

PERFORMANCE INVESTIGATION OF FSO COMMUNICATION
SYSTEM UNDER SUB-TROPICAL WEATHER CONDITION OF
BANGLADESH

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A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master
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M.Sc. Engineering Thesis

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BANGLADESH

DECLARATION

I hereby declare that the study work of this thesis entitled above is my **original work**, and this work has not formed the basis for the award of any degree, association, fellowship, or any other similar title. I also hereby state that the sources I have used for my research work have been duly acknowledged and cited in the thesis paper.



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ABSTRACT

Performance Investigation of FSO Communication System Under Sub-Tropical Weather Condition of Bangladesh

Use of optical signal for primitive communication is very historic. Signaling communication by means of fire beacons and smoke dates back to 800 -150 BC. However, FSO communication system had seen its mature application since 1960s. Today FSO communication competes with radio due to its high bandwidth, easy installation, low initial cost, versatile applications, etc. However, its signal degradation due to environment is inherent and higher than that associated with radio signal. This paper has defined FSO channel models based on MPSK and LPPM modulation schemes while analyzing their performances under the variation of modulation order and environmental factors including the local rain condition. Meijer G function based close-form expressions and MATLAB-based simulation for performance evaluation have been used. The study analysis has confirmed that FSO links degrade heavily under turbulence, misalignment and local rain condition. The study finds that the SNR degradation due to change of turbulence condition is 20 dB for MPSK and 20-27 dB LPPM links at BER value of 10^{-4} . The strong misalignment causes a degradation of 20 dB for MPSK and 18 dB for LPPM schemes. Lastly, the heavy rain conditions of Bangladesh cause a loss of 15-20 dB for MPSK and 14-25 dB for LPPM schemes. The higher order FSO links provide better spectral efficiency with disadvantage of SNR penalty for MPSK, but with the advantage of SNR gain for LPPM schemes. The penalty of MPSK schemes becomes as high as 13 dB when switched from BPSK to 16-PSK link. Conversely, the gain of LPPM schemes becomes 15 dB when switched from 2-PPM to 16-PPM link. Both MPSK-SIM and LPPM based FSO links have their merits and demerits relative to each other. Higher order MPSK is more beneficial for band-width efficiency and high data-rate applications. But it is more sensitive to phase noise and atmospheric turbulence. Besides, its system is more complex due to the need of phase tracking. On the other hand, higher order LPPM is better power efficient and more advantageous in turbulent environment due to its strong resilience against amplitude jitters, although it has sensitivities to timing jitters. Its system has some complexities due to slot and timing synchronization requirement. Considering Bangladesh environment with unfavorable conditions, both schemes are subject to link degradation and even link break due to extreme conditions. The high-speed high-order FSO link with either modulation scheme fits better for short distance application in Bangladesh environment. Even mitigation techniques can be applied to improve SNR performance. The link needs to be adaptive with switching features from high order to low order for maintaining the link continuity.

সারসংক্ষেপ

Performance Investigation of FSO Communication System Under Sub-Tropical Weather Condition of Bangladesh

অপটিক্যাল সংকেত ব্যবহারের মাধ্যমে কমিউনিকেশন খুবই ঐতিহাসিক। আগুন এবং ধোঁয়ার মাধ্যমে সংকেত প্রেরণ ৮০০ খ্রিস্টপূর্ব থেকে ১৫০ খ্রিস্টপূর্ব পর্যন্ত প্রচলিত ছিল। তবে, ফ্রি স্পেস অপটিক্যাল (FSO) কমিউনিকেশন ব্যবস্থার পূর্ণাঙ্গ ব্যবহার ১৯৬০ এর দশক থেকে শুরু হয়। বর্তমানে FSO যোগাযোগ রেডিওর সাথে প্রতিযোগিতা করছে এর উচ্চ ব্যান্ডউইথ, সহজ ইনস্টলেশন, কম প্রাথমিক খরচ, বহুমুখী প্রয়োগ ইত্যাদি এর কারণে। তবে, পরিবেশের কারণে এর সংকেতের অবনতি স্বাভাবিক এবং রেডিও সিগনালের তুলনায় বেশি। এই পেপারটি MPSK এবং LPPM মডুলেশন স্কিমের উপর ভিত্তি করে FSO চ্যানেল মডেল সংজ্ঞায়িত করা হয়েছে এবং মডুলেশন অর্ডার ও পরিবেশগত কারণগুলির মধ্যে যেমন স্থানীয় বৃষ্টিপাতের অবস্থার পরিবর্তনের অধীনে এর কর্মক্ষমতা বিশ্লেষণ করা হয়েছে। কর্মক্ষমতা মূল্যায়নের জন্য Meijer G ফাংশনের উপর ভিত্তি করে ক্লোজ ফর্ম অভিব্যক্তি এবং MATLAB ভিত্তিক সিমুলেশন ব্যবহার করা করা হয়েছে। গবেষণা বিশ্লেষণে নিশ্চিত করা হয়েছে যে টার্বুলেন্স, অসামঞ্জস্য এবং স্থানীয় বৃষ্টির অবস্থার কারণে FSO লিঙ্কগুলির মারাত্মক অবনতি ঘটে। গবেষণায় পাওয়া গেছে যে টার্বুলেন্স অবস্থার পরিবর্তনের কারণে MPSK এর জন্য SNR এর অবনতি ২০ ডিবি এবং LPPM সংযোগের জন্য ২০-২৭ ডিবি হয় যেখানে BER মান 10^{-8} । তীব্র অসামঞ্জস্যতা MPSK এর জন্য ২০ ডিবি এবং LPPM স্কিমের জন্য ১৮ ডিবি অবনতি ঘটায়। শেষ পর্যন্ত, বাংলাদেশের ভারী বৃষ্টিপাতের অবস্থায় MPSK এর জন্য ১৫-২০ ডিবি এবং LPPM স্কিমের জন্য ১৪-২৫ ডিবি সিগন্যাল ক্ষতি হয়। উচ্চতর মডুলেশন অর্ডার ভিত্তিক FSO সংযোগগুলি MPSK এর জন্য SNR এর পেনাল্টির অসুবিধাসহ উন্নত স্পেকট্রাল দক্ষতা প্রদান করে, তবে LPPM স্কিমগুলির জন্য SNR গেইন বৃদ্ধিরও সুবিধা পাওয়া যায়। BPSK থেকে ১৬-PSK সংযোগে পরিবর্তিত হলে MPSK স্কিমের পেনাল্টি ১৩ ডিবি পর্যন্ত বেড়ে যায়। বিপরীতভাবে, ২-PPM থেকে ১৬-PPM সংযোগে পরিবর্তিত হলে LPPM স্কিমের জন্য তা ১৫ ডিবি পর্যন্ত বেড়ে যায়। MPSK-SIM এবং LPPM ভিত্তিক FSO লিঙ্কগুলির একে অপরের তুলনায় তাদের নিজস্ব সুবিধা ও অসুবিধা রয়েছে। উচ্চতর অর্ডারের MPSK ব্যান্ডউইথ দক্ষতা এবং উচ্চ ডেটা-রেট প্রয়োগের জন্য আরও উপকারী। কিন্তু এটি ফেজ নয়েজ এবং বায়ুমণ্ডলীয় টার্বুলেন্সের প্রতি বেশি সংবেদনশীল। এছাড়াও ফেজ ট্র্যাকিংয়ের জন্য সিস্টেমটি আরও জটিল। অন্যদিকে উচ্চতর অর্ডারের LPPM শক্তি দক্ষতায় ভাল এবং আম্পি-টিউড জিটারের বিপরীতে এর শক্তিশালী স্থিতিস্থাপকতার কারণে টার্বুলেন্ট পরিবেশে আরও সুবিধাজনক যদিও এটি টাইমিং জিটারের প্রতি সংবেদনশীলতা রাখে। স-ট এবং টাইমিং সিক্রোনাইজেশন করার ক্ষেত্রে উক্ত সিস্টেমে কিছু জটিলতা রয়েছে। বাংলাদেশের পরিবেশ অনুকূল না থাকায় উভয় স্কিমই চরম পরিস্থিতির কারণে লিঙ্ক এর অবনতি এবং এমনকি লিঙ্ক বিচ্ছিন্ন হয়ে থাকে। উচ্চ গতির উচ্চতর অর্ডারের FSO লিঙ্কটি যে কোনো মডুলেশন স্কিমের সাথে বাংলাদেশের পরিবেশে স্বল্প দূরত্বের প্রয়োগের জন্য আরও উপযুক্ত। লিঙ্কটি উচ্চতর থেকে নিম্নতর মডুলেশনে পরিবর্তনের বৈশিষ্ট্যগুলির সাথে সামঞ্জস্যপূর্ণ এবং লিঙ্কের ধারাবাহিকতা বজায় রাখতে উপযুক্ত প্রশমন বৈশিষ্ট্যগুলি একত্রিত করতে হবে।

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LIST OF ABBREVIATIONS

3D	Three Dimension
4G	Fourth Generation
5G	Fifth Generation
AOA	Angle of Arrival
AOD	Aerosol Optical Depth
AUV	Autonomous Underwater Vehicle
AWGN	Additive White Gaussian Noise
B5G	Beyond 5G
BAN	Body Area Network
BER	Bit Error Rate
BMD	Bangladesh Meteorological Department
BPSK	Binary Phase Shift Keying
BS	Base Station
BW	Bandwidth
CAP	Carrier-Less Amplitude
CH ₄	Methane
CO ₂	Carbon Dioxide
dB	Decibel
DC	Direct Current
DPIM	Digital Pulse Interval Modulation
DPIWM	Digital Pulse Interval and width modulation
DPPM	Differential Pulse Position Modulation
DPSK	Differential Phase Shift Keying
EE	Energy Efficiency
EHF	Extreme High Frequency
FIR	Far Infrared Radiation

FOC	Fiber Optic Communication
FSO	Free Space Optical
GG	Gamma-Gamma
Hetnet	Heterogenous Network
HF	High frequency
IM	Intensity Modulation
IoT	Internet of Things
IR	Infrared Radiation
ISI	Inter-symbol interference
ITU-R	International Telecommunication Union Radiocommunication Sector
LAN	Local Area Network
LED	Light Emitting Diode
LF	Low Frequency
LiDAR	Light detection and ranging
LIR	Long Infrared Radiation
LOS	Line of Sight
LPPM	L-ary PPM
MCSIM	Multi-Carrier Sub-carrier Intensity Modulation
MIR	Mid Infrared Radiation
MF	Medium Frequency
M-FSK	M -ary Frequency Shift Keying
MPAM	M-ary Pulse Amplitude Modulation
MPSK	M-ary Phase Shift Keying
MPPM	Multi-Pulse Position Modulation
MQAM	M-ary Quadrature Amplitude Modulation
NIR	Near Infrared Radiation
NLOS	Non-Line of Sight
OCC	Optical Camera Communication

OFDM	Orthogonal Frequency Division Multiplexing
OOK	On Off Keying
OPPM	Overlapping Pulse Position Modulation
OWC	Optical Wireless Communication
PAM	Pulse Amplitude Modulation
PAN	Personal Area Network
PDM	Polarization Division Multiplexing
PE	Power Efficiency
PFM	Pulse Frequency Modulation
PolSK	Polarization Shift Keying
PPM	Pulse Position Modulation
PWM	Pulse Width Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RoFSO	Radio over Free Space Optics
ROV	Remotely Operated Vehicle
SE	Spectrum Efficiency
SHF	Super High Frequency
SIM	Subcarrier Intensity Modulation
SIR	Short Infrared Radiation
SNR	Signal to Noise Ratio
SS	Spectrum Slicing
TCP	Transport Control Protocol
UAV	Unmanned Aerial Vehicle
UHF	Ultra-High Frequency
UV	Ultraviolet
UWB	Ultra-Wide Band
UWS	Under Water Sensor

VANET	Vehicular Ad hoc network
VHF	Very High Frequency
VL	visible light
VLC	Visible Light Communication
VLF	Very Low Frequency
WAN	Wide Area Network
WBAN	Wireless Body Area Network
WLAN	Wireless Local Area Network
WMAN	Wireless Metro-polytan Area Network
WPAN	Wireless Private Area Network
WDM	Wavelength Division Multiplexing

CHAPTER 1

INTRODUCTION

1.1 Prelude

Free Space Optical (FSO) is simply a technology that uses light as a means of communication for propagation of signal through an unbounded media (water, air or space). As an introductory chapter it starts with its broad overview including its definition and brief history, which is followed by the particulars of FSO communication system link configuration and its application. Thereafter comes the problem statement and the rationale behind the research. The chapter concludes with the objectives of the research and the organization of the paper.

