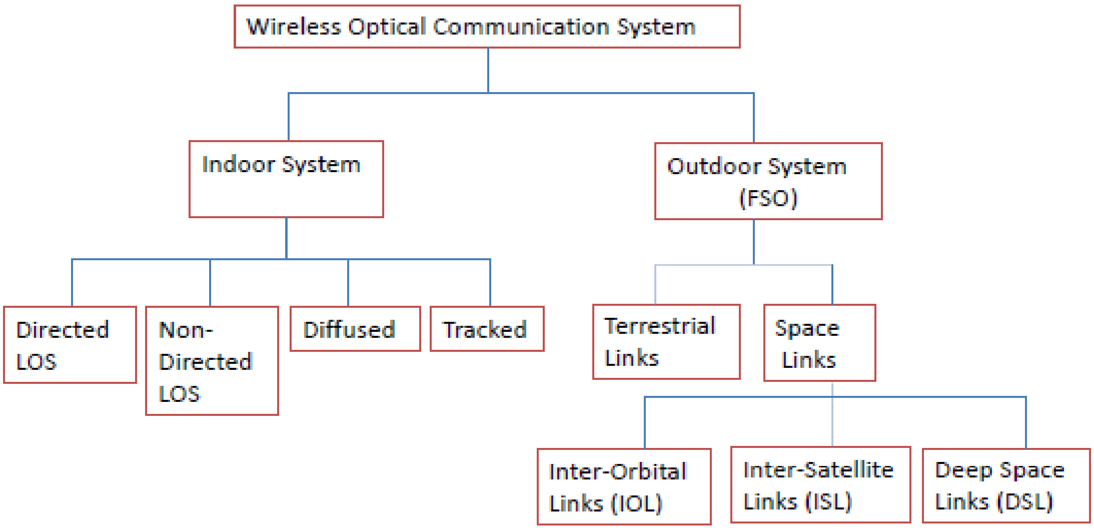


Fig. 2.1 Classification of wireless optical communication system[1]

2.1.1 Indoor Wireless Optical Communication

Indoor wireless optical communication links provide a flexible interconnection within a building where setting up a physical wired connection is cumbersome. It consists of lasers or light-emitting diodes as transmitter and photo detectors as the receiver. These devices along with their drive circuits are much cheaper as compared to radio-frequency equipment or existing copper cables. Further, indoor WOC is inherently secure technology since the optical signals do not penetrate walls unlike electromagnetic waves which can cause interference and thus provides a high degree of security against eavesdropping. These optical waves are either in the visible light spectrum or in the IR spectrum which is able to provide very large (THz) bandwidth. Since these devices consume very little power, they are also suitable for mobile terminal systems. Besides many advantages, indoor optical wireless system is influenced by various impairments that impact the performance of the communication system. Some of the factors that lead to these impairments are:

(i) Limiting speed of optoelectronic devices.

(ii) Large path loss.

(iii) Noisy indoor environment due to incandescent, fluorescent lighting or sunlight that contributes to noise in the detector.

(iv) Multipath dispersion.

(v) Interference due to artificial noise sources.

2.1.2 Outdoor/Free-Space Optical Communication

Free-space optical communication requires line-of-sight connection between transmitter and receiver for propagation of information from one point to another. Here, the information signal from the source is modulated on the optical carrier, and this modulated signal is then allowed to propagate through the atmospheric channel or free space, rather than guided optical fibers, toward the receiver. Ground-to-satellite (optical uplink) and satellite-to-ground (optical downlink) involve propagation of optical beam through the atmosphere as well as in free space. Therefore, these links are a combination of terrestrial and space links.

2.2 Degrading Factors Of An FSO Link

Although FSO appears to be the most promising technology, but it also has some limitations, These limitations include [2]:

2.2.1 Atmospheric Effects

Scintillation effect is the major atmospheric disturbance which occurs due to the temperature and pressure in homogeneities in the atmosphere. This leads to the uneven refractive index of air through which the light beam is travelling . The light beam gets deflected from its path and may not reach the receiver. Absorption of light is another kind of loss which occurs due to water molecules and other gaseous molecules present in air.

Absorption reduces the intensity of light beam. Suspended particles in air scatter the light beam and may cause Rayleigh or Mie scattering depending on the size of scattering particle. Physical obstructions like birds or poles may temporarily block the path of light signal preventing it from reaching the receiver. Combustion of various gases and other substances produces smoke which gathers in the atmosphere making it obscure for the light beam carrying information.

2.2.2 Weather Effects

Clear weather is the most suitable weather condition for successful optical communication through free space, but weathers like rain, fog, snow etc. affect the FSO communication. Different weathers have different effects on the FSO link. Rainfall causes non selective scattering of the light signal because of the fact that the radius of rain dropsis much larger than the optical wavelengths commonly used for transmission .Fog and haze act as the major deterrents to the optical signal and can completely hinder the path of light [2].

2.3 Applications Of FSO System

There are many applications of FSO systems are listed below [1]:

i. **Enterprise Connectivity:** FSO link can easily be deployed to connect various tower/building enabling local area connectivity. It can also be extended to connect metropolitan area fiber rings, connect new networks, and provide high speed network expansion.

ii. **Fiber Pack up**: In case of optical fiber link failure, FSO link can be deployed as a backup link to ensure availability of the system.

iii. **Point-to-Point Links:** It coves inter- (LEO-LEO) and intra-orbital (LEO-GEO) links and satellite-to-ground/ground-to-satellite link. This type of link requires good pointing and tracking system. Here, the output power of the transmitter, power consumption, size, mass, and deployment cost increase with the link range.

iv. **Point-To-Multipoint Links:** Multi-platform multi-static sensing, interoperable satellite communications, and shared space borne processing are unique network application of FSO system.

v. **Hybrid wireless connection/network redundancy:** FSO communication is prone to weather conditions like fog, heavy snow, etc. In order to obtain 100% availability of the network, FSO links can be combined with microwave links that operate at high frequencies (in GHz range) and offer comparable data rates.

vi. **Disaster recovery:** FSO communication system provides high-capacity scalable link in case of collapse of existing communication network.

vii. **Backhaul for cellular networks**: With the advent of 3G/4G cellular communication, there is a growing challenge to increase the backhaul capacity between the cell towers to cope up with the increase in demand of broadband mobile customers. The viable backhaul options for 4G network are to deploy fiber optic cables or to install FSO connection between towers. Deploying fiber cables is time-consuming and an expensive task. So FSO communication system plays an important role in providing backhaul capacity for cellular networks.

2.4 FSO Communication Link

Like any other communication technologies, FSO communication link comprises of three basic subsystems, viz., transmitter, channel, and receiver [1].as shown in figure below:

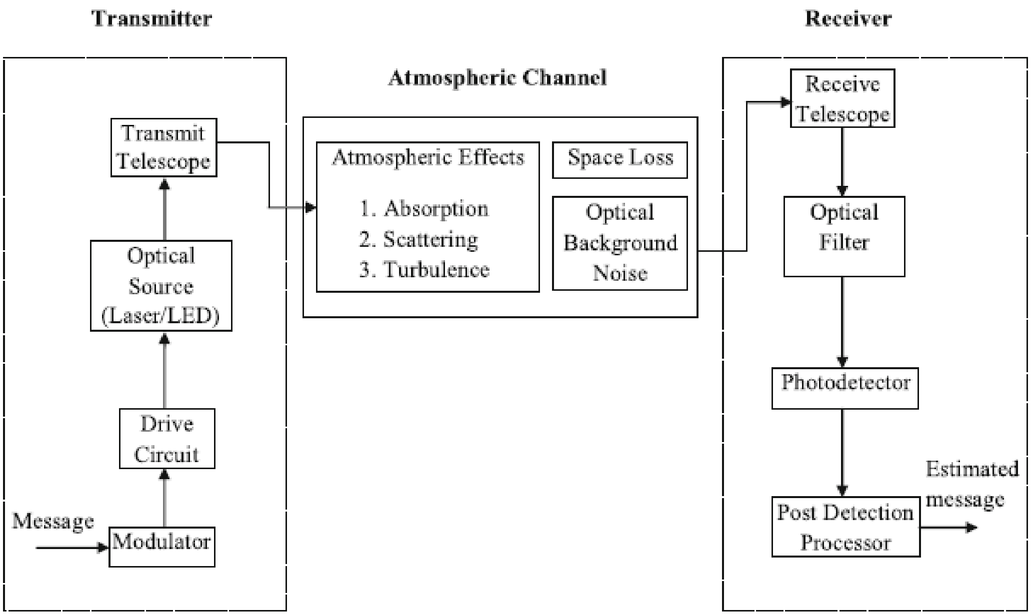


Fig. 2.2 Block diagram of FSO communication link [1].

(i) Transmitter: Its primary function is to modulate the message signal onto the optical carrier which is then propagated through the atmosphere to the receiver. The essential components of the transmitter are (a) the modulator, (b) the driver circuit for the optical source to stabilize the optical radiations against temperature fluctuations, and (c) the collimator or the telescope that collects, collimates, and directs the optical radiations toward the receiver. The most widely used modulation is the intensity modulation (IM) in which the source data is modulated on the irradiance/intensity of the optical carrier. This can be achieved by varying the driving current of the optical source directly with the message signal to be transmitted or by using an external modulator.

(ii) Channel: Since the FSO communication channel has the atmosphere as its propagating medium, it is influenced by unpredictable environmental factors like cloud, snow, fog, rain, etc. These factors do not have fixed characteristics and cause attenuation and deterioration of the received signal. The channel is one of the limiting factors in the performance of FSO system.

(iii) Receiver: Its primary function is to recover the transmitted data from the incident optical radiation. It consists of a receiver telescope, optical filter, photo detector, and demodulator. The receiver telescope collects and focuses the incoming optical radiation onto the photo detector. The optical filter reduces the level of background radiation and directs the signal on the photo detector that converts the incident optical signal into an electrical signal.

2.5 Free-Space Losses

In an FSO communication system, the largest loss is usually due to “space loss,” i.e., the loss in the signal strength while propagating through free space. The space loss factor is given by

$$Ls = [\frac{\lambda}{4\pi R}]^2 \tag{2.1}$$

where R is the link range. Due to dependence on wavelength, the free space loss incurred by an optical system is much larger (i.e., the factor Ls is much smaller) than in an RF system. Besides the space loss, there are additional propagation losses if the signal passes through a lossy medium, e.g., a planetary atmosphere. Many optical links like deep space optical links do not have additional space loss as they do not involve the atmosphere [1].

2.5.1 Beam Divergence Loss

As the optical beam propagates through the atmosphere, it spreads out due to diffraction. It may result in a situation in which the receiver aperture is not able to collect a fraction of the transmitted beam and resulting in beam divergence loss. A typical FSO system transmits optical beam which is 5–8 cm in diameter at the transmitter. This beam spreads to roughly 1–5m in diameters after propagating 1 km distance. However, FSO receiver has narrow field of view (FOV), and it is not capable of collecting all the transmitted power resulting in the loss of energy. The optical power collected by the receiver is given by:

$$P_R = P_T G_T G_R L_P \tag{2.2}$$

where P_T is the transmitted power, L_P the free-space path loss, and G_T and G_R the effective antenna gain of transmitter and receiver, respectively [1].

2.5.2 Loss Due To Weather Conditions

The performance of FSO link is subject to various environmental factors like fog, snow, rain, etc. that leads to decrease in the received signal power. Out of these environmental factors, the atmospheric attenuation is typically dominated by fog as the particle size of fog is comparable with the wavelength of interest in FSO system. It can change the characteristics of the optical signal or can completely hinder the passage of light because of absorption, scattering, and reflection. The atmospheric visibility is the useful measure for predicting atmospheric environmental conditions.

2.6 Effect of Rain

The sizable rain droplets can cause wavelength-independent

Scattering, and the attenuation produced by rainfall increases linearly with rainfall rate.