1.2 Overview of FSO Communication

Optical wavelength, also called as light, offers huge bandwidth and an immense solution as optical wireless communication (OWC) system to the users to overcome the spectrum bottleneck of RF communication [1]. The spectrum designation of radio and optical bands given at table 1.1. The telecommunication network today needs to cope up with huge bandwidth demand of users with data heavy personal devices connected to Internet and also the huge bandwidth needs of Internet of Things (IoT) connectivity. The 5G and the beyond 5G (B5G) cellular networks with heterogenous nets (Hetnets) have promised to offer ultra-huge bandwidth to the homes and a host of mobile users [2]. The solution would be to increase the bandwidth of the communication media, but RF band is reaching its saturation level. Alternatively, the solution would be to add another means of communication as a separate one or as a complimentary configuration. This optical communication system fits well for these types of uses as a basic means of communication or in a hybrid configuration with RF system.

Because of its optical wavelength – infrared (IR), visible and ultra-violet (UV) - the bandwidth offered by OWC is in the order of GHz and THz. However, its transmission distance is low due to its waveband. OWC systems are becoming wide-spread with applications ranging from piconet (inter-chip) to micro net (body network) to wide area network spanning tens of kms as shown at figure 1.1. In general, OWC transmission ranges are classified as ultra-short range (nm), short range (cm), medium range (m), long range (km) and ultra-long range [1]-[3]. On the other hand, the terrestrial FSO

transmission range is generally categorized – although no official classification is available – as short-range spanning from few hundred meters to few km and long range for more than 2 km [1].

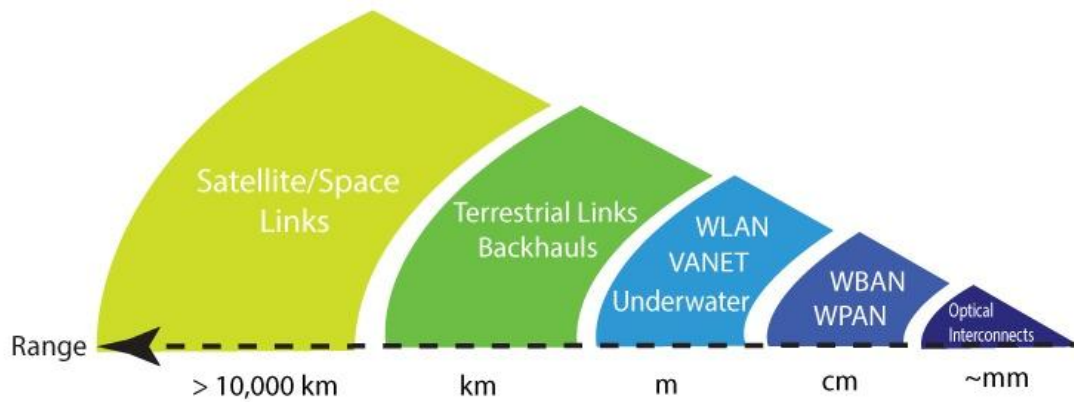


Figure 1.1: Categorization of OWC based on transmission range (adopted from [3])

Table 1.1: Spectrum Designation [3]

Electro-Magnetic Wave		Frequency	Wavelength		
Radio	Very low frequency (VLF)	3-30 kHz	100-10 km		
	Low Frequency (LF)	30-300 kHz	10-1 km		
	Medium frequency (MF)	0.3-3 MHz	1000-100 m		
	High frequency (HF)	3-30 MHz	100-10 m		
	Very high frequency (VHF)	30-300 MHz	10-1 m		
	Ultra-high frequency (UHF)	0.3-3 GHz	1-0.1 m		
	Super-high frequency (SHF)	3-30 GHz	100-10 mm		
	Extremely high frequency (EHF)	30-300 GHz	10-1 mm		
	/Millimeter wave				
Microwave	10 x sub-bands	0.225-100 GHz	1330-3 mm		
Optical	IR	FIR	0.3-20 THz	1-0.015 mm	
		Thermal IR	LIR	20-37.5 THz	0.015-0.008 mm
			MIR	37-100 THz	0.008-0.003 mm
			SIR	100-214.3 THz	3000-1400 nm
			NIR	214.3-394.7 THz	1400-760 nm
	Visible	Red	394.7-491.8 THz	760-610 nm	
Orange	491.8-507.6 THz	610-591 nm			
Yellow	507.6-526.3 THz	591-570 nm			
Green	526.3-600 THz	570-500 nm			
Blue	600-666.7 THz	500-450 nm			
Violet	666.7-833.3 THz	450-360 nm			
UV	9 x sub-bands	0.750-30 PHz	400-10 nm		

In fact, FSO system is a quite old technology that transmits data and information through an optical frequency or waveband carrier. The photophone, experimented by Alexander Graham bell in 1880, is an example of earliest generation FSO communication. Again, ancient days primitive communication methods like smoke and fire beacon used for signaling were also one kind of optical means of communication. Then in the late 18th century semaphore method of communication came into existence. All these methods fall under FSO communication. The electronic FSO communication system truly came into being after the discovery of solid-state electronics in 1960s. The kind of OWC using GaAs LED had transmitted TV signal at a distance of 48 km in 1962 as an experiment basis [4]. During that period, FSO communication technology had witnessed some applications in commercial as well as military domain.

The 1970s discovery of low loss fiber-optic communication (FCO) had lessened the attention on the development and the application of FSO technology. Its applications were then limited to military and deep-space satellite-satellite communication [1]. However, the maturity of opto-electronics, the demand of huge bandwidth and the gradual saturation of RF spectrum had seen the jump of FSO related research and development works during 2000s or few years back. FSO system presently supports several Gbps data speed. Besides, its power consumptions are low and it is more secured than RF signal. FSO system is extremely high bandwidth, unlicensed spectrum, easy to deploy, Line of Sight (LOS) communication, low power consumption (approx. 1/2 of RF), compact size (approx. 1/10 of RF antenna diameter) and of like many features that have generated interests among developers in discovering many potential applications including last mile solution [4].

With the immense benefits of FSO communication comes its impairments. The terrestrial FSO system experiences detrimental effects induced by the atmosphere [5]. The optical signal is more subject to many kinds of signal degradation processes like spreading, scattering, absorptions, fluctuations, divergence, etc. due to the presence of air particles and impurities, atmospheric inhomogeneity, atmospheric turbulence, and the weather events like wind, rain, snow, fog, haze, etc. than its counter-parts RF signal. Inherently due to its huge propagation loss, the propagation distance it covers are much smaller than that of radio signal.

The thesis is on the terrestrial FSO communication system performance in Bangladesh sub-tropical weather condition. Accordingly, FSO system in Bangladesh weather will be subject to the above signal attenuation processes and events, because of the fact that almost all the processes and events (except snow) are more or less prevalent here. Here two specific modulation schemes based FSO links - the M-ary phase shift keying (MPSK) based sub-carrier intensity modulation (SIM) and L-ary pulse position modulation (LPPM) – have been chosen for the study. The OOK (on-off keying) based FSO link, although very commonly used, cannot deliver high bandwidth demand. The two schemes under the subject to this thesis - the SIM and pulse modulation (figure 2.2) – serve very high bandwidth applications. These schemes are very widely used in today’s FSO system. However, LPPM is very suitable for low power application while MPSK SIM for high-speed application with seamless connection with RF signal. Accordingly, these two modulation schemes have been chosen for their performance investigation.

1.3 OWC vs FSO

Optical wireless communication (OWC) covers an ultra-wide unlicensed spectrum. The OWC system has emerged as a complimentary/ alternate solution to overcome conventional RF spectrum scarcity and spans a distance ranging from nm to several kms. The optical frequency band of near IR (NIR), visible light (VL) and ultra-violet (UV) - shown at table 1.1 - falls under the domain OWC where each band has unique features and characteristics. For example, NIR band is not used for illumination and it gives highest range among the three bands due to its comparatively lower frequency. It works in LOS communication with narrow beam. On the other hand, UV frequency band supports very high data rate application through LOS and None LOS (NLOS) short distance communication. However, VL band can provide extreme transmission speed for indoor applications and not effective for outdoor services due to obstacle of light. It is commonly used for VL communication (VLC), LiFi (light fidelity) and optical camera communication (OCC) covering short and medium distances [2].

The FSO, on the other hand, covers NIR band [1]-[3] as subset of OWC or long range terrestrial OWC, although many scholars interchangeably use FSO as OWC. In terms of band (table 1.2), however, ultra-short IR (USIR) and short IR (SIR) optical spectrum are used for long distance FSO communications. Whereas, medium IR (MIR) and long IR

(LIR) spectrum are used in military applications and thermal imaging purpose respectively. Besides, IR also commonly used in LiFi and OCC for short and medium transmission distances; covers long distances for Light detection and ranging (LiDAR) technologies. Although FSO predominantly uses NIR band, it can also use VL and UV under FSO protocol [4]. In fact, FSO is a communication system with some defined protocols (table 1.3) while OWC is more of a generic optical communication name.

Table 1.2: IR wavebands for various application [3]

IR Categories	Wavelength range	Remarks
NIR	750-1400 nm	Used for FOC and FSO system. Eye-safe power restriction
SIR	1400-3000 nm	1550 nm used for FSO long distance communication
MIR	3000-8000 nm	Used for guiding missiles in military application
LIR	8000-15 μ m	Used in thermal imaging
FIR	15 μ m- 1 mm	Used in astronomy

Table 1.3: Comparison of different Wireless Technologies (adopted from [4])

Factors	LiFi	VLC	OCC	FSO	RF
Light Source	LED/LD	LED/LD	LED	LD	Antenna
Receiver	PD	PD	Camera	PD/LD	Antenna
Modulation	OOK, OFDM, CDMA	OOK, OFDM, CDMA	OOK, PAM, CDMA	OOK, OFDM, QAM, SIK	ASK, PSK, FSK, QAM, OFDM, CDMA
Licensed Spectrum	No	No	No	No	Yes (most)
Link Coverage	10m	20m	200m	> 1 km (terrestrial)	>100 km (microwave link)
Environment effect	yes	Yes	No	yes	Yes
Bit rate	100 Gbps	100 Gbps	54 Mbps	40 Gbps	6 Gbps
Spectrum	IR/VL/UV	VL	VL	IR/VL/UV	Radio
Path loss & interference	Medium & Low	Medium & Low	Low & nil	High & low	High & very high
Link Topology	Bi-directional	Uni- or Bi-directional	Uni-directional	Bi-directional	Omni-directional
Security	high	High	high	high	Low

1.4 Link Configuration

FSO system in its crudest form consists of one transmitter which transmits signal in the air or space. The intelligence signal after converted to electrical signal modulates the optical modulator of the transmitter. The optical signal, after propagating through the intervening space between the transmitter and receiver, is received by one receiver and after demodulation converted into the electrical signal. However, the link configuration depends on the application type, modulation scheme used, diversity technique applied, transmission types, etc. The figure 1.2 shows one coherent MPSK based FSO system where local oscillator elements are added with both transmitter and receiver to make it a coherent system.