The specific attenuation for rain rate R (mm/hr) is given by

$$\beta_{rain} = 1.076R^{0.67} \qquad (2.3)$$

The rain attenuation for FSO links can be reasonably well approximated by empirical formula and is given by

$$\alpha_{rain} = \frac{2.8}{V} \qquad (2.4)$$

where V is visibility range in km and its values based on rainfall rate is

summarized in Table:

Table 2.1 Rainfall rates and their visibility ranges

Rainfall type	Rainfall rate, R (mm/hr)	Visibility range, V (km)
Heavy rain	25	1.9–2
Medium rain	12.5	2.8–40
Light rain/drizzle	0.25	18-20

2.7 Related works

In [3] WDM/ multi beam FSO network having sixteen wavelengths with standard downlink channel spacing of 0.8 nm (100 GHz) was proposed. The hybrid WDM/multi beam FSO technique improved the performance of an FSO link in terms of the received power, link distance, data rate, and scalability under heavy rain attenuation of 19 dB/km. The proposed technique provided access data to sixteen end users, each at a data rate of just 1.25 Gb/s along an FSO link distance of 1090 m.

Authors in [11] analyzed the performance of WDM-FSO communications, using NRZ modulation technique over different weather conditions. Based on this technique the received signal power, signal to noise ratio, Q. factor, and BER were analyzed. Simulation results indicate that the performance of WDM-FSO are more suited for strong attenuation Therefore, WDM –FSO system has achieved very good results, it has many problems, such as heavy attenuation coefficient. For the heavy rain condition the maximum link range about 1.2 km at BER 10-9.

In [6] Single beam and multiple beam FSO system is designed and analyzed to produce the best system capable of tackling the effect of tropical weather. The performance evaluation and applicability of multi-beam FSO system, in tropical weather was explored and investigated using WDM multiplexing. The study was carried out based on simulation, and verified using on site attenuation and rain intensity measurements.

It was realized that four-beam FSO system can operate successfully for a link distance of 1141.2 m at BER of 10e-9 with a received optical power of -34.5 dBm, proving the fact that multi beam FSO is sensitive even to very low optical power.

In [5] a hybrid Wavelength Division Multiplexing (WDM) based multi beam Free Space Optical (FSO) link was designed and simulated for different rain conditions and the performance of the system was analyzed by using parametric optimization. OptiSystem7.0 was used as simulation tool to simulate the link for the data-rate of 2.5 Gb/s with input power 7.7 dBm. Their results includes major improvement in received power, link range and quality factor. It concludes that for heavy rain maximum link distance of 2540 m and 3030 m for medium rain conditions with minimum acceptable BER of 10-9.

Chapter Three

System Model and Simulation

3.1 Introduction

Free space optics (FSO) is a promising communication technique for various types of services in the optical access network. An FSO system is a line-of-sight communication system; thus, no laying of fiber optic cables is needed, no expensive rooftop installations are required, and no security upgrades are necessary. In addition to all these advantages, upgrading of the system can be easily performed and no RF license is required. Although the FSO system has all these advantages, it suffers from degradation from atmospheric occurrences such as absorption, scattering, and nonselective scattering due to large-sized raindrops[3].

Rain is the major attenuation factor in environment for light ray that's why FSO link is very much affected. Large drops of rain scattered the optical beam and effect is known as scattering. Other parameters that degrade the FSO transmitted power are its physical characteristic such as the installation, location, and increase in the link distance between the transceivers.Single beam FSO system in tropical rainy weather is vulnerable to atmospheric rain attenuation, limited received power, limited distance, and limited scalability. To overcome all these noted drawbacks a hybrid WDM/multi-beam FSO network is proposed and evaluated [5].

3.2 Wavelength Division Multiplexing

Wavelength division multiplexing (WDM) is a technique which multiplexes multiple optical carriers onto a single optical fiber or a single beam transmitted through free space. These carriers are called channels and differ in their wavelength. Figure 3.1 shows the WDM technology, .It uses a multiplexer at the transmitter to club the input signals and a demultiplexer at the receiver to demultiplex the individual signals from the received signal. An add-drop mux can be used anywhere in the channel to add new signal to the multiplexed signal or remove some signals from it. [4]

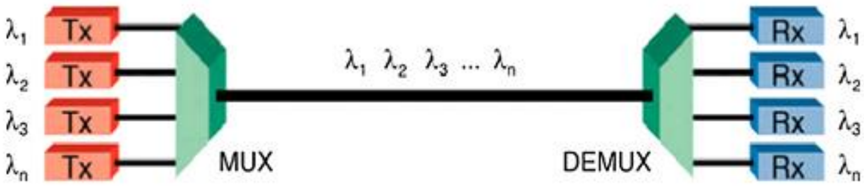


Fig. 3.1 WDM Technology [4]

the appearance of the WDM technique and the high demand for

broadband communications has become a new study in communication area This technique is proposed to overcome the limited received power, limited distance, and limited scalability, which are experienced by ordinary single-beam FSO systems. Implementing the WDM technique and multi-beam concept in an FSO system results in two beneficial outcomes which are; an increase in the number of end users (EUs) capable of accessing high data rate at low price, and decrease in heavy rain attenuation resulted from tropical weather[3].

3.3 FSO-WDM System

The main aim of every communication system is to increase the transmission distance and speed. In the field of FSO communication, the wavelength division multiplexing (WDM) is one of the efficient techniques used to provide high-capacity long distance transmission. The block diagram of WDM-FSO system is shown in Figure 3.2.

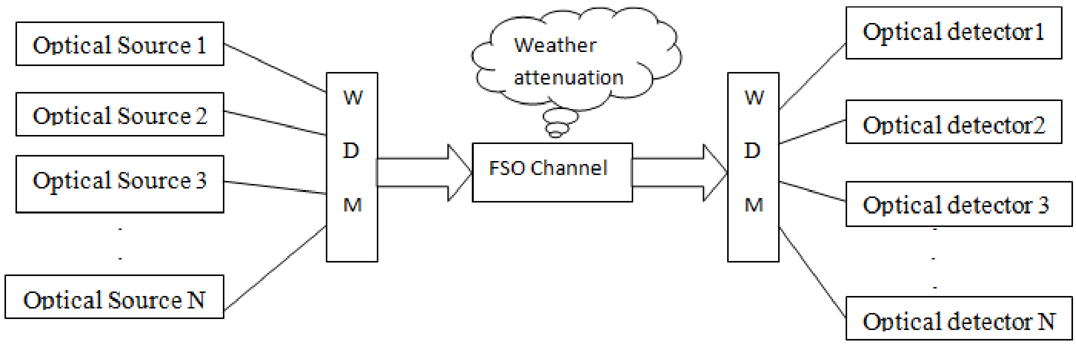


Figure 3.2: FSO-WDM System [7]

It is a technique in which multiple signals are transmitted over single channel. WDM technique becomes most popular due to the fact that capacity of system can be increased by increasing the number of channels and tapering the channel spacing without using more than one FSO link. So WDM approach can be applied in FSO systems to maximize bandwidth usage in cheaper way. WDM system is designed to solve the problem of FSO signal degradation due to atmospheric disorder. WDM system has high capacity so that it has ability to achieve high data rate and longer link distance due to more laser power [7].

3.4 Multi Beam Technique

Multi beam technique as the name suggests is a technique in which multiple beams carrying the same information traverse the channel and reach the receiver. These beams are transmitted by spatially diverse transmitters and follow independent paths in the channel. Each beam undergoes different attenuation and thus the received power of each beam is different. The beam which has maximum received power at the receiver is selected and processed for data extraction. The spacing between the beams is generally of the order of centi metres. This technique is also called spatial diversity because of spatially diverse transmitters which transmit the beams. [4]

One of the most important advantages of a multi-beam or also known as multiple-aperture FSO system shown in Figure 3.3 is that, the unavailability or temporary blockage of the beam by obstructions is significantly minimized, because the probability that all beams would be blocked is rare. In addition, from an operational viewpoint, using multiple apertures with multiple lasers on the transmission side can provide redundancy of the transmission path in the event that a particular laser source should fail. From an atmospheric perspective a multiple-aperture can be very beneficial in the reduction of attenuation created by heavy rain. Minimizing the effect of heavy rain is important when FSO systems are installed over longer distances and in tropical regions known for its heavy rainfall. [6]

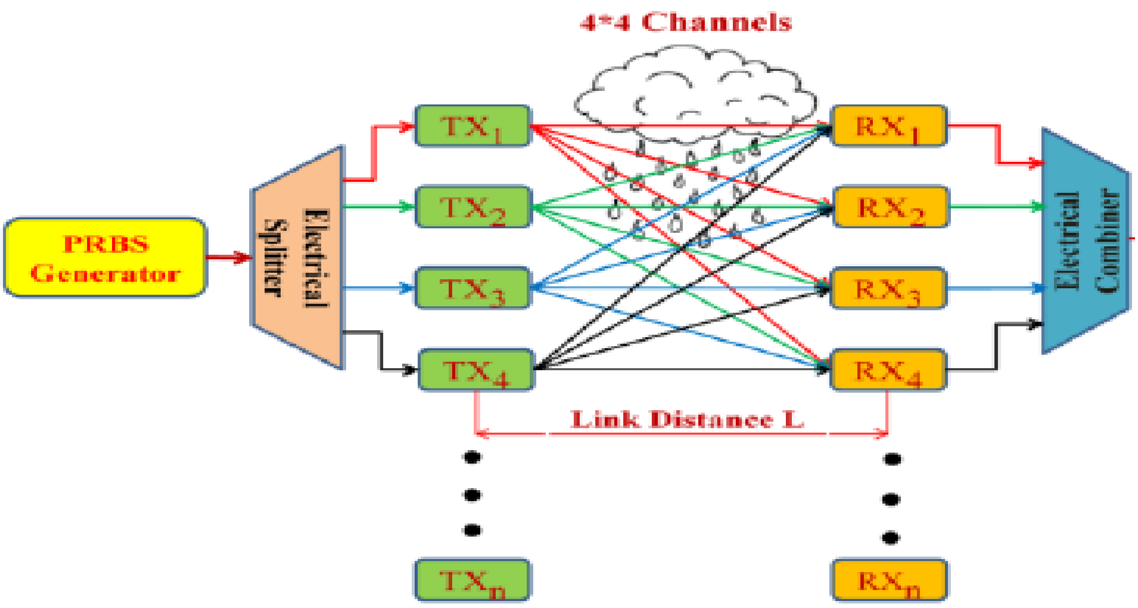


Fig. 3.3: Block diagram of a multi-beam FSO system [6]

3.5 Hybrid WDM/Multi-Beam FSO System

WDM system used in combination with FSO are called WDM FSO and can be classified into two types: single beam and multi beam systems. Single beam system uses one pair of transmitter and receiver. Only one beam carrying the information travels through the channel. In case of FSO systems, if the light beam is obstructed by an object, which prevents it from reaching the receiver, the signal is lost and communication stops. The multi beam WDM uses more than one beams of the multiplexed signal. Each beam travels a different path, and thus its attenuation is different. This technique uses spatially diverse transmitters and so it is also called Spatial Diversity Technique. At the receiver, the beam that has undergone least attenuation is selected and processed for data extraction. This technique serves as a solution for various FSO limitations like physical obstructions, scintillation effect, weather effects, etc. Multi beam system improves the link achievability and reduces the probability of link failure to a large extent. When WDM FSO system uses multiple beams for transmission, they are called "Hybrid multi beam WDM FSO systems". Figure 3.4 shows a hybrid multi beam WDM FSO, which combines the advantages of WDM and spatial diversity to increase the system capacity and link reliability.[9]

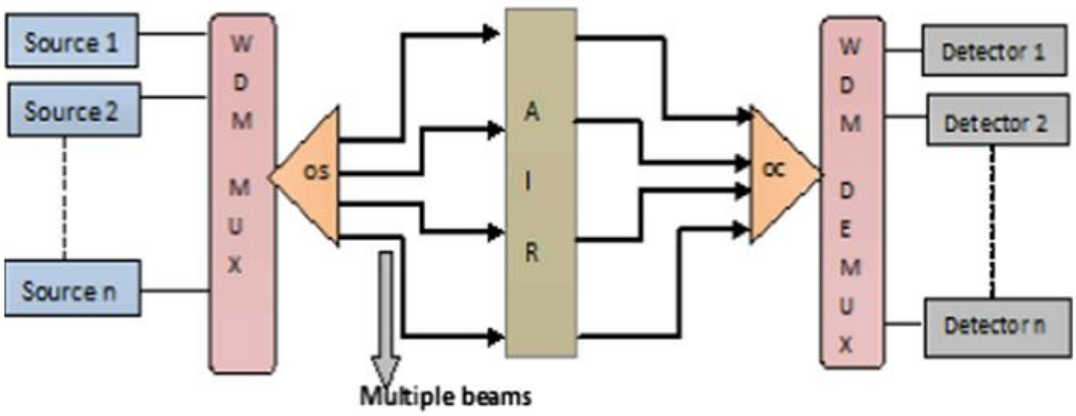


Fig. 3.4 Hybrid Multi beam WDM-FSO System [9]

3.6 Weather Effects

Clear weather is the most suitable weather condition for successful optical communication through free space, but weathers like rain, fog, snow etc. affect the FSO communication. Different weathers have different effects on the FSO link. Rainfall causes non selective scattering of the light signal because of the fact that the radius of rain drops is much larger than the optical wavelengths commonly used for transmission [2].