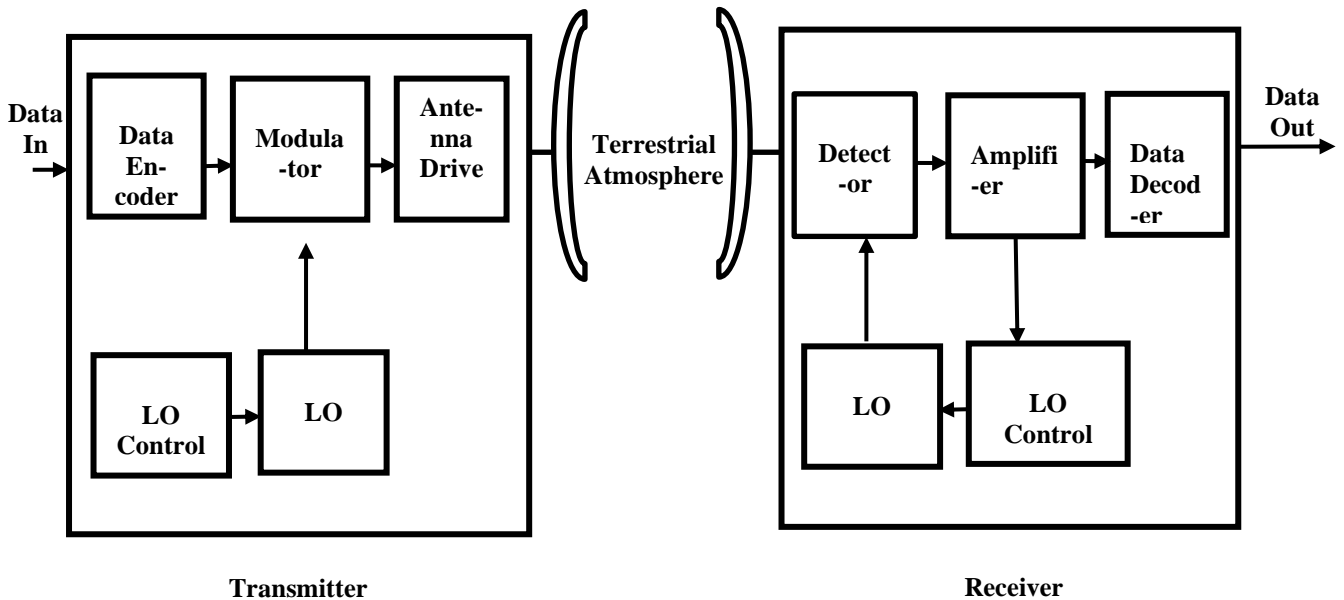


Fig. 1.2: Block diagram of a coherent FSO communication system.

Most FSO systems are of LOS communication type. Few are non-LOS (point to multi-point), diffuse and tracked type [3], [10]. Depending upon type of modulation, the system may be synchronous, direct, coherent or non-coherent type and accordingly required elements will be added to suit the type. Depending upon the mitigation technique employed on the physical level, the transmitter and receiver section and antennas would change. Depending upon the type of applications, the system may be simple FSO, multi-hop FSO [8], mixed FSO link with RF [7] like Radio over FSO (RoFSO) as in figure 1.3, mixed FSO link with optical fibre, or complimentary link with RF [4]. Operating wavelength (in the range 400 nm-1600 nm) is also a vital parameter of link configuration

as many factors of the link performance depend on the waveband. Few studies rather consider different optical bands (750nm to 1600nm) as FSO Band. This thesis considers the latter one focusing on the particulars of NIR band. Gain is high at lower wavelength, but higher wavelength offers better distance. Some wavelengths cause eye damages due to retinal impact, and have restriction on their maximum power transmission. Wavelengths above 1500 nm are eye safe, and it can transmit about as much as 10 times optical power of 850 nm system [1]-[4], [8].

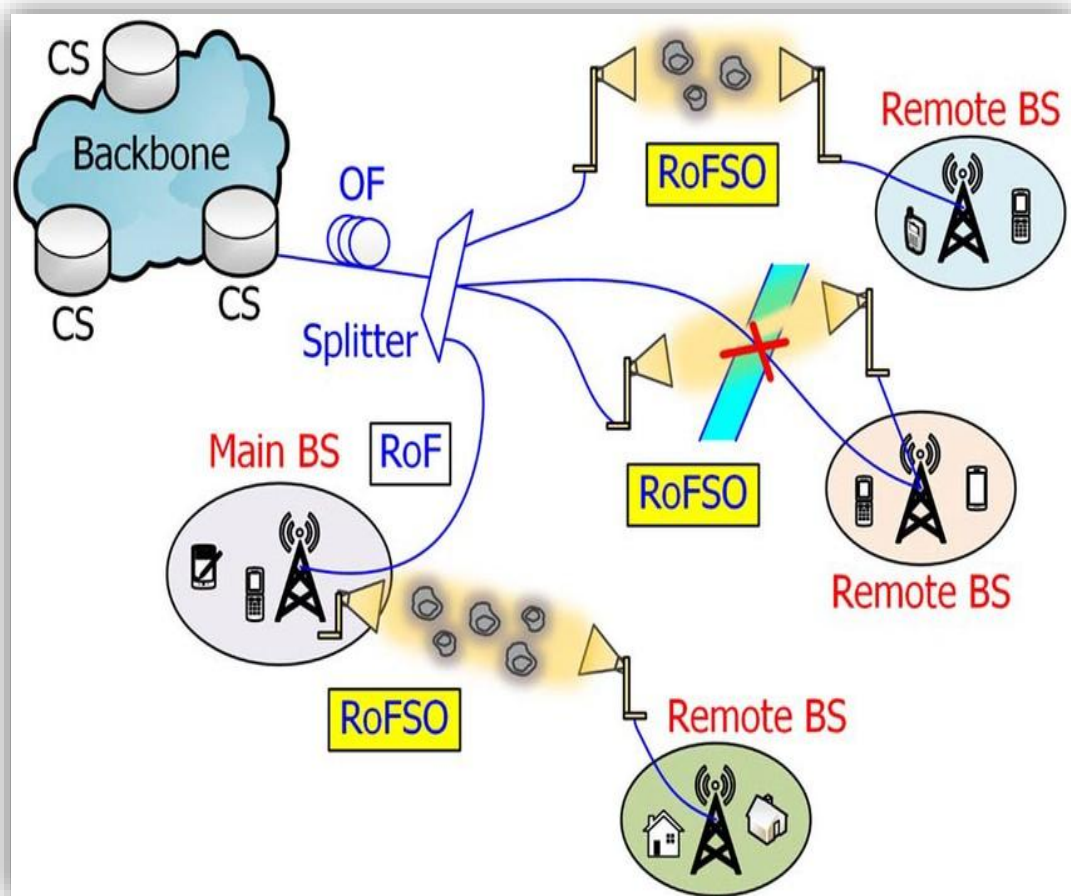


Fig. 1.3: Broadband connectivity through RoFSO system (adopted from [6])

1.5 Applications of FSO System

FSO system has become one important element of IoT connectivity, back-haul links, 5G with ultra-dense Hetnets and B5G cellular communication system. It has the potentiality to offload heavy data traffic from RF network through the application of hybrid RF/FSO and also RoFSO mixed links. Modern modulation techniques are being applied to FSO system for seamless connection with RF system to realize hybrid or mixed RF-FSO based

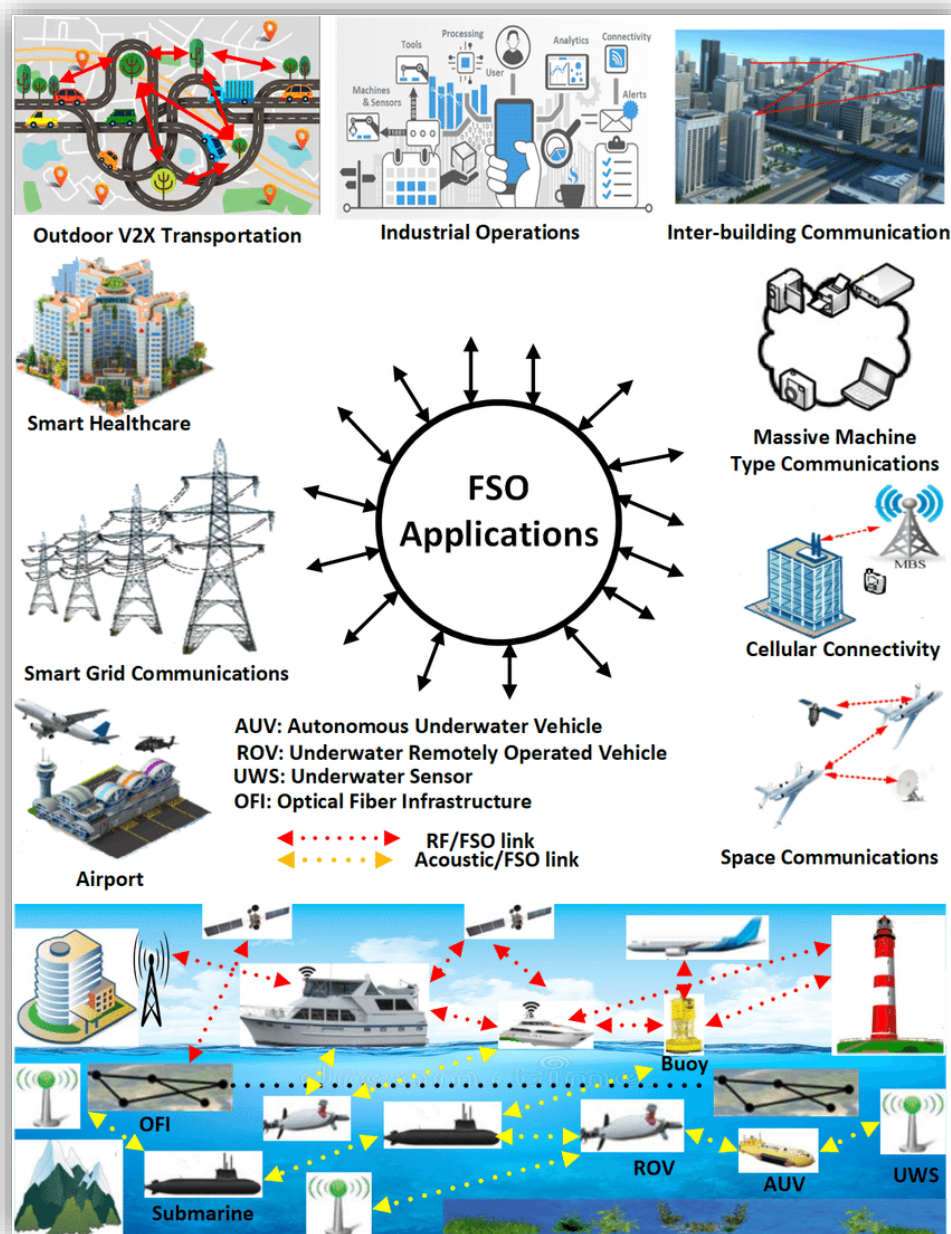


Fig. 1.4: Some applications of FSO Communication (Adopted from [4])

links. FSO system also finds applications in remote monitoring of ultra-wide band (UWB) based secure body area network (BAN). Other notable applications are VLC, OCC (used with smart device image sensor camera), Li-Fi communication, LiDAR, etc. LiDAR, an active remote sensing technology, is used to measure distance as well as object's 3D parameters using NIR band pulsed light with potential applications for cellular devices, self-driving cars, robots, drones, UAVs, etc. [11]. In addition to wide area surveillance applications. FSO system also has applications in underwater communication system alongside acoustic links [9], [10].

The figure 1.4 shows few FSO applications above and under water in hybrid or mixed link concepts with RF and acoustic media respectively. The application of FSO system include video surveillance, campus connectivity, backhauling for cellular networks, LAN-to-LAN connectivity, inter-chip connectivity, underwater communication, space communication, fiber backup, etc. Overall, FSO system has many remarkable features like wide spectrum, ultra-high bandwidth, low latency time, seamless integration with RF or FOC signals, low cost, low power, high reliability, no EM interference promising to address the bandwidth demands of future cellular networks, etc.

1.6 Problem Statement

Like many countries around the world, Bangladesh has a high demand for high bandwidth communication and internet connectivity. Today and in the near future too, the world needs to cope up with the ultra-high bandwidth need due to the ever-growing uses of high-capacity hand-held devices. With the entry in the satellite communication network by launching its own satellite, Bangladesh demand of communication bandwidth is growing day by day. Therefore, ISPs and mobile operators need better solution than existing RF and FOC technologies to meet the growing demand [11].

While FOC technology provide very reliable high-speed connection it is very costly in terms of infrastructure and also a challenging to install in difficult terrain. Again, RF system is a matured (more than 100 years old) technology and most-preferred method of communication. Through the increase of its spectrum range (3 KHZ to 300 GHZ) and under a modulation scheme (spread spectrum), the bandwidth and the security of RF have been increased. But its licensed spectrum still cannot cope up with the increased bandwidth demand. It is also a costly option as initial infrastructure investment.