Figure 3.5 shows a compact view of degrading elements of an FSO link.

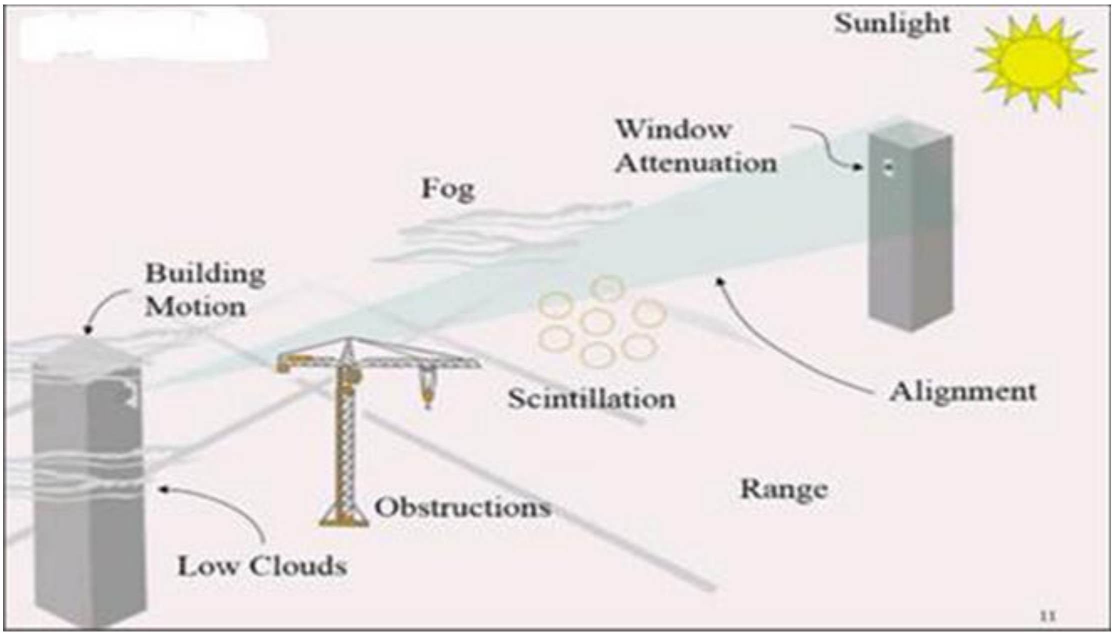


Fig. 3.5 A compact view of degrading elements of an FSO link [2].

3.7 Geometrical Loss

In FSO communication system, the geometrical losses directly affect the optical power and laser beam which spread the light from one point to another point of the link [10]. Geometrical effect can be calculated by received power:

$$P_{Received} = P_{Transmitted} \frac{dR2}{(dT+\theta R)2} 10^{\frac{-\tau ATMR}{10}} \qquad (3.1)$$

Where d_R = received aperture diameter (m), d_T transmitter aperture diameter (m), θ = beam divergence (mard), R = link range (km) and τ_{ATM}= atmospheric attenuation (dB/km).

3.7.1 Rain Attenuation

The highest attenuation factor in the environment is rain attenuation for light so it also effects FSO, The rain can reduce the visibility of FSO system. Due to Rain intensity factor, the FSO System and laser power are effected. The attenuation due to rain is:

$$\tau_{rain} = 1.076R^{0.67} \text{ (dB/km)} \qquad (3.2)$$

Where R represents the rainfall rate, The increase in rainfall rate and rain drop size causes a linear increase in attenuation. The scattering due to rain is non-selective as attenuation coefficient has no dependence on laser wavelength [10].

3.8 System Model

The fundamental elements of FSO communication system are Transmitter, transmission channel, and receiver. To analysis the performance of single versus multi beam WDM FSO system the simulator software namely Optisystem version 7 is used.

A WDM system is designed to overcome the challenge of FSO signal degradation due to atmospheric attenuation which is shown in Figure 3.6.

The FSO transmitte consist of PRBS (Pseudo Random Bit Sequence) Generator which generates random binary sequence for the system to transmit. Then NRZ pulse generator is used to convert the binary sequence to the electrical signal. The CW (Continuous Wave) laser is used to transmit the input signal with wavelength 1550nm. Then, Mach-Zehnder Modulator does intensity modulation of laser output, which is optical signal for given power, according to the NRZ pulse generator output .In the receiver part, to detect the optical signal we use APD photodiode, which generates electrical signal according to incident optical beam. Then low pass Bessel Filter is used to filter the noise from signal, followed by 3R regenerator to Retiming, Reshaping and Regenerating the original signal. BER Analyzer is used to measure the Q-factor and minimum BER.

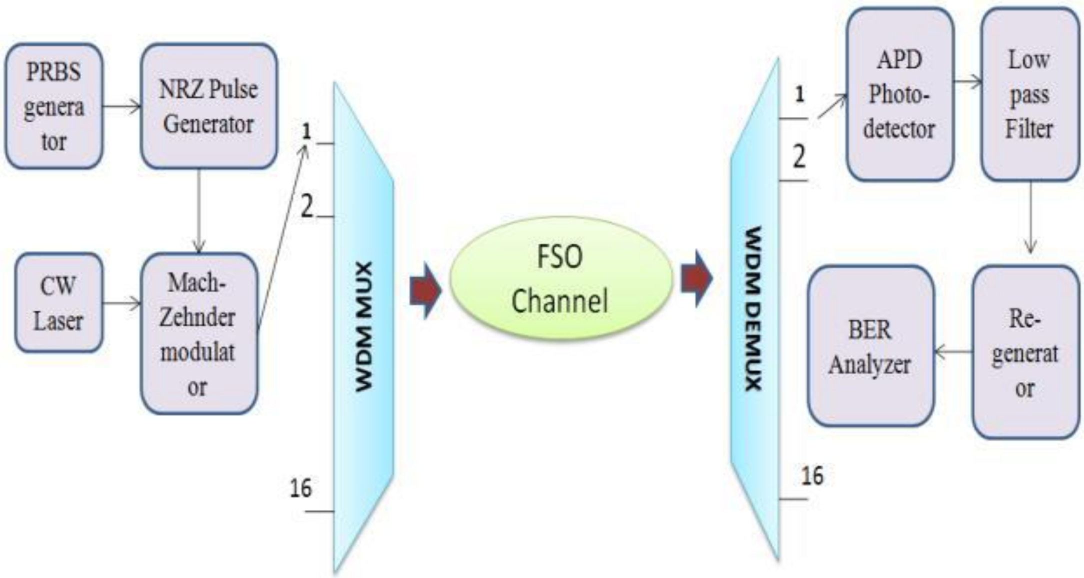


Fig. 3.6: Block diagram of WDM-FSO system [5]

3.9 Design Parameters:

The specification of the simulation design is shown in Table 3.1. Signals are optically multiplexed using WDM MUX into one downlink signal carrying 16 wavelengths (1550, 1549.2, 1548.4 ....1539.6, 1538.8, and 1538) nm. with channel spacing of 100GHz (0.8nm) following the ITU-T G standard.

The multiplexed signal is transmitted into one beam (single beam system) and they were spitted into four beams (B1, B2, B3 and B4) in multi beam system using an Optical Splitter (OS).

The continuous wave laser used operates at 1550 nm, data rate used is 10 Gbps, transmitter and receiver apertures are kept to be 15 cm and the beam divergence for the optical beam is taken to be 2 mrad.

Table 3.1 Specification of the simulation design:

parameter	value
Data Rate	10Gb/s
Wavelength	1550nm
Power	40 dBm
Gain	35dB
Number of input ports	16
Bandwidth	10 GHZ
Channel Spacing	0.8 nm
Range	500 to 130000 m
Transmitter Aperture diameter	15cm
Receiver Aperture diameter	15cm
Gain	3

3.10 Simulation Explanation

Simulations have been done in OPTISYSTEM v 7.

3.10.1 System I: Single Beam System

The laser power used for the analysis of system I under clear weather is 10 dBm as shown in figure 3.7. Attenuation on a clear sky day is taken to be 0.233 dB/km and transmitter and receiver apertures are kept to be 15 cm as shown in figure 3.8, then Fig. 3.9 show the Layout of System-I (16 channels WDM-FSO system without multi-beam).

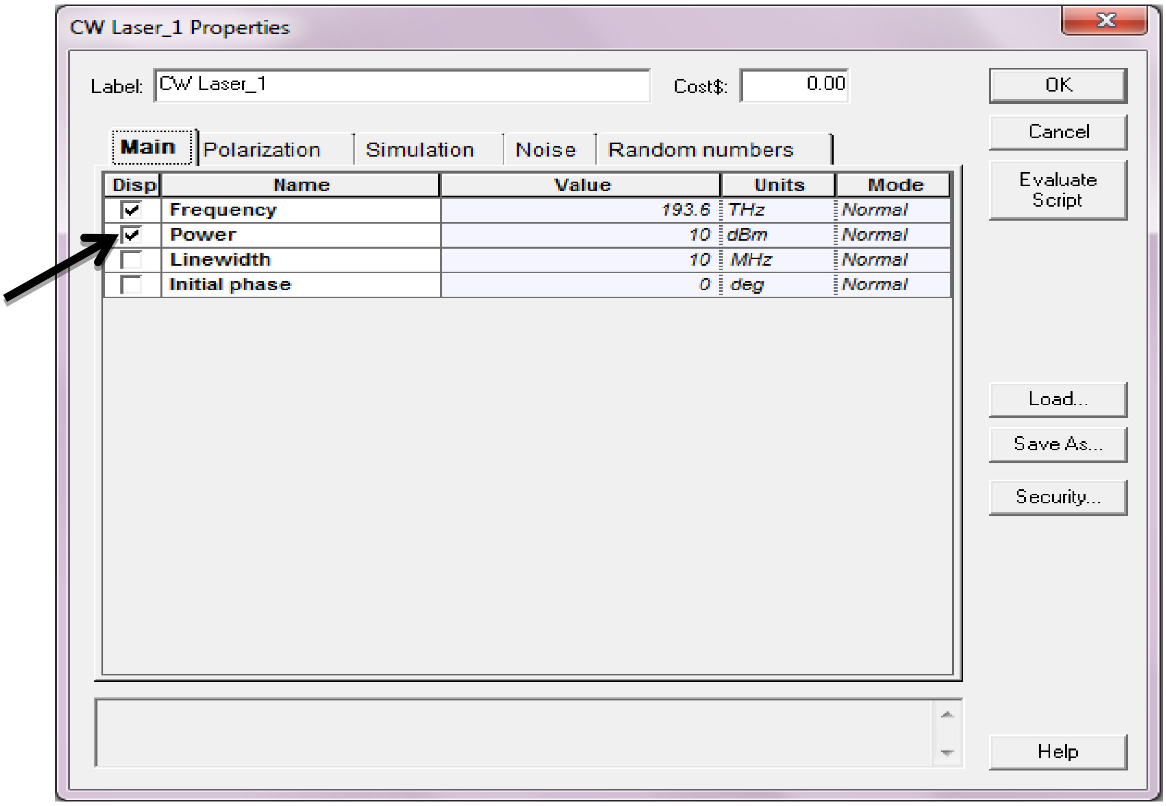


Figure 3.7: CW laser Properties

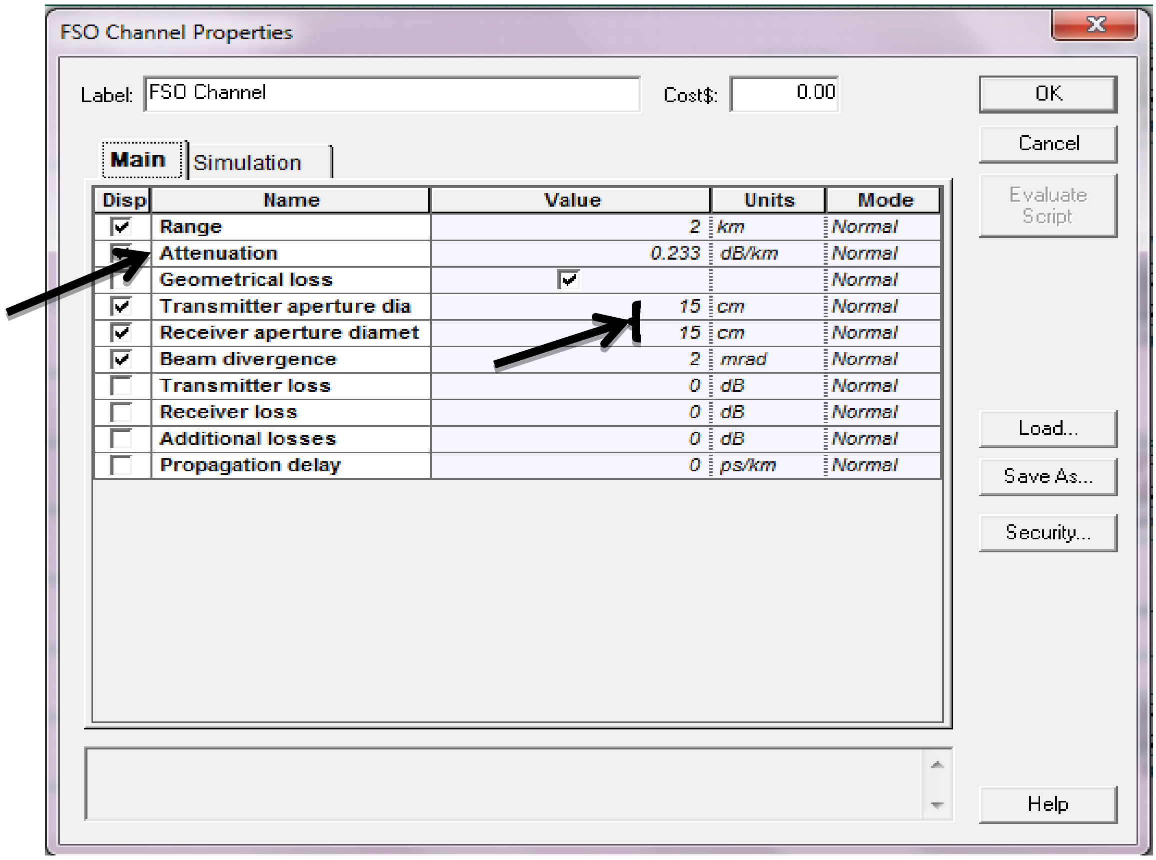


Figure 3.8 FSO channel properties

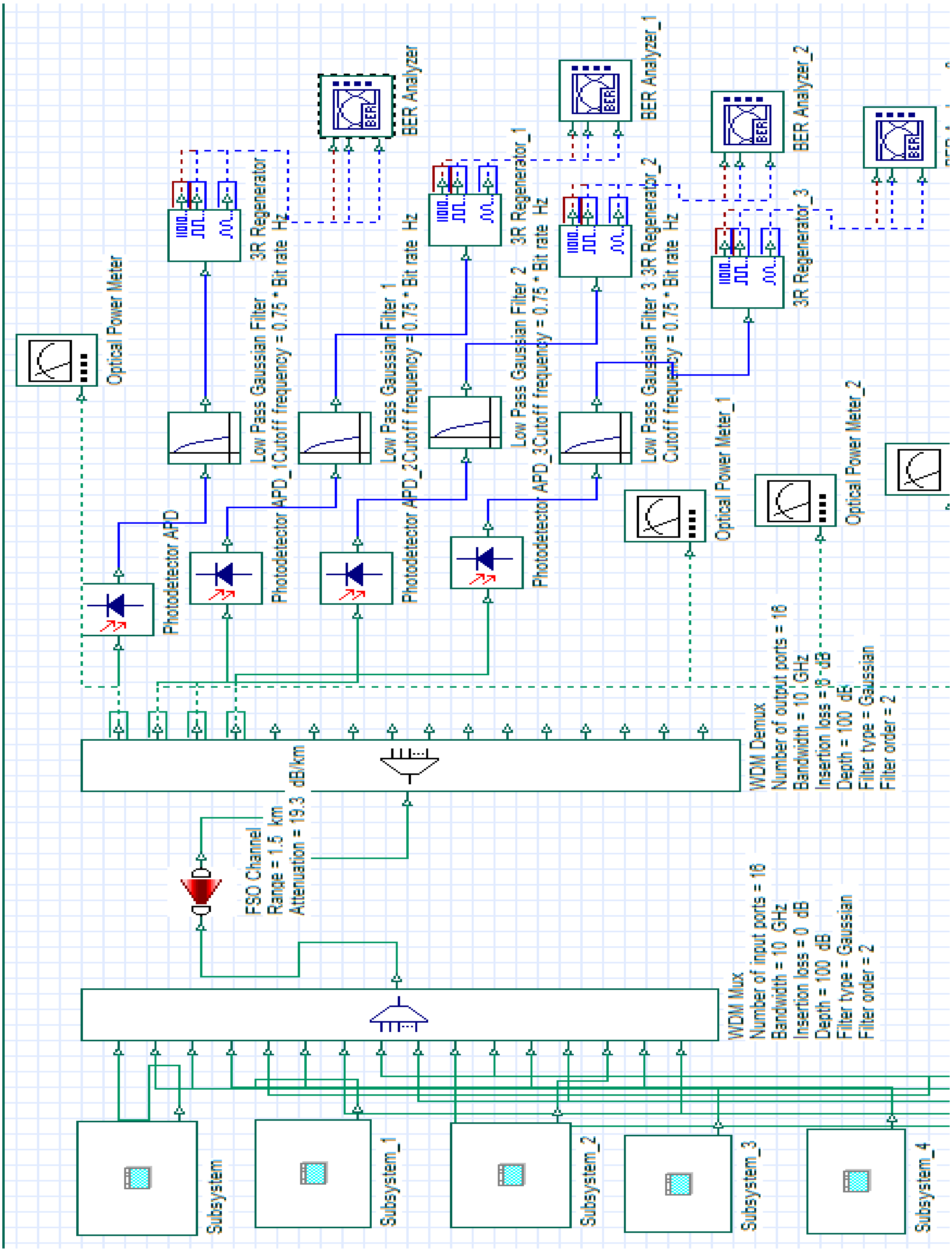


Fig. 3.9 Layout of System-I (16 channels WDM-FSO system without multi-beam).

3.10.2 System II: Multi Beam System:

The hybrid WDM-multi-beam FSO network is proposed to provide a significant improvement in the link distance, received power and BER. It comprises of sixteen transmitters, one unit of 16_1 WDM multiplexer, one optical splitter and sixteen spatially diverse lenses. There are sixteen laser diodes (LDs) which produce optical carrier signals at different wavelengths (λ1, λ2, λ3,…,λ16) with a transmitted power of 40 dBm. These downlink wavelengths are selected in the 1550 nm band with channel spacing (Δλ) of 0.8 nm (100 GHz) following the ITU-T G.694.1 standard from 1538 nm to 1550 nm, as shown below in Figure 3.10 and figure 3.11 shows system II designed in Optisystem.

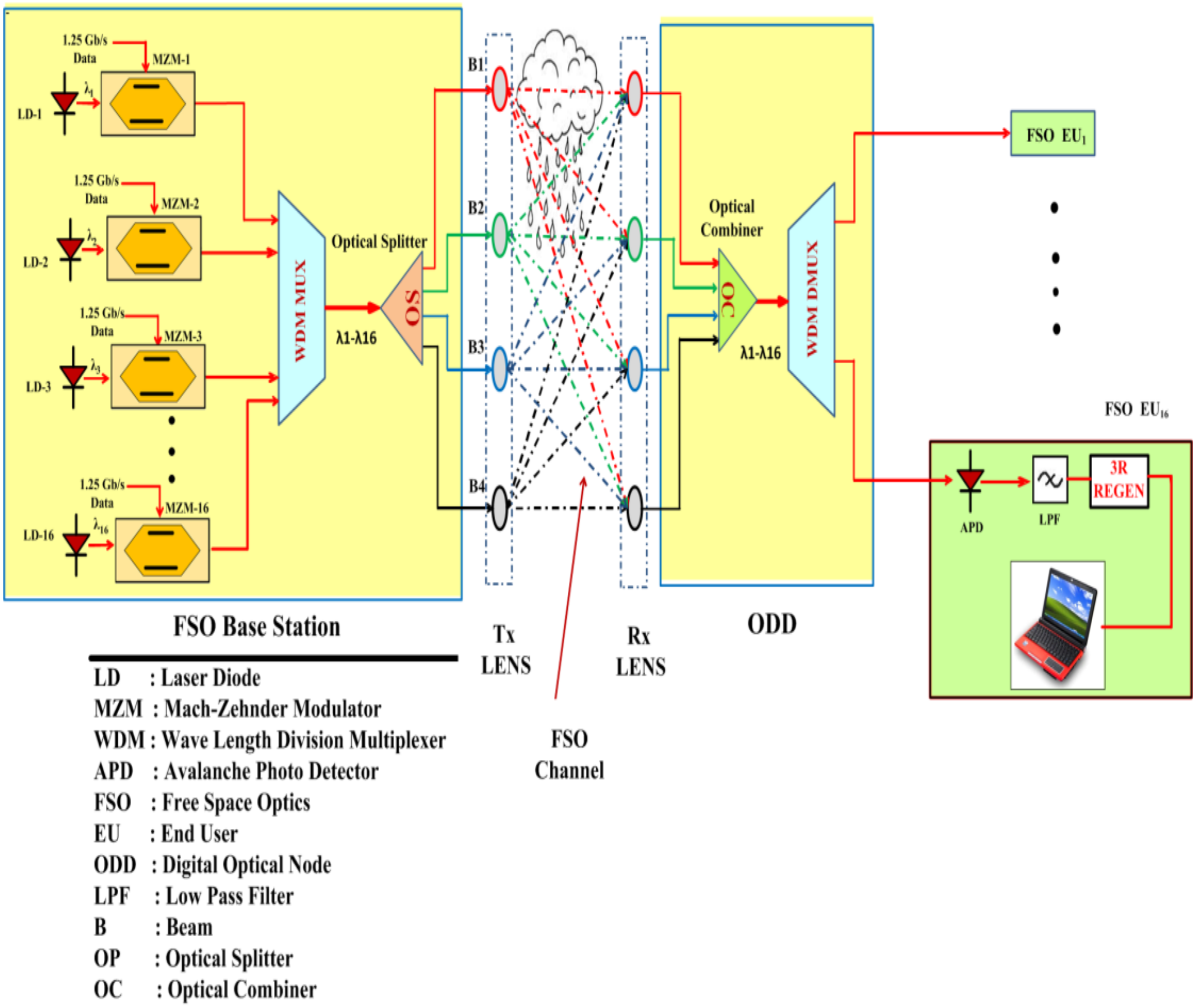


Fig. 3.10 Block diagram of Hybrid WDM/multi-beam FSO system [1]