FSO can be a natural fit as a solution against this requirement issue. Due to its operating wavelength (400 nm to 1550 nm), its hardware is small, low cost with fast deployment and very high bandwidth scope. But Bangladesh weather condition is a challenge for FSO performance. The key issues are air impurities (dust and aerosols), atmospheric turbulence, monsoon climate, etc. These attenuate and distort the signal greatly. A typical FSO can operate 2-3 times greater than naked eye capability. Even during clear weather condition, FSO performance is seen to be limited to short range [2]-[4]. The same is true

and applicable in Bangladesh weather condition. However, only few studies have been conducted on FSO performance in Bangladesh weather conditions. This thesis aims to address this gap analytically by examining the recorded atmospheric data, investigating the channel models and analyzing the BER performance of the suggested model. It would lead to improved understanding of FSO system with respect to link reliability prospects and challenges in the local weather condition.

1.7 Motivation of the Research

FSO technology has become a viable means of telecommunication and computer networking in the world side by side with RF and FOC means of communication. Its applications are wide-spread starting from inter-chip nm communication to few meters body network including TV remote control, and short distance point to point communication to several kms long distance communication. It is so ubiquitous that its span covers device, home, PAN, LAN, WAN, back-haul, 5G, B5G, indoor, outdoor, under-water and space communication [4]. Its military applications are also critical considering the fact that the electro-optic sensors compliment radar sensors in short distance surveillance and reconnaissance functions [13].

Growing economy, digital Bangladesh and public dependency on internet are driving the demand for high bandwidth communication and internet in Bangladesh [11]. FSO offers a good solution in this regard due to many unique features of it: high bandwidth, cost effectiveness, rapid deployment, better security, unlicensed spectrum, flexibility, wide applications, etc. As weather conditions heavily degrade FSO performance, it is imperative to determine the impact of local weather conditions, to identify the best possible mitigation techniques, and to recommend the suitable link configuration based on the application requirement. The study would enable developers to assess on the potentials of the FSO system to enhance the communication infrastructure and the internet access across the country in all weather conditions throughout the year.

1.8 Objectives of the research

The specific objectives of the thesis are as follows:

- i. To study the characteristic properties of atmospheric channels under Bangladesh

- weather condition and to review the models expressing their impacts on FSO communication system.
- ii. To analyze the BER performance analysis of FSO communication system based on MPSK-SIM and LPPM under weak to strong atmospheric turbulence and varying pointing errors.
 - iii. To investigate the higher order MPSK-SIM and LPPM FSO communication links in varying rain intensity conditions of Bangladesh.

1.9 Organization of the Thesis

The chapter plan of the thesis is as follows:

- Chapter one: Introduction – it introduces the research background, define the research subject and concept highlighting the applications, problem statement, motivation of the study and the research objectives.
- Chapter two: Literature Review – it presents the literature review focusing on the research gap.
- Chapter three: Methodology – it states and explains the research methodology
- Chapter four: Result and Discussion – this chapter is on the data analysis and the discussion based on the interpretation on the findings
- Chapter five: Conclusion & Recommendation – the last chapter summarizes the findings and presents recommendations for future research works.

1.10 Conclusion

This chapter has amply described the thesis topics and relevant issues highlighting the background of FSO system technology, the definition of FSO and OWC, link configuration and applications of FSO system. The chapter concludes with problem statement, motivation of the study, research objectives and thesis outline.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter reviews the FSO communication related research works and the theoretical studies including books and publications to furnish background information and also to provide the importance of the research work being conducted. It not only finds the gaps in the existing literatures that motivates the study, but also provides foundation of the framework that supports the study. Since FSO communication is heavily affected by environmental factors, whose effects are defined by various impact models, it is important that latest literatures are consulted to review the impact models. The parameters which are important to observe the performance of the models have been extracted from literatures and discussed afterwards. As shown in the figure 2.1, these impact models are applied to compute analytical expression for performance analysis. The study focuses the impact analysis of FSO communication in Bangladesh under its local environment factors. It is important to gain insight into the latest works related Bangladesh environment factors and how they impact the communication. Different models applicable in the study has been discussed to gather operational knowledge in line with the objectives of the study.

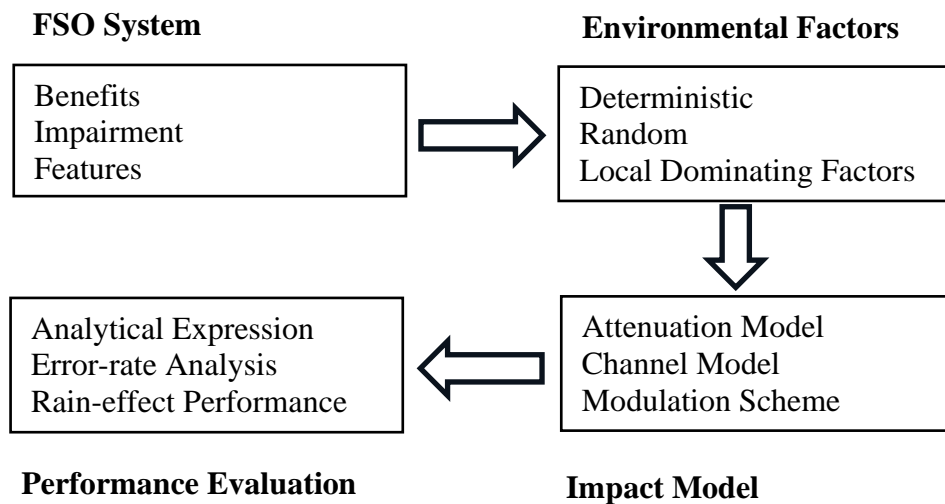


Fig. 2.1: Study Flow Chart.

2.2 FSO Communication

2.2.1 General Features

Optical communication - both FOC and OWC - offers huge bandwidth to meet the current and emerging needs of high data rate applications. It uses IR, visible and UV band (10^{12} – 10^{16} Hz as optical carrier frequency), which offers to accommodate 20% of its carrier band as data bandwidth (an estimate of 2000 THz) [2]. The free space optics – currently operate in NIR wavelengths from 750 to 1600 nm - have particularly addressed the access network bottleneck. Not all wavelength in the NIR bands is very transparent in the atmosphere due to the presence of various kinds of molecules and particles here. As reported at [4], [14] in the FSO band there are several transmission windows in the region of 850, 1060, 1250 and 1550 nm where atmospheric absorption is very low – about 0.2 dB/km. The details have been shown in figure 3.2. Here 850 and 1550 nm windows - also used in FOC system - are very popular for FSO system commercial application. Other wavelengths such as LIR (10 μ m) and UV wavelengths are being investigated for FSO communication application owing to their resistance to environment impairments such as fog attenuation and pointing errors respectively [2].

2.2.2 Applications and Benefits

Details of the applications and benefits are reported in numerous literatures through review of previous works as well as experimental/ simulation works. Few literatures that have presented numerous FSO system applications are referred to this thesis [1]-[4], [8], [10], [14]. Owing to its operating carrier frequency over 300 GHz, FSO system is inherently very light weight and compact compared to RF systems. The band is unlicensed and free making it easier, cheaper and faster for deployment, dismantling and redeployment as small distance high data rate applications. Its beam is very narrow owing to carrier frequency standard and laser technology, and so it is less susceptible to exploitation and electromagnetic interference. It provides one of the best solutions for last mile access network problem. Keeping same modulation scheme, it can offer seamless integration with FOC backbone signal avoiding signal and circuit conversion needs. It has huge bandwidth advantages compared to counterpart RF systems and so it has many scopes of potential applications of high data rate systems.

Other than access network features, the FSO system technology offers many other applications. To name few, in the campus and corporate networks, the FSO systems connect building through inexpensive roof-top setups supporting ultra-high data speeds. The military and public safety applications include video surveillance and monitoring. To allow much higher throughput FSO systems are also being used in cellular networks. As again the system can be easily installed, dismantled and reinstalled, it is being readily deployed temporarily in disaster situation to provide quick and flexible means of data connectivity when local infrastructure remains in damaged condition. Even for broadcasting live events FSO links are being deployed to bridge between camera and broadcasting vehicle from where high-quality transmission is forward to central office through satellite stations.

2.2.3 Impairments and Improvement Factors

The problems of terrestrial outdoor FSO application are very natural: its lower link distance than that of its counter RF applications and also its weather dependency. It experiences link outages in rainy seasons and stormy weather conditions. The path loss can reach about 100 dB/km loss during very heavy rain condition. Again, the value as high as 500 dB/km attenuation loss is reported during heavy maritime foggy condition [15]. These inherent properties pose many challenges, although it is not unique for FSO technologies. The RF and satellite communication also suffer from adverse weather condition. Besides, it is also a LOS communication system with narrow beam width of transmission. Although it offers many advantages, it needs precise alignment and tracking to avoid losses and link-break situation. To counteract the propagation losses, optical power can be increased or modulated signal can be amplified, but it must be limited to within the stipulated safety limit.

There are in practice several improvement factors being applied in the transmission side to counteract environmental losses. This might involve power control scheme, less susceptible wavelength choice, suitable beam shaping, application specific modulation scheme, adaptive optics, etc. The intensity fluctuation on the receiver due to the fading associated with atmospheric turbulence can pose serious limitation on the FSO system performance. Many improvement techniques focus on this fading issue. Such techniques are adaptive

channel coding, diversity techniques, aperture averaging, relay transmission, delayed transmission, adaptive transport control protocol (TCP), etc. [1], [2].

2.3 Environmental Factors

2.3.1 Deterministic Factors

Like radio communication, but unlike FOC, FSO faces environmental challenges that can affect signal strength and quality. The performance and reliability can be significantly influenced by deterministic environmental factors. Some key deterministic environmental factors:

- **Weather:** Rain, snow, fog, and even clouds can block or scatter the light signal, reducing its intensity and increasing the likelihood of data errors.
- **Clear Weather:** Offers optimal conditions with minimal signal attenuation.
- **Rain:** Causes scattering and absorption of the optical signal, leading to power loss. The extent of this attenuation depends on the rain rate and droplet size.
- **Snow:** Similar to rain, snowflakes scatter and absorb light, but the impact varies with flake size and density.
- **Fog:** Highly detrimental to FSO communication due to water droplets in fog scattering and absorbing the optical signal, leading to severe attenuation.
- **Atmospheric Gases:** Certain gases in the atmosphere, like water vapor and carbon dioxide, absorb light at specific wavelengths. This can weaken the signal, especially for longer communication distances.
- **Background radiation:** Sunlight, especially during the day, can act as background noise, interfering with the weaker FSO signal and reducing its effectiveness.

These factors are predictable and measurable. They individually reduce the signal strength by a scaling factor. They can be compensated understanding their modeling with respect to local dominating issues.

2.3.2 Random Factors

FSO transmission is susceptible to various random environmental factors that can disrupt the signal. They are as follows:

- **Temperature:** Temperature fluctuations can cause variations in the refractive index of air, leading to beam bending and misalignment. This can cause the signal to miss the receiver.
- **Wind:** Strong winds can cause the transmitter and receiver to vibrate slightly, introducing jitter into the beam and reducing coupling efficiency.
- **Turbulence:** Air turbulence caused by wind, temperature and pressure variations (causing variation of refractive index) can bend the light beam, causing scintillation (rapid fluctuations in intensity) and ultimately data loss.

The temperature, wind and pressure variation cause signal fading and misalignment. These issues are random in nature and they change quickly and unpredictably, making FSO communication more susceptible to outages compared to FOC and RF signal. The issues are modeled through statistical analysis. Although air particles arising from fast change of local weather factors are sometimes assumed to cause deep fades, but still, they fall within the category of deterministic factors.

2.4 Impact Model

2.4.1 Attenuation Model

As discussed early, weather factors affect FSO transmission of light through atmosphere. There are various attenuation models, particularly power law theory, that quantify the impact of those factors on signal strength. The attenuation model equations have complexity and depend on various factors including particle size, concentration, and the specific wavelength used. Models like the Kim and Kruse model for fog, Marshall-Palmer distribution for rain, ITU-R recommendations for snow, and Mie scattering theory for particulate matter provide frameworks to estimate these effects [4].