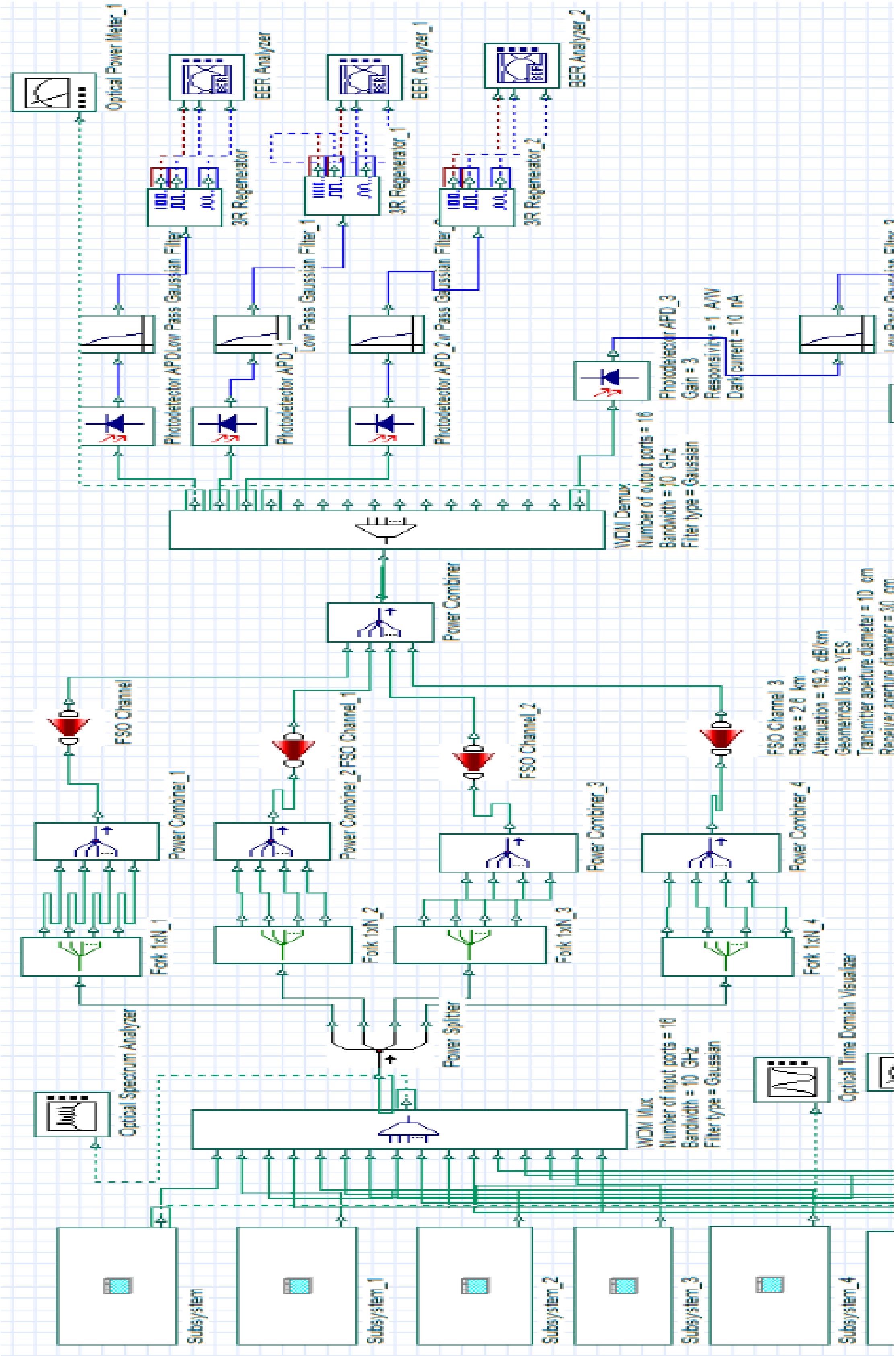


Fig. 3.11 Layout of System-II (16 channels WDM-FSO system with multi-beam)

Chapter Four

Result and Discussion

4.1 Introduction

In the present work, two WDM-FSO systems have been analyzed under weather effects. One of the systems is the single beam system which is the pre-existing system and the second system is the multi beam system. The single beam system consist of 16 channels WDM-FSO without multi-beam will be referred to as 'System I' and the multi beam system consist of 16 channels Hybrid WDM –FSO with multi-beam. as 'System II .

4.2 Descriptive Analysis

Comparative analysis has been done using parameters: received optical power (dBm) bit error rate and Q-factor .Also, a comparison is shown for light rain, medium rain and heavy rain. Using this maximum achievable link range is determined for light rain medium rain and heavy rain condition. Simulation have been done using OPTISYSTEM v 7.

The geometrical losses are considered in this simulation. It is noticed that during light rain condition, acceptable transmission for System I is observed till 4 km and the range decreases as the attenuation level increases. The attenuation rises as the rainfall rate increases. An optimum Q factor is obtained and eye opening is analyzed.

The proposed system, System II is analyzed using multi beam at both sides, i.e. after multiplexer and before de multiplexer. It is observed that the link range increases in multi beam System.

4.3 Results and Discussion

Single beam system and multi beam system have been analyzed under clear weather and different rain conditions.

4.3.1 Comparative Analysis of Single Beam System and Multi Beam System under Clear Weather:

The laser power used for the analysis of single beam system and multi beam system under clear weather is 10 dBm and attenuation on a clear sky day is taken to be 0.233 dB/km. Simulation results show that the achievable link distance for system I is 2 km and 130 km for system II. If the link range is increased beyond this values, the quality factor value falls below the value acceptable for successful communication. BER analyzer gives the values of Q factor and BER as shown in table 4.1.

Table 4.1 Comparison of system 1 and system II under clear weather

	Laser power used = 10 dBm Attenuation =0.233 dB/ km		
	Max range	Min BER	Q factor
System 1	2 km	1.72883e-007	4.10318
System 2	130 km	1.456e-007	5.071

It can be clearly seen from the graph in Fig. 4.1, that the Q factor decreases below the acceptable value around 2 km of link distance in single beam system (system 1), but for multi beam system (system II) it remains above the acceptable value, till 130 km. Hence, the successful transmission distance for multi beam system is much greater than that of single beam system.

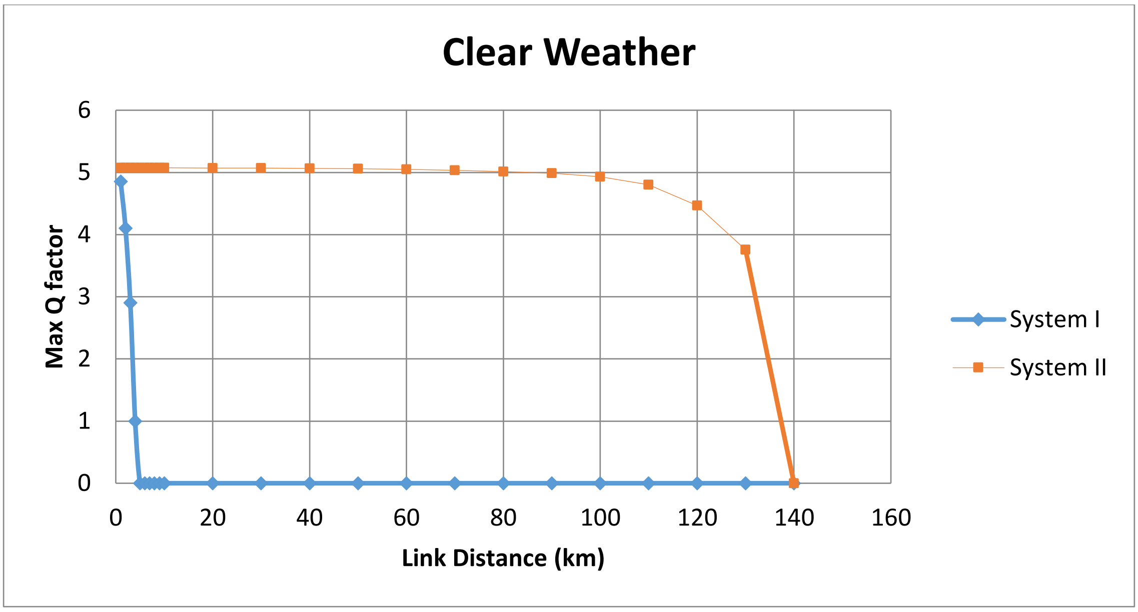


Fig. 4.1 Max Q-factor v/s Link Range

Also the received optical power in multi beam system is more than that of single beam system as shown in Figure 4.2. And the eye diagrams in Fig. 4.3 (A) and (B) clearly shows the remarkable difference in eye opening of the two systems.

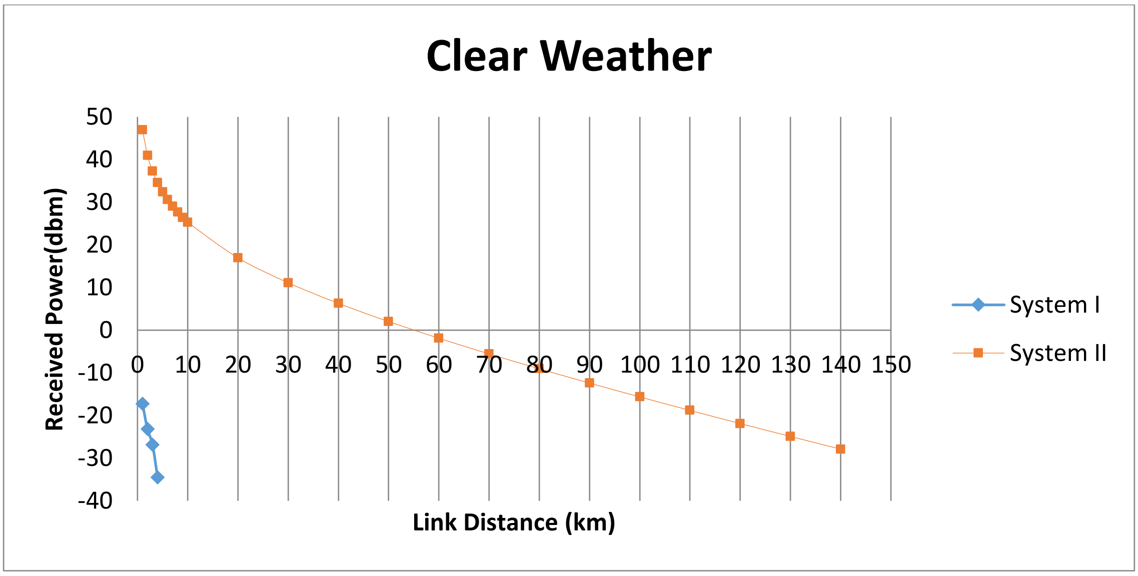
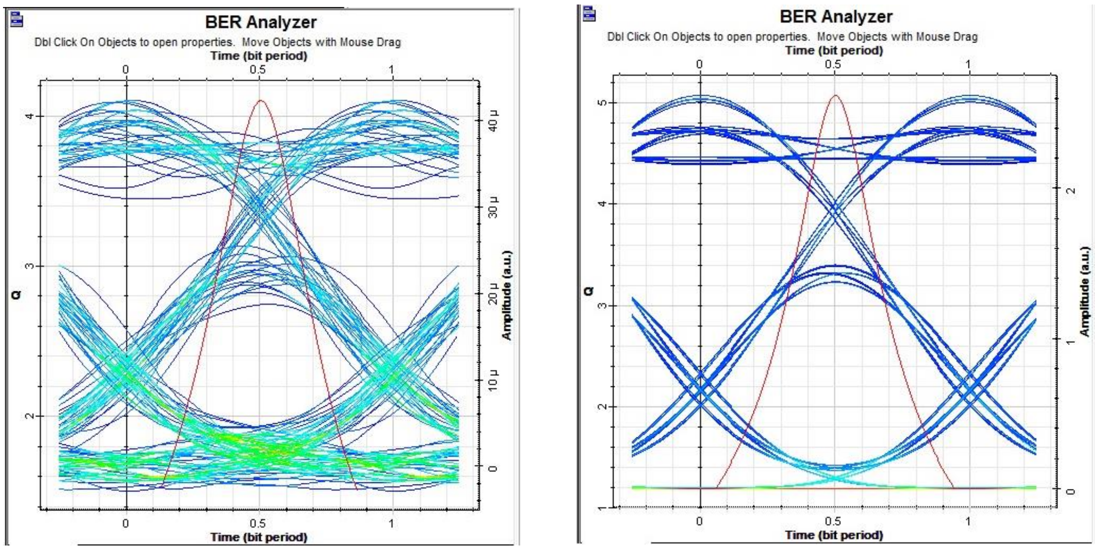


Fig. 4.2 Received power v/s Link Range



(A) (B)

Fig.4.3 Eye diagrams comparing system I (a) and system II (b) under clear weather conditions.

4.3.2 Comparative Analysis of Single Beam System and Multi Beam System Under different rain conditions

Both the systems have been compared in terms of achievable link distance using same system parameters. The analysis has been done up to the acceptable values of Quality factor (Q) and minimum BER for successful communication.

Comparative Analysis of single beam system and multi beam system has been done under different rain condition: light, medium and heavy rain. The single beam system will be referred to as ‘System I’ and the multi beam system as ‘System II’.

4.3.2.1 Light Rain

To see the effect of light rain on FSO link, single beam system and multi beam System was analyzed. The laser power used in this case was 40 dBm. Attenuation due to light rain is taken to be 6.2 dB/ km.

The values of maximum range show that in Light rain condition; signal can be transmitted to a larger distance using system 2 as compared to system 1, as shown in table 4.2.

Table 4.2 Comparison of system 1 and system II under light rain:

	Laser power used = 40 dBm Attenuation =6.2 dB/ km		
	Max rang	Min BER	Q factor
System 1	4 km	0.000196	3.5
System 2	8.5 km	1.781e-5	4.1

Figure 4.4 denote that for system I, there is a steep fall in the value of Q factor value after 3.5 km and signal quality is acceptable only up to 4 km. But for system II, Q factor remains almost constant till 7.5 km and decreases after that. The Q factor for system I becomes ‘0’ at 4.5 km whereas for system II it is not ‘0’ even at 8.5 km. So, it can be inferred that system II performs much better than system I.

Also the received optical power in system II is more than that of System I as shown in Figure 4.5. And The eye diagrams in Fig.4.6 (a) and (b) obtained using the BER analyzer clearly depict that in Light rain weather the quality of reception of system 2 is much higher than that of system 1.

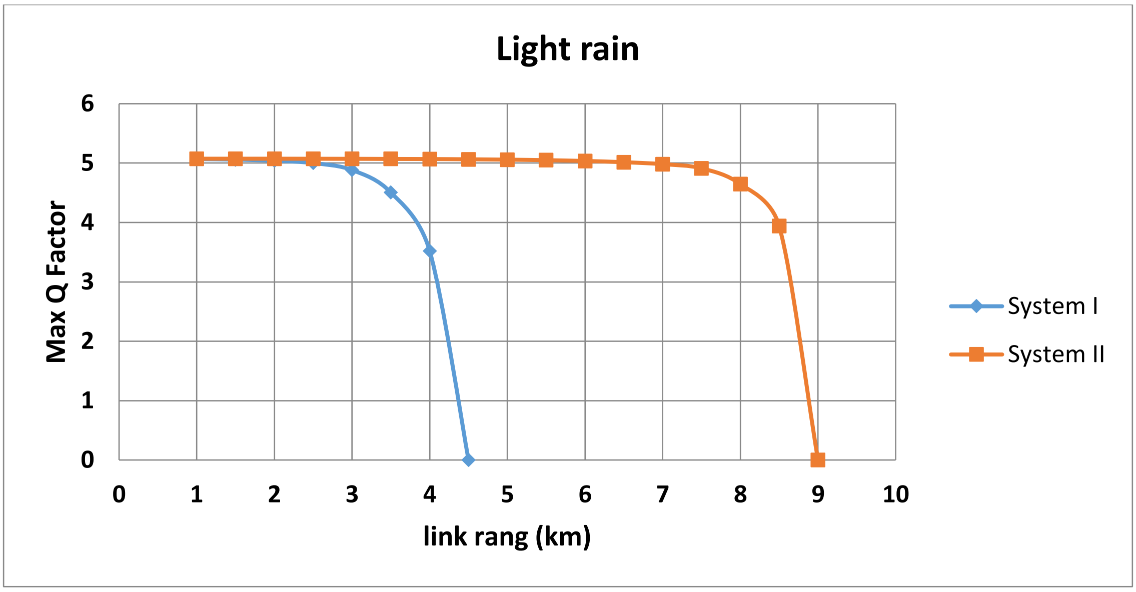


Fig. 4.4 Comparison of system I and II under light rain in terms of Max Q factor v/s link distance graph.

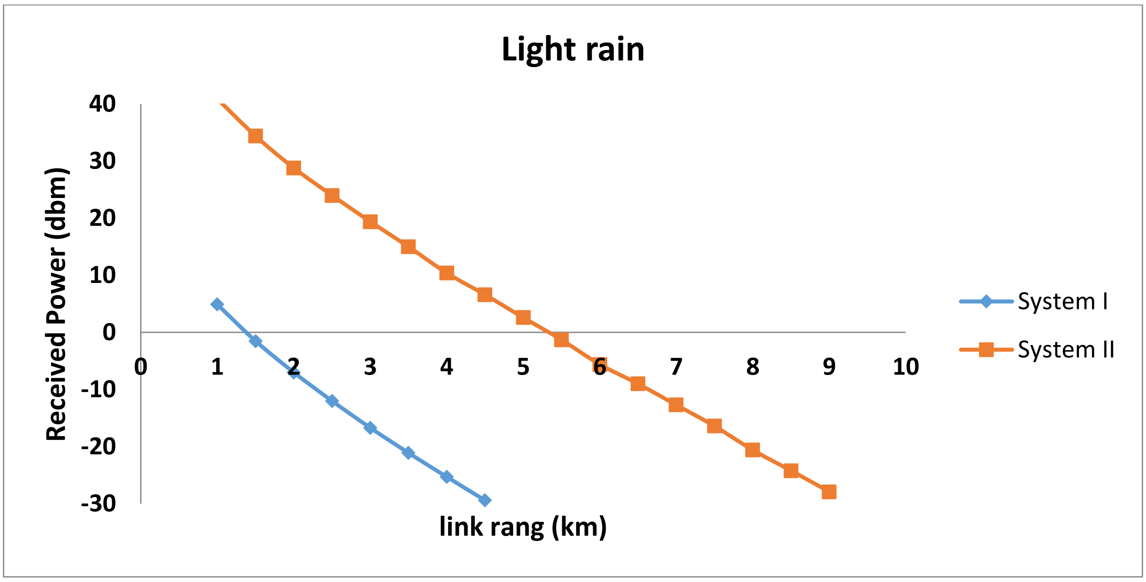
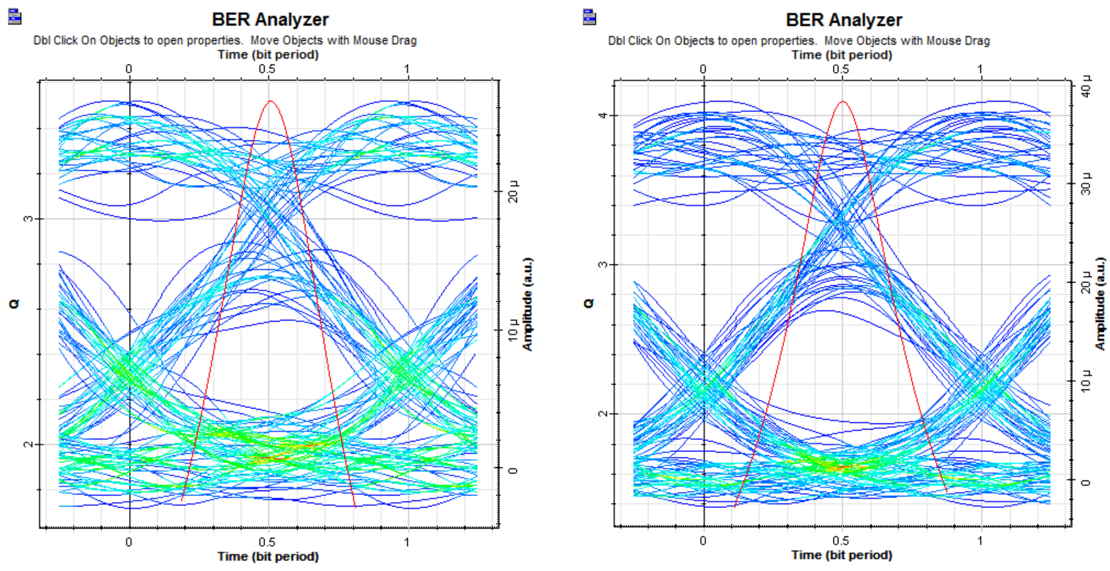


Fig. 4.5: Received power v/s Link Range.



(A) (B)

Fig.4.6 Eye diagrams comparing system I (a) and system II (b) under light rain condition.

4.3.2.2 Medium Rain

In case of medium rain weather both systems have been compared in terms of Max Q factor value, Max link distance and Min BER as shown in table 4.3.

Table 4.3 Comparison of system 1 and system II under medium rain:

	Laser power used = 40 dBm Attenuation =9.2 dB/ km		
	Max rang	Min BER	Q factor
System 1	3 km	0.0004355	3.3
System 2	6 km	1.042e-5	4.2

Graphs shown in Fig. 4.7 analogize the two systems in terms of Q factor variation with link distance. It can be inferred that system 2 can work for very larger distance compared to system 1 and the Q factor at any distance for system 2 is more than that of system 1 at the corresponding distance.