2.4.2 Channel Model

This section of the paper has discussed the channel model associated with atmospheric turbulence as well as misalignment problem. First is the channel model for atmospheric turbulence. There are several FSO channel models related to scintillation. Among them the most common channel models are log-normal distribution and gamma-gamma distribution. The log-normal distribution is a widely used model for weak to moderate turbulence. This is generally used for relatively short ranges under weak turbulence. It assumes the received signal intensity follows a log-normal distribution. Experimental data shows this model does not work for longer ranges under moderate to strong turbulence condition. The Gamma-Gamma (GG) distribution model offers more flexibility and can represent a wider range of turbulence conditions compared to the log-normal model. This model is called a universal model on atmospheric attenuation. It involves two gamma-distributed variables to describe the fading process. This paper has used the GG model in defining its analytical model expressions. There are many other models as variants of the above models that have been proposed as per different environments [1]-[4]. There are many variations of the above models presented to suit the requirement of specific environment to better fit the experimental data. These have not been discussed here as they are out of scope of the thesis work.

Misalignment is another significant random factor affecting the performance of FSO communication systems. Accurate modeling of misalignment involves understanding geometric losses, beam divergence, and the statistical nature of pointing errors. Many studies were conducted on statistical modeling of pointing errors which follow an independent Gaussian distribution for elevation and for horizontal direction, and Rayleigh distribution for radial direction. The combined effect of misalignment and turbulence have been studied in several works [16], [17]. In [16] it is proposed to model the random attenuation of the channel as the product of path loss, geometric spread, pointing errors and atmospheric turbulence. The current thesis follows the same approach for FSO system performance investigation.

2.4.3 Modulation Schemes Application for FSO System

The main three types of intensity modulation (IM) schemes applied for FSO signals are on-off keying (OOK), subcarrier intensity modulation (SIM) and pulse modulation (figure 2.2)

[5]. Among them the simplest and easiest one is OOK. But OOK needs dynamic threshold for detection due to fading effect or maximum likelihood detection can be applied for detection of individual pulse. It has relatively poor energy efficiency (EE) and spectral efficiency (SE).

Other modulation schemes are applied to avoid disadvantages. Particularly PPM, to increase energy efficiency (EE), employs position within the symbol duration for modulating the signal under consideration. Under the constraints of peak and average power, it can attain bandwidth capacity nearly close to maximum channel capacity. Because of its high EE, PPM is better suited for deep space communication. There are many variants of PPM namely multi-pulse PPM, PWM, DPIM, DPPM, OPPM, etc. In PPM and PWM, the inputs are mapped into a fixed duration symbol and hence they require slot and symbol-level synchronization. Here comes the complexity of the receiver circuitry. Because of such synchronization requirement, these modulation schemes (PPM and PWM) are called synchronous modulation.

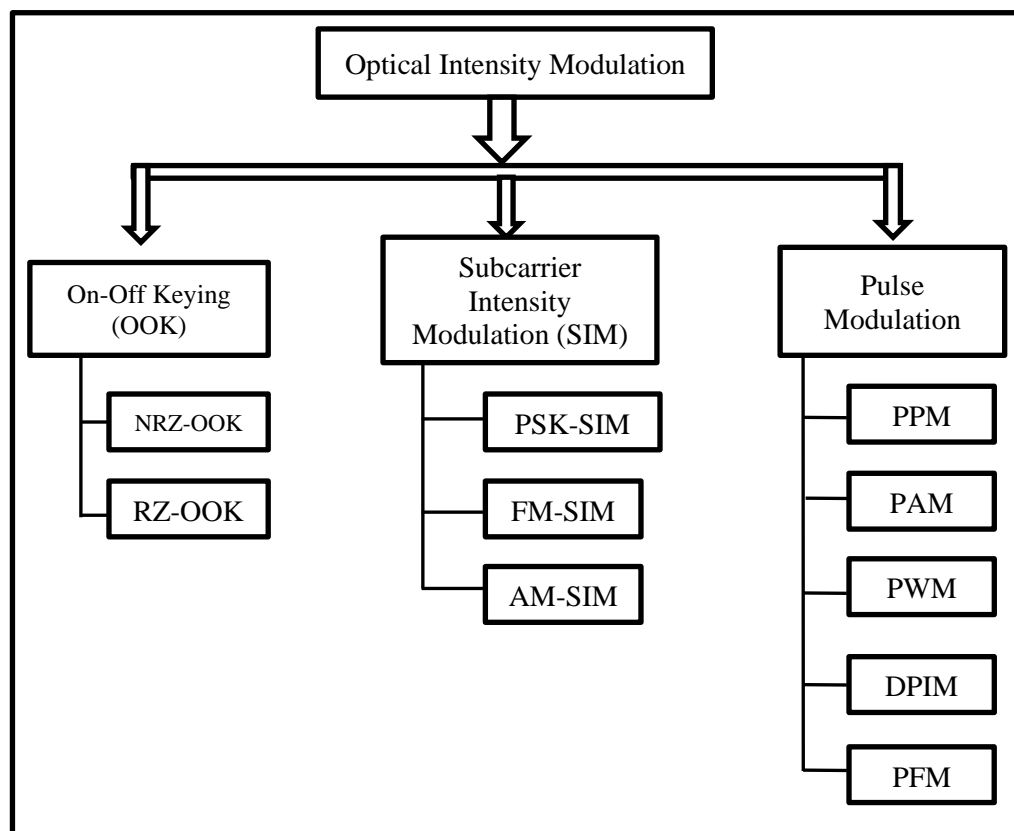


Fig. 2.2: Basic Modulation Schemes of FSO Links (adopted from [5]).

With the ASK, PSK and FSK based SIM scheme, the ultra-high data can be accommodated using multiple channels. The MPSK based multi-SIM (MSIM) schemes consist of several SIM channels (each is a RF sub-carrier modulated by user baseband data) combined together to intensity modulate the optical source carrier. The immediate advantage is huge capacity improvement and cost-effective implementation. It can easily cope up with FOC network signal carriers as because of similar signal format used making it almost a seamless connection. However, it has poor energy efficiency due to the requirement that a DC bias needs to be applied to the combined SIM signal before optical intensity modulation [1].

2.5 Performance Evaluation

The performance evaluation of FSO communication system is done following system concept. A FSO receiver is assumed with certain beam shape and configuration. The initial input to the system is beam wander, beam shape, Angle of Arrival (AOA), multiple receivers, etc. Another important input is the scintillation index (low, media or high). The channel is random (stochastically dynamic) due to the factors like atmospheric turbulence and misalignment. The FSO communication signal after passing through absorbent atmosphere and losing strength undergoes complex temporal and spatial changes before arrival in the receiver. Following the impacts of complex processes and changes the system performance is evaluated in terms of SNR, BER, outage probability, etc. This can be done analytically deriving equation or analytical expression and solving it for an average condition. Again, the performance evaluation can be done through input to and analysis of software application-based simulation. For Bangladesh weather condition, the dominant factors need to be considered in the analytical expression and various input-output parameters need to be evaluated for performance investigation.

2.6 Analysis of Previous Studies on FSO Communication System

The thesis however has analytically investigated the BER performance of LPPM and SIM-MPSK based FSO link with GG distribution model in Bangladesh environment. The analytical derivation in a closed form expression has been achieved using Meijer G function [18]. The study area has been so chosen due to the fact that there remains a scope of study in Bangladesh environment to assess FSO communication performance in respect of multiple factors like environment, application, technology, modulation, improvement, etc.

Because of its inherent high data rate, easy installation, and advancement of optoelectronics technology, FSO has the potentiality of widespread use including indoor, outdoor and space applications [1]. Particularly, it has promised to solve the access network bottleneck. According to [2]-[4] FSO system has become an essential element of IoT connectivity, back-haul links, 5G with ultra-dense Hetnets and B5G cellular communication system. It has the potentiality to offload heavy data traffic from RF network through the application of hybrid RF/FSO and also RoFSO mixed links.

Weather and environment pose huge challenges making FSO link reliability in question [1], [4]. Under link budget design, the received optical power can be easily estimated in a FOC although, it is very unpredictable and complex in air because of the spatial distribution of FSO channel, inhomogeneity in pressure and temperature of the atmospheric layers and atmospheric fluctuations. Since optical propagation through air is severely affected by atmospheric conditions, resulting in signal loss or phase shifting/fluctuations of signal intensity, thereby limiting the performance as well as link availability. Among the visibility factors like rain, fog, haze, media particles, etc. the rain effect is more prominent in Bangladesh weather specially during monsoon period [11], [19]. However, under the presence of dense fog (when visibility is below 50m), the signal losses can be as high as 400 dB/km or even more [20]. High power laser exploiting the third transmission window may partly address the link availability issue. Again, the heavy or very heavy rain droplets lead to higher attenuation loss. As per [19], the heavy rain (7.6 to 50 mm/hr) incur attenuation of ten times than the light rain droplets (below 2.5 mm/hr) ranging from 1 dB/km to 10 dB/km for 1500 nm wavelength. The signal loss (due to very heavy rain) of 30dB or more has been reported. Snow condition effect lies between the fog and rain effects.

Atmospheric turbulence causes beam wandering when the size of induced eddies with different refractive indices becomes more than beam radius. On the other hand, when the size becomes comparable with the beam dimension, the eddies cause tempo-spatial irradiance fluctuation, also called scintillation, at the receiver. The variation of refractive index and multiple scattering along the propagation path results in phase and intensity fluctuations of the received optical signal. The effect of scintillation induced by temperature and spatial fluctuations of light intensity lessen the FSO link performance even under clear weather [5]. Turbulent cells also degrade wavefront coherence causing signal loss. Again,

misalignment problem between the transmitter and receiver causes beam wandering, which is more prominent in high wind situation. Although cloud is not an issue for terrestrial FSO, but may partially block satellite uplink or downlink communication. Other air-borne particles like carbon due to fossil fuel burning domestic or industrial, greater level of water particles due to high humidity and other impurities, and their sudden appearance also lessen the wavefront coherence quality resulting in signal loss and fading in worst condition [21].

Many studies have been conducted for a long while to investigate the performance turbulent FSO links under many weather conditions affecting the performance. Particularly several statistical models have been proposed to characterize the fading of optical signal under turbulence where G-G model (including many of its variants) works under all types of turbulence and provides better result [1], [4], [6]. The study of ergodic capacity of the channel has been conducted for the cases of Gamma-Gamma, Rayleigh, Nakagami-m, Malaga, Rician and log-normal fading taken into consideration of AWGN receiver noise. Again, outage probability, BER analysis and throughput performance have also been intensely studied under the same fading models with mitigation techniques. For example, [22] proposes a jointly adaptive transmission and power control schemes assuming Gamma-Gamma turbulence channels aiming to achieve target BER and outage probability. The visibility factor effects including the rain attenuation are computed by several power law theories or some numerical model based on power law [7]-[10].

Many researches are being conducted to examine application specific modulation-based FSO links (with or without improvement schemes) with better performance under atmospheric uncertainty and fluctuations. The traditional single carrier based OOK and PPM schemes have their simplicity, but with their own drawbacks [4] like low SE and EE, unreliability during extreme channel impairments, and adaptive threshold detection (for OOK), synchronous detection (for PPM), etc. Also due to high Inter-symbol interference (ISI) they are not suitable for high data rate application. Many PPM variants like multi-pulse PPM (MPPM), PWM, DPIM, OPPM, DPPM, DPIWM, etc. have been suggested with their pros and cons [23]. To improve both SE and EE compared to binary modulation, several multi-level modulation schemes with or without multi-carrier SIM (MCSIM) based OFDM have been proposed like MPAM, MPSK, MQAM, MQPPM, etc. including their variations like DPSK and carrier-less amplitude and phase (CAP) modulation [1]-[4]. Improvement of link reliability by means of innovative, adaptive modulation scheme

including hybrid modulation are being investigated within a specific link configuration for example spectrum slicing (SS)-WDM [24], baseband-passband combination like PPM_QAM [25], PolSK-QPSK [26], PDM-BPSK-WDM [27], RF-PPM based hybrid SIM [28], etc.