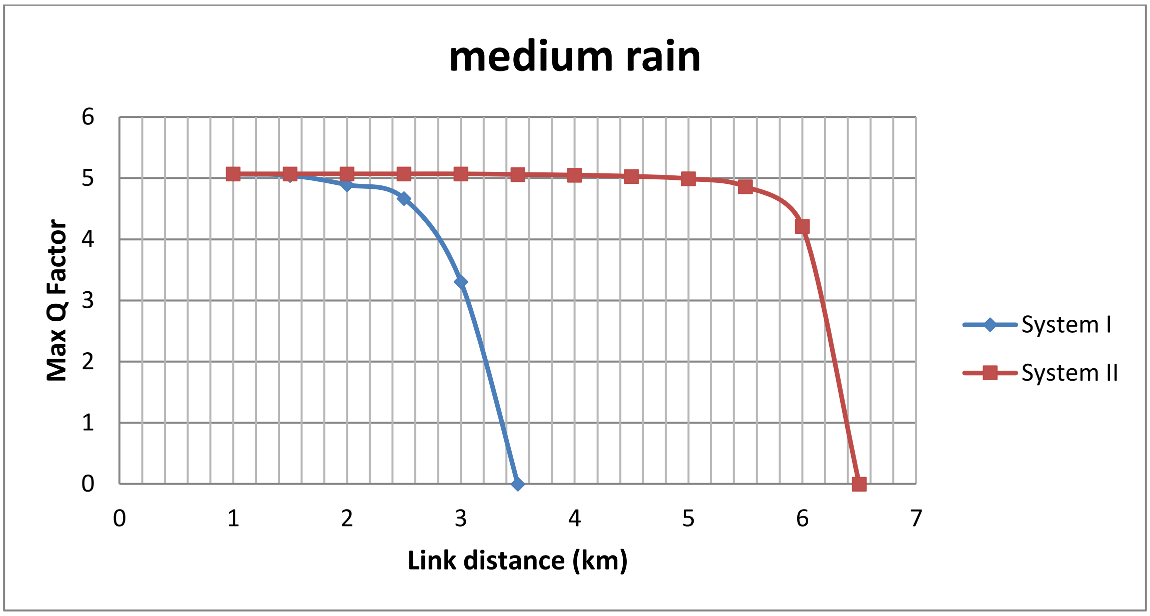


Fig. 4.7 Comparison of system I and II under medium rain in terms of Max Q factor v/s link distance graph.

Fig. 4.8 analogize the two systems in terms of received power variation with link distance.

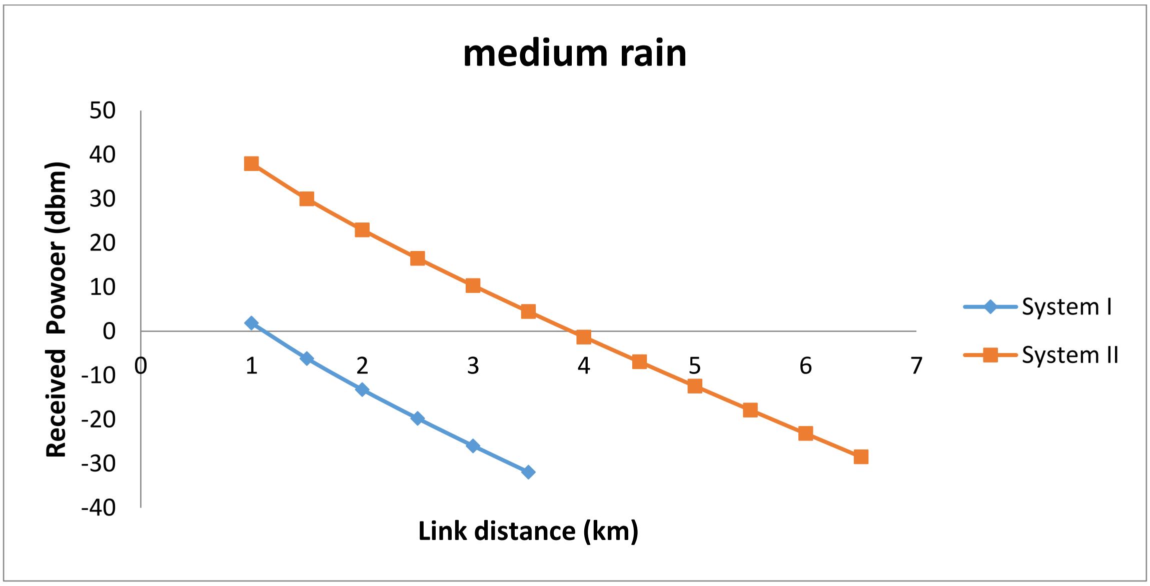


Fig. 4.8: Received power v/s Link Range.

The eye diagrams for the two systems are depicted in Fig. 4.9 (a) and (b), It is clearly seen that the eye opening for system 2 is better than eye opening of system 1, which mean the received signal by system 2 is better than that received by system1.

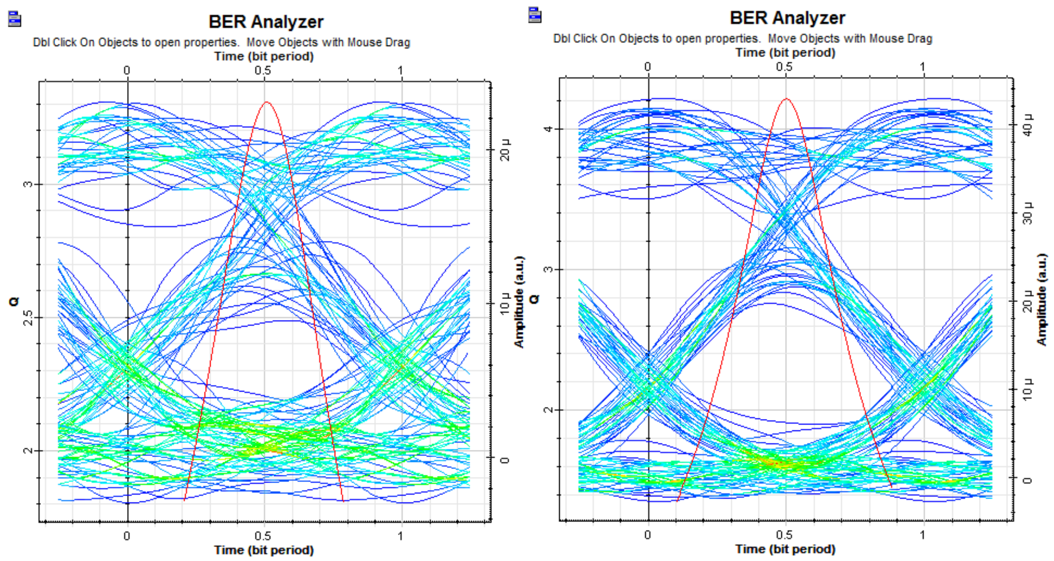


Fig.4.9 Eye diagrams comparing system I (a) and system II (b) under medium rain condition.

4.3.2.3 Heavy Rain:

In case of heavy rain condition, with 19.3 dB/km attenuation, and 40 dBm laser power, both systems have been compared in term of Max Q factor value, Max link distance and Min BER as shown in table 4.4. The maximum link in system 2 is 3 km with 4.7 Q factor and 9.3e-7 BER, which limits to 1.5 km with 4.5 Q factor and 2.8e-6 BER in the case of system1.

Table 4.4 Comparison of system 1 and system II under heavy rain:

	Laser power used = 40 dBm Attenuation =19.3 dB/ km		
	Max rang	Min BER	Q factor
System 1	1.5 km	2.8e-6	4.5
System 2	3 km	9.3e-7	4.7

The Figure 4.10 present systems performance in terms of Q factor variation with respect to link distance and illustrates the difference in quality of received signal at various link lengths. Graph shows that system 1 works till around 1.5 km whereas for system 2, signal quality is acceptable up to 3 km.

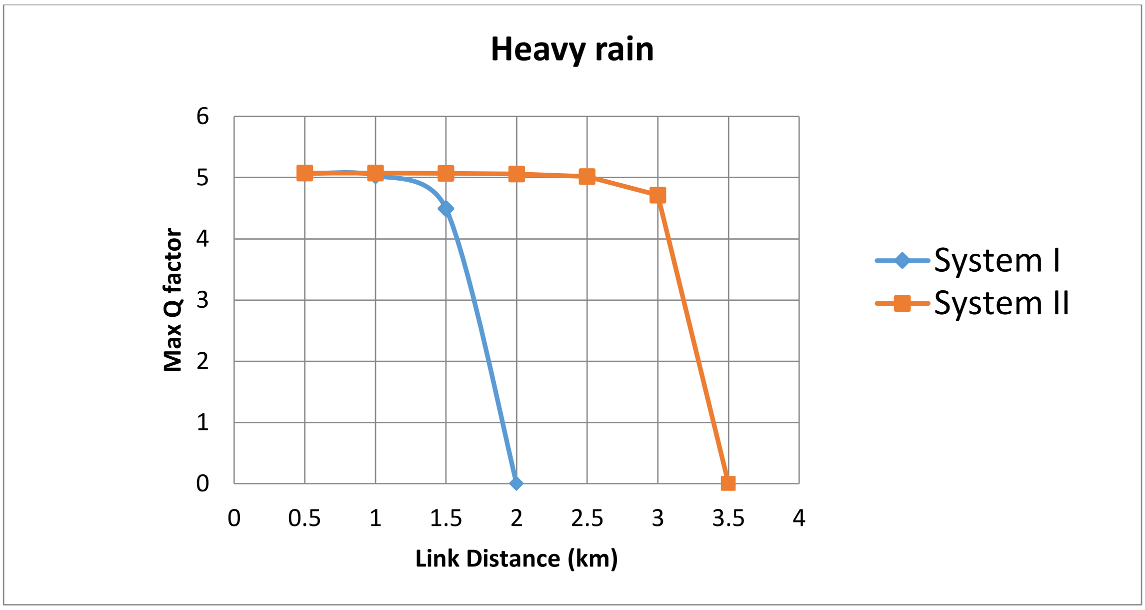


Fig. 4.10 Comparison of system I and II under heavy rain in terms of Max Q factor v/s link distance.

The figure 4.11 shows that the received optical power of system 2 is always greater than that of system 1 when plotted against the link distance.