Table 2.1: Key Literatures on region specific FSO link performance

Study Year	Study Area	Model/ Methodology	Observation
[20] 2002- 2005	211 EU airports for 4-year periods	a. Commercial FSO link of 850 nm waveband was used across the airports to generate visibility records at 100m interval with sampling period of 15 min to one hour b. The objective was to investigate the impact of fades on the link reliability.	The outage probability due to long fades (due to precipitation like fog, rain, snow) and short fades (due to atmospheric attenuation) was found to be 0.1-1% that is one or two day per year (at link margin 80 dB/km). Maximum loss was found to 130 dB/km. Such rate of link unavailability is acceptable.
[21] 2011	Malaysia	a. Rain attention Model b. Experimental measurement	The work involves comparison between prediction output of rain attenuation model and actual measurement on ground. Prediction models used are Carbonneau, Japan, Marshal- Palmer and Joss model. Malaysia usually experiences heavy rainfall and FSO communication faces heavy attention. No model output matches the actual measurement. The former two models overestimate the actual loss and the latter two underestimate the same. However, error-limit for Carbonneau model is less than that of Japan model.
[30] 2012	Malaysia	a. Simulation software optical system version 7 has considered geometric loss, Transmission-Reception loss, atmospheric attenuation for heavy rain condition of the area b. The link is 16 channel WDM at 1550 nm wavelength with 100 GHz channel spacing	The simulation result shows the system can support 2.5 Gbps at 2.4 km distance. WDM FSO system has capability to accommodate the channels more than 16. By introducing the error correction code or balance detection, the transmission distance might be increased further.

[20] 2014 during winter period	Sudarban Forest Area of India and Bangladesh	<p>a. Aerosol Optical Depth (AOD) measurement at a remote island near Sundarban forest using sun-photometer instruments</p> <p>b. A campaign to address fog-induced changes in optical and physical properties of aerosols transported from urban area of Kolkata and Dhaka</p>	<p>AOD was found to be increased by a factor of three during foggy condition and black carbon (BC) mass increased by 30%. The trapping of increased BC plumes transported from urban/ industrial zone under high RH and calm conditions can have serious effects in solar dimming, radiative forcing and atmospheric heating due to significant absorption of solar radiation.</p> <p>The foggy condition along-with BC trapping will be very detrimental to FSO link performance.</p>
[31] 2016	Pakistan	<p>a. Present a methodology to estimate rain attenuation at short FSO link (500m). This model takes account of drop size distribution and requires as input the local mean yearly accumulated rain.</p> <p>b. The method is applied to estimate rain attenuation in the city of Hyderabad, Pakistan</p>	<p>The study proposes a method to find a rain rate PDF with 1-minute integration time interval from average annual rainfall data of a place and some information of global database. It also proposes a link margin required for a particular locality to compensate rain attenuation for a short FSO link.</p> <p>The result can be applied to long range FSO with unequal rain rate, and hence attenuation rate along the path instead of assuming a fixed value. This can be applied to Bangladesh case for short range FSO.</p>
[32] 2016	Bangladesh	<p>a. Kim & Kurse model for visibility condition prediction</p> <p>b. Optisim 13 app software</p>	<p>The visibility parameters for different weather condition of Bangladesh, particularly rainy condition is given as input to Optisim 13. Based on input, the system provides output as eye diagram analyzer and optical power meter. The study is mainly based on software simulation.</p>
[24] 2016	Changsha, China	<p>a. Analysis of spectrum slicing (SS) WDM based FSO link performance for rain heavy environment of the area for data rate upto 1.56 Gbps at 1550 nm wavelength. The 4-channel SS-WDM with each channel modulated with OOK signal. The link is investigated upto 3 km.</p> <p>b. Optisystem 7 based simulation and performance assessment with</p>	<p>The SS-WDM FSO link shows marked improvement over WDM FSO link. Its adaptive and scalable network architecture supports high bandwidth and wide coverage even under heavy rain weather.</p>

optical power meter, BER analyser
and eye-diagram

[33] 2017	India	<p>a. Analysis of spectrum slicing (SS) WDM based FSO link performance under Vellore weather condition.</p> <p>b. Experimental FSO link setup at urban area to assess the performance in height and wind speed variation</p>	<p>SS-WDM FSO provides better performance than WDM FSO system in terms of BER vs link distance. Again 16 channel SS-WDM system performs better than 4- and 8-channel system. Increase of windspeed and increase of building heights also adversely affects FSO links. Also forest area experiences more turbulence than urban area due to higher evaporation rate.</p>
[19] 2018	Bangladesh	<p>a. Kim attenuation model</p> <p>b. BMD rain data</p> <p>c. Optisim app software for BER vs link distance prediction</p>	<p>The work provides optisim software-based performance prediction as BER vs link distance. The high order modulation (16 - QAM) based channel link shows better performance under 4X4 multiple transceiver system. The work is of software simulation outcome.</p>
[34] 2019	Bangladesh	<p>a. BMD data on visibility, rain and wind speed of 7 cities</p> <p>b. The corresponding attenuation data due to rain and turbulence condition of the selected cities.</p>	<p>The study used power law equation for rain attenuation calculation, and empirical equation for turbulence related attenuation loss calculation. This is simply a graphical and tabular presentation based on BMD data. This is a very simple paper.</p>
[35] 2009	Poland	<p>An experimental FSO link with 830 nm wavelength was set up to operate on a 100m-long path in Prague.</p>	<p>The visibility and attenuation were measured during fog events and compared with the standard models like Kurse, Kim, Alnaboulsi_advection and Alnaboulsi_convection. These models slightly underestimate the fog attenuation for visibility less than 1 km.</p>
[27] 2024	Bangladesh	<p>a. G-G model and visibility factor attenuation model</p> <p>b. Optisim 17 app software</p> <p>c. 16 channel hybrid PDM-WDM, each channel with 40 Gps QPSK optical data</p>	<p>The study compares the performance of single channel (traditional model) vs proposed 16 channel hybrid model. It has designed the full optical circuit which has given graphical output such as optical power spectrum, Q factor eye-diagram and BER vs link distance performance curve. The study concludes proposed model provide better throughput and SE at 3 km link distance with</p>

Like RF communication system, FSO communication by now has turned into matured field of study and innovation. However, researchers are still conducting studies on its improvement factors for modern applications. Considering the above analyses, it is evident that contemporary studies on FSO system still now focus on link performance under suitable combination of channel model, modulation scheme, mitigation techniques and link configuration (simple FSO link, hybrid RF/FSO link, mixed RF-FSO link, FSO link with suitable relays). However, there remains a clear gap on the analytical study of FSO link performance under Bangladesh environmental condition as very few studies were conducted on FSO link performance under Bangladesh weather conditions. However, most of those studies conducted were of simple studies based on the solution of power law equations or related empirical expressions and OptiSim software application without analytical model analysis [19], [27], [32], [34]. Many FSO works focus on experimental and real-system measurement and compare the results with empirical expressions results [20], [21], [29], [33], [35]. These are explained in the table 2.1. This paper addresses this gap analytically by proposing to model the random attenuation of the FSO channel under Bangladesh environment as a product of path loss, geometric spread, pointing error and atmospheric attenuation with a particular focus on the impact of rain like the work [16], [17].

2.7 Conclusion

This chapter has covered various aspects of FSO communication in general and Bangladesh environment in specific through wide review of literatures old and latest. Finally, it has carried out a brief analysis of the contemporary studies and explained the literature gap, on which the current study is founded. A number of literatures particularly focusing on ground experiments and on-field measurement under Bangladesh and other regions based have been analyzed through a tabular presentation. Although initial discussion seems a brief background, however it has been covered through evidences and theories extracted from literatures.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter explains the mathematical expressions, computational methods or analytical models used to examine the performance of FSO system in Bangladesh. This includes attenuation models used to estimate the impact of deterministic factors, the statistical model used to quantify the impact of random factors, the specific modulation based BER performance mathematical model, combined impact channel models, etc. The necessary local weather data (rain) is listed and analyzed here for input into the overall impact model. MATLAB software has been used to generate performance results and curves, which have been shown in the next chapter of this thesis.

3.2 Specific Location based Rain Data

To examine the performance of FSO system in Bangladesh weather condition, the rain and wind data specific to certain locations have been collected from Bangladesh Meteorological Department (BMD). Total 14 locations along the coastal lines from Mongla to Teknaf area, and one inland point Dhaka were selected for rain data considering the fact that coastal locations are more prone to wind and rain, and the optical surveillance functions of ships and crafts are mostly conducted here. Besides, the rain data on monthly basis (from 1983 to 2017) for several locations of Bangladesh including several island points have been collected from BMD. The data and information obtained from BMD as per above have been analysed to understand the season-wise rain patterns under Bangladesh weather conditions in addition to finding the rain related attenuation using power law equations. These are amply covered in the result and discussion chapter.

3.3 FSO Channel Characteristics

The channel characteristic covers deterministic and statistical factors, their impact characteristics, and their computational models. Combined all factors into a single entity generates the channel statistical models. The impact factors which are prominent and which have been considered according to the objectives of the thesis are mainly focused here.

3.3.1 System Model

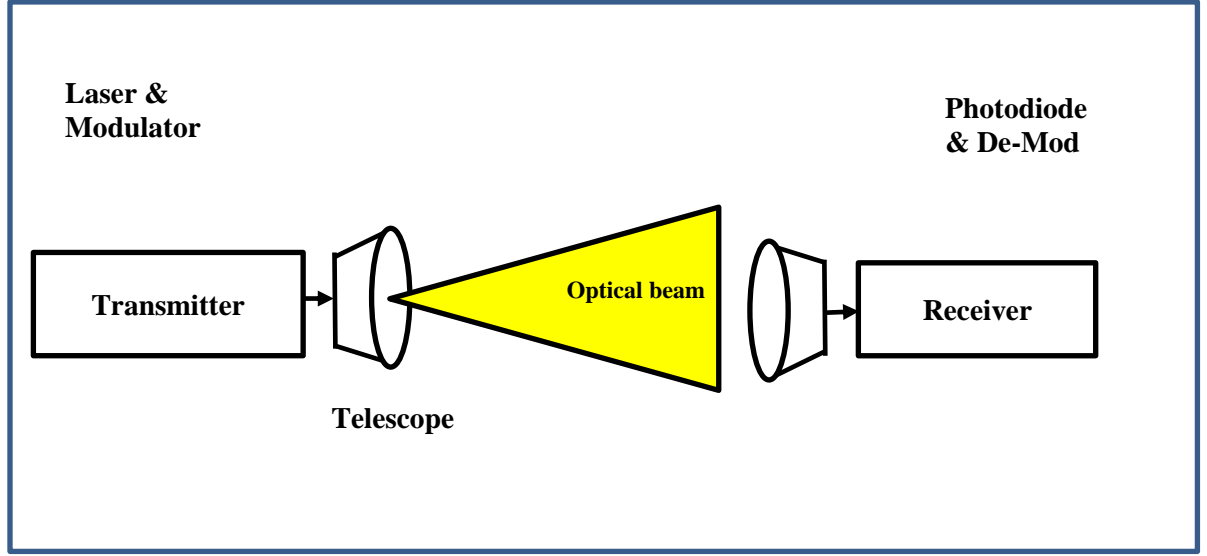


Fig. 3.1: Block Diagram of a Basic FSO System.

As per figure 3.1, optical signal of transmitter after traversing the intended distance is received by the receiver and converted into photocurrent. The photocurrent y at the receiver is related to the incident photon power or intensity due to transmitted signal x modified by channel state and the receiver responsivity R :

$$y = hRx + n \quad (3.1)$$

where n is the signal independent additive-white noise with Gaussian variance σ_n^2 and h is the channel state defined by [36]:

$$h = h_l h_p h_a \quad (3.2)$$

Here h models the random attenuation of the propagating media and it depends on three factors as above: the path loss h_l , geometrical spread with pointing misalignment h_p and atmospheric turbulence h_a . The latter two factors are random while the former one is deterministic.

The received electrical signal to noise ratio is [5]:

$$SNR(h) = \frac{(RhP_t)^2}{\sigma_n^2} \quad (3.3)$$

Here, P_t is the transmitted signal and σ_n^2 is the variance of the channel noise.

Table 3.1: Weather condition and association particle (adopted from [37])

Condition	Particle Type	Radius (μm)	Concentration (Cm^3)
Air	Molecule	10^{-4}	10^{19}
Haze	Aerosol	$10^{-2} - 1$	$10^3 - 10$
Fog	Water Droplet	$1 - 10$	$100 - 10$
Cloud	Water Droplet	$1 - 10$	$300 - 10$
Rain	Water Droplet	$10^2 - 10^4$	$10^{-2} - 10^{-5}$

3.3.2 Atmospheric Attenuation

Fog, rain, dust, snow, smoke, and other aerosol particulate matters are the primary cause of atmospheric attenuation accounting for h_1 . Photon absorption by gas molecules is wavelength dependent. The individual absorption lines (figure 3.2) are caused by the vibrational-rotational absorption lines of water vapor, CO_2 , CH_4 , and other gases in the atmosphere [11]. Scattering of signal by air particles also causes attenuation including the beam spreading and increased BER (figure 3.3). The scattering mechanism is dependent on the ratio of particle size to radiation wavelength. The size of the various scatterers that affect FSO communication is as shown here (table 3.1). There are three types of scattering: Rayleigh, Mie and non-selective [1], [4].

Rayleigh scattering is negligible in IR waveband. It occurs when particle (air molecules) size is much smaller than operating wavelength. It is strongest at shorter wavelengths (blue light). Mie scattering occurs when the scatterer size is equal or more than the operating wavelength (dust, fog droplets). It is a major cause of signal attenuation in hazy or foggy days. On the other hand, non-selective scattering occurs when particle size is much larger than operating wavelength (rain droplets, large dust particles). The last two factors heavily attenuate the signal in the entire FSO spectrums. Considering atmospheric transmittance windows (figure 3.2), laser sources available for FSO communications are in the spectral range close to wavelength 785 nm, 830 nm, 1084 nm and 1550 nm [7].

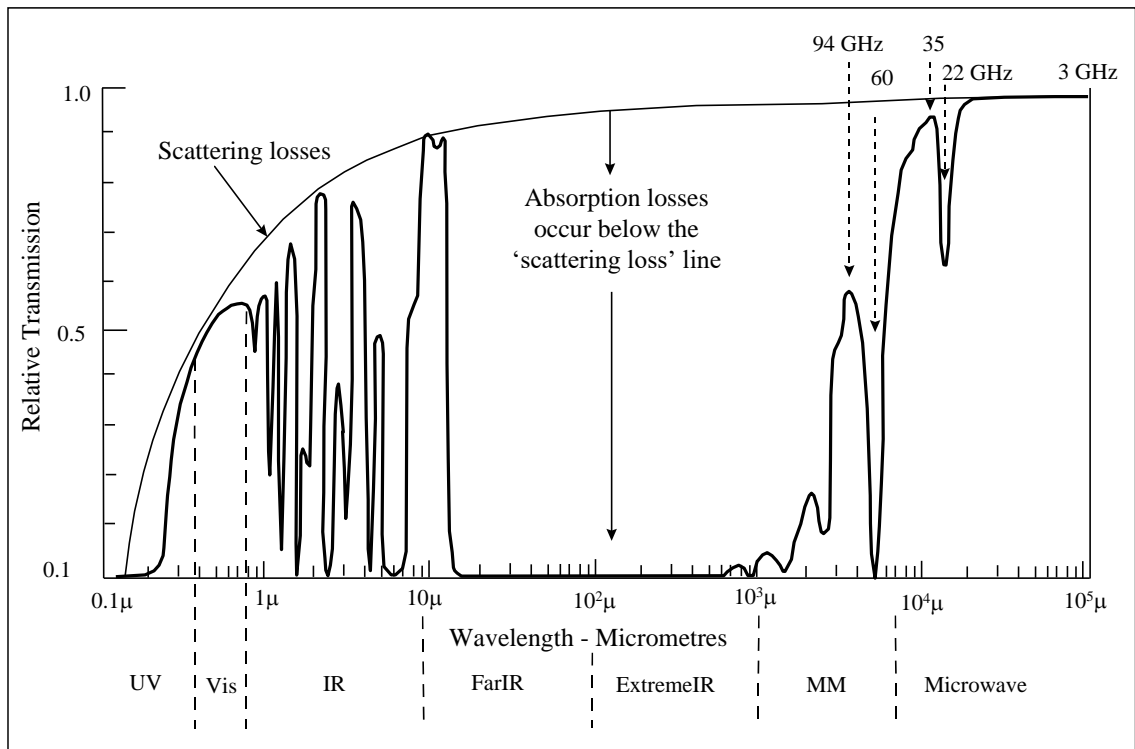


Fig. 3.2: Atmospheric transmittance at sea level along 1820 m path (adapted from [12])

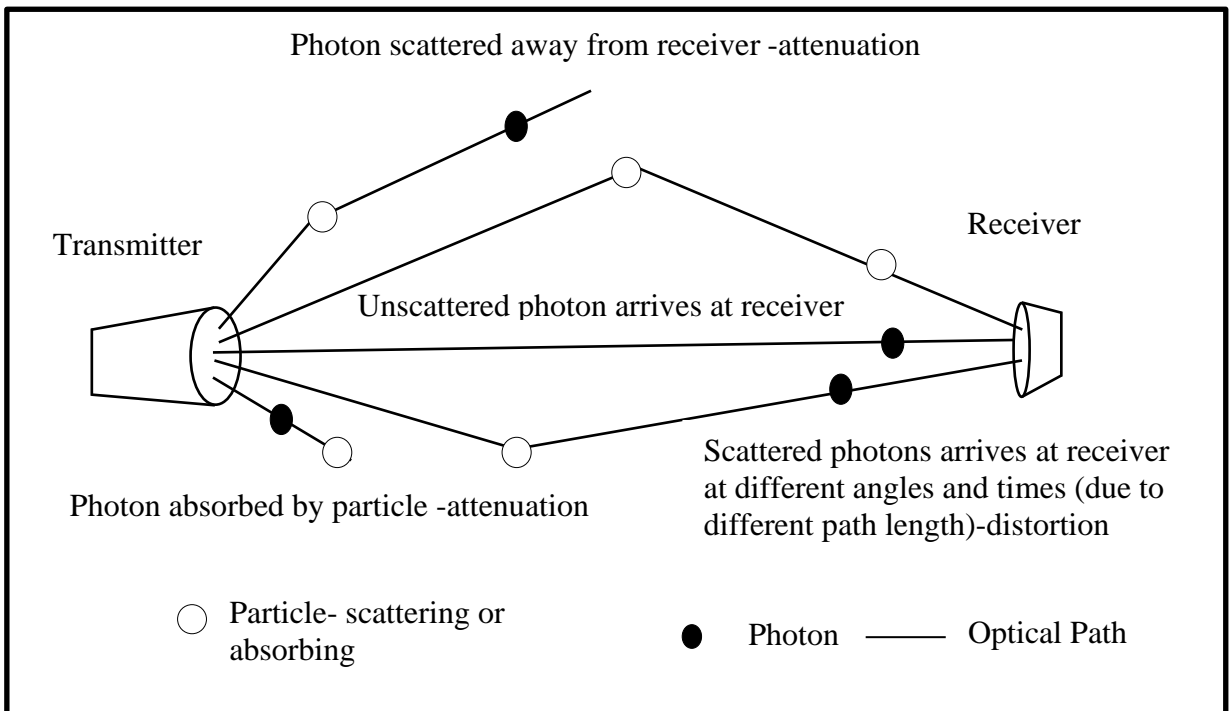


Fig. 3.3: A Schematic Illustration of Multiple Scattering and Absorption [10].

3.3.3 Rain

Rain attenuation in FSO communication is severe and it usually happens during monsoon season in Bangladesh. Although fog attenuation can be more severe than rain attenuation, but its geographical extent and duration is far less than that of rain in Bangladesh. Again, both issues appear as a scaling factor in BER expression.

3.3.3.1 Power Law based Rain Attenuation Model

Rain attenuation (dB/km) is represented by power law [29]:

$$A = kR^\alpha \quad (3.4)$$

where, R is the rain rate in mm/hr, k and α are power law parameters.

Two empirical rain attenuation models worth mentionable here are Carbonneau and Japan model [28] as per table 3.2.

Table 3.2: Rain attenuation model recommended by ITU-R [29]

Model	Origin	Author	K	α	Note
Carbonneau	France	ITU-R[17]	1.076	0.67	Temperate region
Japan	Japan	ITU-R[17]	1.58	0.63	Temperate region

3.3.3.2 Drop Size Distribution based Rain Attenuation Model

Again, values of the constant (k and α) of Marshal-palmer and Joss distributions are developed by considering measured drop size distribution (table 3.3). There are big differences on the values of k of these four models discussed.

Table 3.3: Other Rain Attenuation Model [29]

Attenuation	Relation
Drizzle or light rain (Joss) ($R < 3.8$ mm/hr)	$0.509 R^{0.63}$
Main rain (Joss) (3.8 mm/hr $< R < 7.6$ mm/hr)	$0.319 R^{0.63}$
Strong rain (Joss) ($R > 7.6$ mm/hr)	$0.163 R^{0.63}$
Rain (Marshal and Palmer)	$0.365 R^{0.63}$

However, the considering the fact that due to raindrop size (100-1000 μm) being significantly larger than the FSO operating wavelength and hence the non-selective scattering of rainfall, the rain scattering coefficient can be calculated using Stroke Law [10]:

$$\beta_{rain\ scatt} = \pi r^2 N_r Q_{scat} \left(\frac{r}{\lambda}\right) \quad (3.5)$$

Here, r is the radius of raindrop in cm, N_r is the rain drop distribution in cm^{-3} and Q_{scat} is the scattering efficiency. The raindrop distribution N_r can be calculated by using the following equation:

$$N_r = \frac{R}{1.33(\pi r^3) V_L} \quad (3.6)$$

Where, R is the rainfall rate (cm/sec); and V_L is the limiting speed of raindrop which is given by

$$V_L = \frac{2r^2 \rho g}{9\eta} \quad (3.7)$$

Here, r is the radius of the raindrop, ρ is the density of raindrop, g is the acceleration due to gravity and η is the dynamic viscosity of air.

Therefore, the rain attenuation using the value as table 3.4 for link distance, D (in km) can be calculated by using Beer's law as given (equation 3.8). Based on this data and the expressions, the rain attenuation computed at Bangladesh pre-monsoon, monsoon and post-monsoon are at 6.5, 23 and 3 dB/km respectively [19].

$$\tau = \exp^{-\beta_{rain\ scatt} D} \quad (3.8)$$

Table 3.4: Raindrop Parameter of Bangladesh Weather Condition [19]

Parameter	Value
Gravitational Constant, g	980 cm/s^2
Viscosity of air, η	1.8×10^{-4} (g/cm)
Radius of raindrop, r	0.05 cm (local measurement)
Water density, ρ	1 g/cm^3
Wavelength, λ	1550 nm
Q_{scat}	2 (local factor)

3.3.4 Fog

Outdoor FSO are mostly affected by the fog droplets with Mie scattering phenomenon. The scattering coefficient β_a is expressed as [2]:

$$\beta_a = \left(\frac{3.912}{V}\right) \left(\frac{\lambda}{550 \text{ nm}}\right)^{-p} \quad (3.9)$$

Where, V is the visibility in km, λ is the incident laser beam wavelength in nm and p is the size parameter of the scattering particles which varies from 0.7 to 1.6 corresponding to visibility conditions from poor to excellent (table 3.5). With visibility data of BMD, [19] finds that attenuation due to light, moderate and heavy fog condition of Bangladesh environment are at 12.5, 34 and 85 dB/km respectively. The corresponding visibility was 0.9, 0.5 and 0.2 km respectively [19].