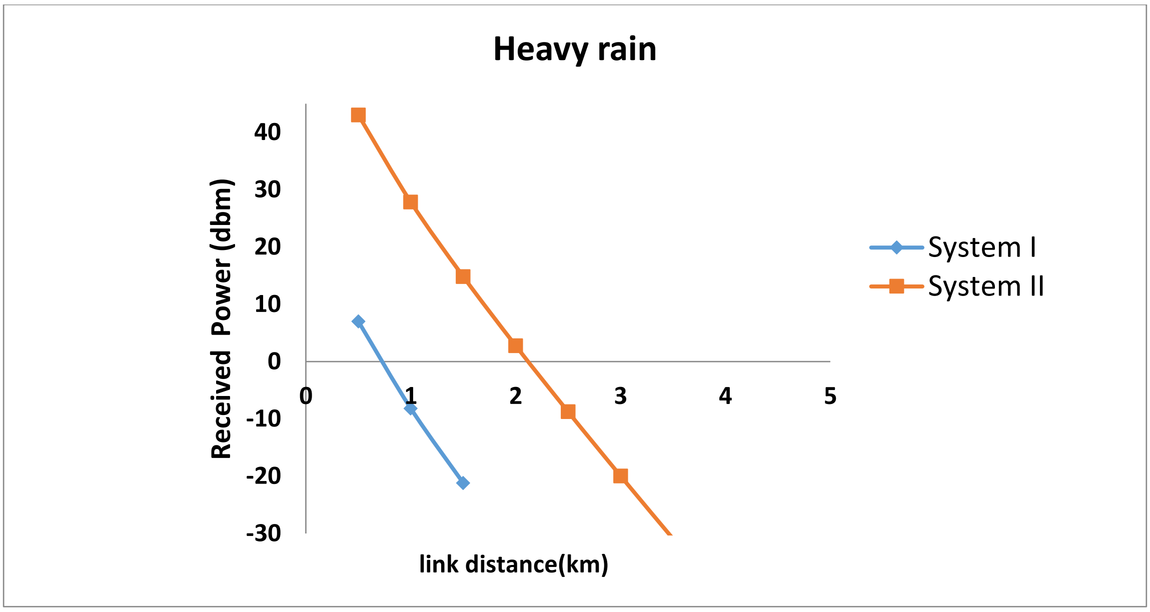
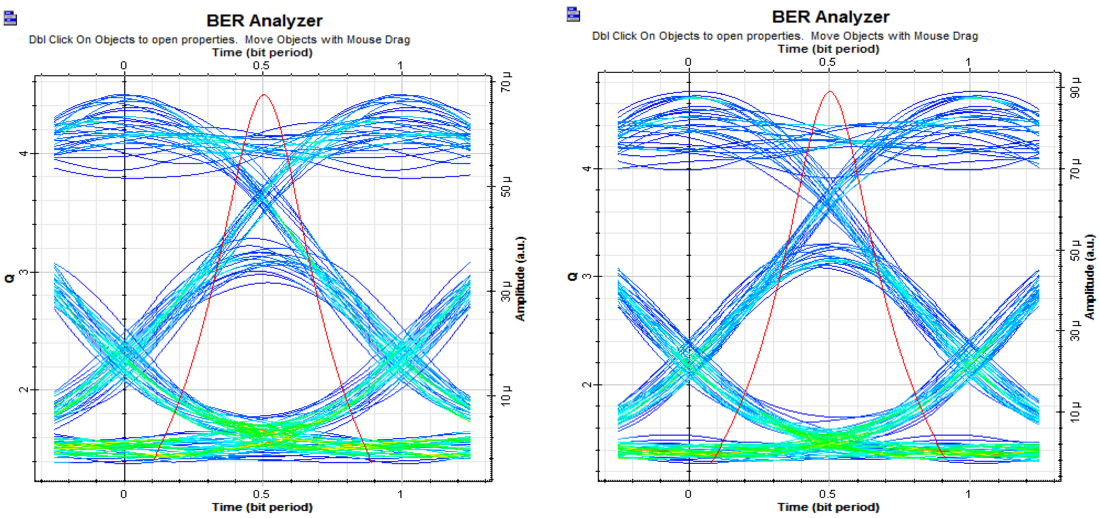


Fig. 4.11: Received power v/s Link Range.

The eye diagram comparison done in Fig. 4.12 depicts the difference in the quality of received signal of both the systems which again favours system II.



(a) (b)

Fig.4.12 Eye diagrams comparing system I (a) and system II (b) under heavy rain condition.

4.3.3 Comparison of Two Systems

The comparison of maximum range, received power, BER and Q factor values for single beam and multi beam system are shown in table 4.5 and 4.6 respectively.

Table 4.5 Comparison of performance values of single beam:

Intensity of rain	Power (dBm)	Max. Ranng (km)	Q factor	BER
light	-25.3	4	3.5	0.0002
Medium	-25.9	3	3.3	0.00004
heavy	-21.2	1.5	4.5	0.000002

Table 4.6 Comparison of performance values of multi beam:

Intensity of rain	Power (dBm)	Max. Ranng (km)	Q factor	BER
light	-23.6	8.5	4.1	1.78111e-5
Medium	-23.2	6	4.2	1.04207e-5
heavy	-19.9	3	4.7	9.34094e-7

As observed from the tabulated results, it is clear that where the range for light rain condition is 4 km for single beam system, it increases to 8.5 km for multi beam system which is 112.5% as improvement ratio. The analyzed results for medium and heavy rain conditions for multi beam system are also better than single beam system which shows maximum range increase by 100% with acceptable transmission .

Chapter Five

Conclusion and Recommendations

5.1 Conclusion

Atmospheric effects play a major hurdle in FSO communication system limiting its use in distant communication. Studies for amalgamating various techniques are being carried out to reduce these effects. One such hybrid technique has been analyzed in this work which combines a multi beam FSO system with a WDM-FSO system. This system has been compared with the conventional single beam system by simulating both systems under clear weather and different rain conditions using same parameters.

The results are compared in terms of Q factor, min. BER and link distance achieved by both systems. Analysis shows that the successful transmission distance for multi beam system under clear weather is 130 km with 3.8 Q factor and 7.68e-5 BER, and that for the single beam system is 3 km with 2.9 Q factor and 0.0013 BER. For light rain weather multi beam system works up to 8.5 km with 4.1 Q factor and 1.781e-5 BER, whereas the single beam system works for only 4 km with 3.5 Q factor and 0.0002 BER. For medium rain weather system 2 can communicate up to 6 km with 4.2 Q factor and 1.042e-5 BER, whereas system 1 can establish a successful link for only 3 Km with 3.3 Q factor and 0.0004 BER. The link distance for heavy rain condition is also increased To 3 km with Q factor value of 4.7 and 9.341e-7 BER in case of multi beam system, whereas single beam system can establish a successful link for only 1.5 km with 4.5 Q factor and 2.807e-6 BER.

So, For a transmission rate of 10 Gbps an input power of 40 dBm it has been inferred that the multi beam system performs considerably well and outperforms single beam system under different rain conditions. The comparison of results done by simulating both systems using OptiSystem7.0

5.2 Recommendations

After finishing these research there are some other issues can be considering for future research, these include:

- Increasing the capacity of the hybrid WDM/multi-beam FSO system can be studied and implemented to reach up to 32 or 64 channels WDM.
- The proposed WDM FSO system can proved using hybrid optical amplifiers to be a cost effective and efficient system.
- Multi beam WDM-FSO System can used as a Solution for Hazy Weather Conditions.
- They can use data rate more than 10 Gbps with input power more than 40 dBm.

3.5 References

[1] H. Kaushal, V.K. Jain, S. Ka, Free Space Optical Communication, Springer India 2017, pp.60

[2] Grover M, Singh P, Kaur P, Madhu , "WDM-FSO system: an optimum solution for clear and hazy weather conditions, " Wireless Personal Communications, 97(4): 5783–5795 August 2017.

[3] Samir A. Al-Gailani1, Abu Bakar Mohammad and Redhwan Q. Shaddad1, "Scalable Hybrid WDM/Multi-beam Free Space Optical Network in Tropical Weather ," 1st International Conference of Recent Trends in Information and Communication Technologies ,12th -14th September, 2014.

[4] Singh, P., Kaur, P., Grover, M., Madhu, C.: Multi beam WDM FSO system: an optimum solution for clear and hazy weather conditions. Wirel. Pers. Commun. 97, 1–13 (2017)

[5] N. Sahu and J. C. Prajapti, "Optimization of WDM-FSO link using multiple beams under different rain condition", Int. J. Adv. Res. Electron. Commun. Eng., vol. 4, pp. 1125–1131, 2015.

[6] Abu Bakar Mohammad, "Optimization of FSO System in Tropical Weather using Multiple Beams," IEEE 5th International Conference on Photonics (ICP), Kuala Lumpur, 2-4 Sept, 2014.

[7] H. Singh and M. Arora, "Investigating Wavelength Dependency of Terrestrial Free Space optical Communication Link", International journal of Scientific Research in Science and Technology, Vol. 2, May (2016), no. 2395-6011.

[8] J. Kaur and M. Kaur, "Design & Investigation of 8x5Gb/s & 8x10 Gb/s WDM-FSO Transmission Systems Under Different Atmospheric Conditions", SSRG International Journal of Electronics and

Communication Engineering (SSRG-IJECE) – Volume 4 Issue 5 – May 2017.

[9] M. Grover, P. Singh, and P. Kaur, “ Mitigation of Scintillation Effects in WDM FSO System using Multi beam Technique”, Journal of Telecommunication and Information Technology – February 2017.

[10] J. Kaur, M. Aggarwal, “Design and Analysis of 32 channel WDM MIMO Free Space Optics link under Different Atmospheric Conditions”, International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering – Vol. 6, Issue 6, June 2017.

[11] Mazin Ali A. Ali, “Performance analysis of terrestrial WDM-FSO Link under Different Weather Channel”, Journal (World Scientific News), Vol. 56, November (2016).

[12] M. Khalighi, M. Uysal, "Survey on free space optical communication: A communication theory perspective", IEEE Communication Surveys & Tutorials, vol. 16, no. 4, pp. 2231-2258, 2014.

[13] S. Hitam, S. N. Norziela, A. Noor, S. B. Anas and R. Sahbudin "Performance Analysis on 16-Channels Optical Transmission under Tropical Regions Environment",Journal of Computer Science 8 (1): 145-148, 2012.

[14] https://www.researchgate.net/publication/319067458

[15] A., Malik, P., Singh: Free Space Optics: Current Applications and Future Challenges, International Journal of Optics, Vol. 7. Article ID 945483 (2015).

[16] S. Chaudhary , Preety Bansal and Manisha Lumb , “Effect of Beam Divergence on WDM-FSO Transmission System ,” International Journal of Computer Applications (0975 – 8887) Volume 93 – No 1, May 2014.

[17] Aditi and Preeti, “An Effort to Design a Power Efficient, Long Reach WDM-FSO System,” International Conference on Signal Propagation and Computer Technology (ICSPCT), 2014.

[18] Dhaval Shah and Dilip Kumar Kothari, “Optimization of 2.5 Gbps WDM-FSO link range under different rain conditions in Ahmedabad,” Annual IEEE India Conference (INDICON), 2014.

[19] Mbah, Afamefuna Maduka (2016) Hybrid fibre and frees pace optical solutions in optical access networks. PhD thesis, University of Nottingham.

[20] R.Jee and S.Chandra, “Performance Analysis of WDM-Free-Space Optical Transmission system with M-QAM Modulation under Atmospheric and optical nonlinearities” in Proceeding of IEEE, International Conference on microwave, optical and Communication engineering, IIT Bhubaneswar, India,(2015).

[21] S.parkash, A.Sharma, H.Singh and H.P Singh, “performance investigation of 40Gb/s DWDM over free space optical communication system using RZ modulation format”, advances in optical technologies, Vol.2, (2016), article id 4217302, pp. 8.

[22] Malik, A., & Singh, P. (2015). Comparative analysis of point to point FSO system under clear and haze weather conditions. Wireless Personal Communications, 80(2), 483–492.

[23] Ankita Shivhare and Ankita Mowar , “ A 4×50 Gbps WDM Free - Space Optical Communication System ,” International Journal of Advanced Research in Electronics and Communication Engineering ,Volume 3, Issue 12, December 2014.

[24] Abisayo O. Aladeloba, Malcolm S. Woolfson, and Andrew J.Phillips, “WDM FSO Network With Turbulence Accentuated Interchannel Crosstalk,” J. Opt. Commun. Netw./Vol. 5, No. 6,June 2013.

[25] Charu Sharma, Sukhbir Singh and Bhubneshwar Sharma, "Investigations on Bit Error Rate Performance of DWDM Free Space Optics System Using Semiconductor Optical Amplifier in Intersatellite Communication," International Journal of Engineering Research & Technology ,Vol. 2 Issue 8, August – 2013.

[26] (Optics and Photonics Series) Achyut K. Dutta, Niloy K. Dutta, Masahiko Fujiwara-WDM Technologies_ Optical Networks (Optics and Photonics Series)-Academic Press (2004).

[27] M. A. Esmail, H. Fathallah, M. S. Alouni, channel modeling and performance evaluation of FSO communication systems in Fog, 23rd International Conference on Telecommunications (ICT), Thessaloniki, 2016.

[28] H. A. Fadhil, A. Amphawan, H. A. B. Shamsuddin, T. Hussein Abd, H. M. R. Al-Khafaji, S. A. Aljunid, and N. Ahmed, "Optimization of free space optics parameters: An optimum solution for bad weather conditions", Optik Int. J. Light Electron. Opt., vol. 124, no. 19, pp. 3969–3973M, 2014.