Table 3.5: Size parameter at different Visibility Range (Kim Model)

Scattering size parameter, p	Visibility Range (km)
1.6	$V > 50$
1.3	$6 < V < 50$
$0.16V + 0.34$	$1 < V < 6$
$V - 0.5$	$0.5 < V < 1$
0	$V < 0.5$

3.3.5 Atmospheric Turbulence

Atmospheric turbulence causes signal variation due to inhomogeneity in the temperature, pressure and wind variation resulting in the refraction index fluctuation [5]. Even during clear sky, it may become a dominant factor. The turbulence eddies as shown graphically in figure 3.4 results in the random interference pattern and wave front distortion along propagation path. The gamma-gamma distribution model is used to describe PDF of the irradiance intensity [5]:

$$f_{h_a}(h_a) = h_a \frac{2(\alpha\beta)^{\frac{(\alpha+\beta)}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_a^{\frac{\alpha+\beta}{2}-1} K_{(\alpha-\beta)}(2\sqrt{\alpha\beta h_a}) \quad (3.10)$$

Here $\Gamma(\cdot)$ is the Gamma function, $K_{\alpha-\beta}(\cdot)$ is the modified Bessel function of the second kind, h_a is the atmospheric turbulence, α and β are the variances of the small- and large-scale eddies respectively defined by equation (3.11) and (3.12):

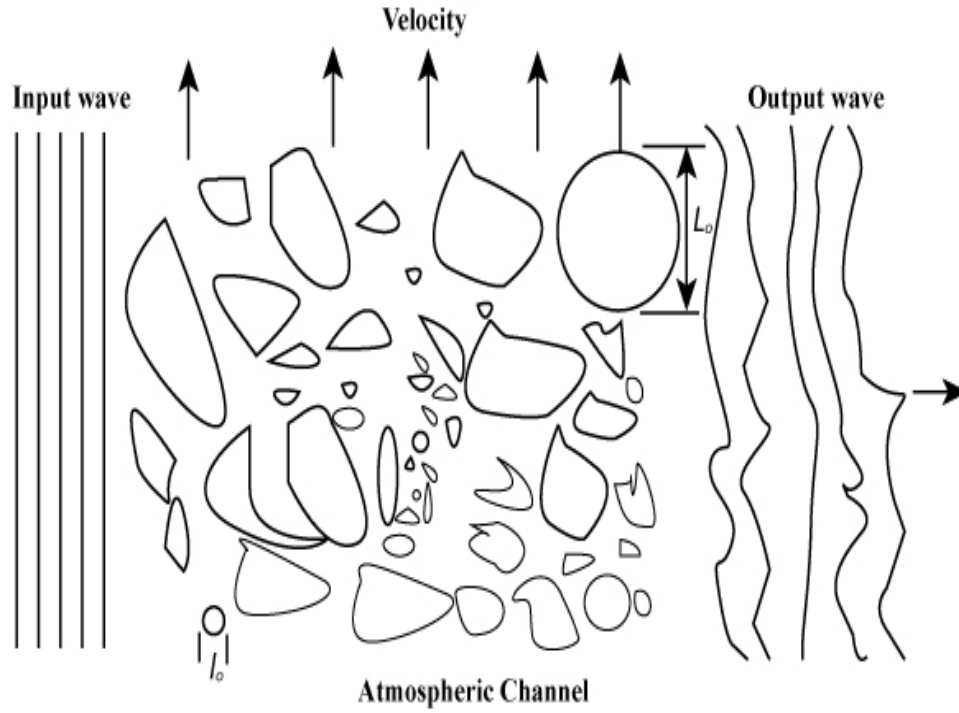


Fig. 3.4: Atmospheric channel with turbulent eddies (adopted from [5]).

$$\alpha = \left[\exp \left(\frac{0.49\sigma_R^2}{\left(1 + 1.1\sigma_R^{\frac{12}{5}}\right)^{7/6}} \right) - 1 \right]^{-1} \quad (3.11)$$

$$\beta = \left[\exp \left(\frac{0.51\sigma_R^2}{\left(1 + 0.69\sigma_R^{\frac{12}{5}}\right)^{5/6}} \right) - 1 \right]^{-1} \quad (3.12)$$

Where the Rytov variance is: $\sigma_R^2 = 1.23 C_n^2 k^{\frac{7}{6}} Z^{\frac{11}{6}}$, $K = 2\pi/\lambda$ is the wave number, Z is the link distance. Here C_n^2 , the refractive index structure parameter, determines the turbulent strength. It clearly depends on location, altitude, and time. There are several parametric

models formulated to describe the C_n^2 profile. One commonly used model is Hufnagel-Valley model as follows [19]:

$$C_n^2(h) = 0.0059 \left(\frac{v}{27}\right)^2 (10^{-5}h)^{10} \exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16} \exp\left(-\frac{h}{1500}\right) + T_o \exp\left(-\frac{h}{100}\right) \quad (3.13)$$

where, h is the altitude in meter, v is the wind speed at high altitude in m/s and T_o is the turbulence strength at the ground level, $T_o = 1.7 \times 10^{-14} m^{-2/3}$. Considering the value of altitude and wind, C_n^2 is calculated to vary between 1.15×10^{-14} to $1.7 \times 10^{-14} m^{-2/3}$ in Bangladesh weather [18]. At the change from moderate to strong turbulence condition under Bangladesh weather condition, BER deteriorates by 9 times from the order of 10^{-3} to the order of 10^{-2} [19].

3.3.6 Geometric Spread and Pointing Error

In LOS FSO communication links, pointing accuracy is an important issue in determining link performance and reliability. However, wind loads and thermal expansions result in random building sways, which, in turn, cause pointing errors and signal fading at the receiver [1]. In this section, a statistical model has been utilized for pointing error loss due to misalignment, which considers detector aperture size, beam width, and jitter variance [10], [16], [17], [36]. For a Gaussian beam, the normalized spatial distribution of the transmitted intensity at a distance z from the transmitter is given by:

$$I_{beam}(\rho; z) = \frac{2}{\pi w_z^2} \exp\left(-\frac{2\|\rho\|^2}{w_z^2}\right) \quad (3.14)$$

where ρ is the radial vector from the beam centre, and w_z is the beam waist (radius calculated at $\exp(-2)$) at distance z . The beam waist w_z of a Gaussian beam propagating in atmospheric turbulence can be approximated as [27]

$$w_z \approx w_0 \left[1 + \varepsilon \left(\frac{\lambda z}{\pi w_0^2}\right)^2\right]^{\frac{1}{2}} \quad (3.15)$$

Where w_0 is the beam waist at $z = 0$, $\varepsilon = (1 + 2w_0^2/\rho_o^2(z))$, and $\rho_o(z) = (0.55C_n^2 k^2 z)^{-3/5}$ is the coherence length, C_n^2 is the refractive index structure constant which quantifies the strength of atmospheric turbulence and k is the wavenumber of the beam. Consider a circular

detection aperture of radius a and a Gaussian beam profile at the receiver I_{beam} as shown in Fig. 3.5.

The attenuation due to geometric spread with pointing error r is expressed as,

$$h_p(r; z) = \int_A I_{beam}(\rho - r; z) d\rho \quad (3.16)$$

Where $h_p(\cdot)$ represents the fraction of the power collected by the detector, and A is the detector area. When a pointing error of r is present, h_p is a function of the radial displacement and angle. Due to the symmetry of the beam shape and the detector area, the resultant $h_p(r; z)$ depends only on the radial distance $r = \|r\|$. Therefore, without loss of generality, we can assume that the radial distance is located along the x' -axis. The fraction of the collected power at a receiver of radius a in the transverse plane of the incident wave can be expressed as,

$$h_p(r; z) = \int_{-a}^a \int_{-\zeta}^{\zeta} \frac{2}{\pi w_z^2} \exp\left(-2 \frac{(x'-r)^2 + y'^2}{w_z^2}\right) dy' dx' \quad (3.17)$$

Where, $\zeta = \sqrt{(a^2 - x'^2)}$. This integration can be approximated as the Gaussian form,

$$h_p(r; z) \approx A_0 \exp\left(-\frac{2r^2}{w_{zeq}^2}\right) \quad (3.18)$$

Where $v = \sqrt{\pi} a / \sqrt{2} w_z$ and

$$A_0 = [\text{erf}(v)]^2 \quad (3.19)$$

$$w_{zeq}^2 = w_z^2 \frac{\sqrt{\pi} \text{erf}(v)}{2v \exp(-v^2)} \quad (3.20)$$

Here A_0 is the fraction of the collected power at $r = 0$, and w_{zeq} is the equivalent beam width. Independent identical Gaussian distributions for the elevation and the horizontal displacement (sway) have been considered. The radial displacement r at the receiver is modelled by a Rayleigh distribution,

$$f_r(r) = \frac{r}{\sigma_s^2} \exp\left(-\frac{r^2}{2\sigma_s^2}\right) \quad r > 0 \quad (3.21)$$

Where σ_s^2 is the jitter variance at the receiver.

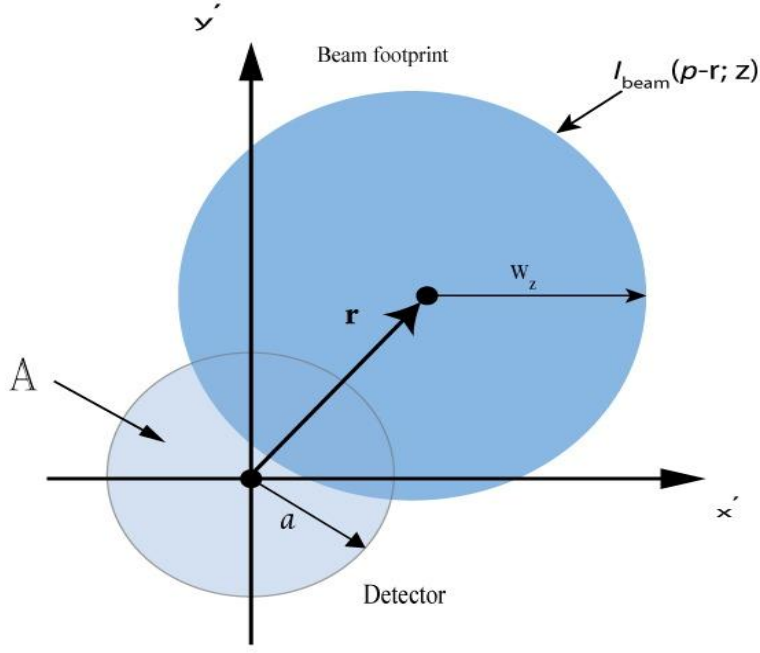


Fig. 3.5: Detector and Beam Footprint misalignment.

Combining the equations, the probability of pointing error is expressed as,

$$f_{h_p}(h_p) = \frac{\gamma^2}{A_0 \gamma^2} h_p^{\gamma^2-1}, 0 \leq h_p \leq A_0 \quad (3.22)$$

Where $w_{z_{eq}}^2 = w_z^2 \frac{\sqrt{\pi} \text{erf}(v)}{2v \exp(-v^2)}$, $A_0 = [\text{erf}(v)]^2$, $\gamma = \frac{w_{z_{eq}}}{2\sigma_s}$, $w_{z_{eq}}$ is the equivalent beam radius at the receiver, w_z is the propagating beam width, σ_s is the jitter strength.

3.3.7 Channel Statistical Model

The probability distribution of $h = h_l h_p h_a$ can be expressed as:

$$f_h(h; w_z) = \int f_{h|h_a}(h|h_a) f_{h_a}(h_a) dh_a \quad (3.23)$$

Where $f_h(h; w_z)$ is a family of PDFs parameterized by the beam width w_z , and $f_{h|h_a}(h|h_a)$ is the conditional probability given a turbulence state h_a . Considering h_l as a scaling factor, the resulting conditional distribution can be expressed as [9],

$$f_{h|h_a}(h|h_a) = \frac{1}{h_a h_l} f_{h_p}\left(\frac{h}{h_a h_l}\right) = \frac{\gamma^2}{A_0 \gamma^2 h_a h_l} \left(\frac{h}{h_a h_l}\right)^{\gamma^2-1}, 0 \leq h \leq A_0 h_a h_l \quad (3.24)$$

From the above equations we get,

$$f_h(h; w_z) = \frac{\gamma^2}{(A_0 h_l)^{\gamma^2}} h^{\gamma^2-1} \int_{h/A_0 h_l}^{\infty} h_a^{-\gamma^2} K_{(\alpha-\beta)} f_{h_a}(h_a) dh_a \quad (3.25)$$

This channel state distribution is expressed for gamma-gamma turbulence model by:

$$f_h(h; w_z) = \frac{2\gamma^2(\alpha\beta)^{(\alpha+\beta)/2}}{(A_0 h_l)^{\gamma^2} \Gamma(\alpha)\Gamma(\beta)} h^{\gamma^2-1} \int_{h/A_0 h_l}^{\infty} h_a^{(\alpha+\beta)/2-1-\gamma^2} K_{(\alpha-\beta)}(2\sqrt{\alpha\beta h_a}) dh_a \quad (3.26)$$

Here, $K_{(\alpha-\beta)}$ is the modified vessel function of second kind.

This integration is expressed in closed form by Meijer-G function as [38], [39]:

$$f_h(h) = \frac{\alpha\beta\gamma^2}{A_0 h_l \Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{3,0} \left[\frac{\alpha\beta h}{A_0 h_l} \middle| \begin{matrix} \gamma^2 \\ \gamma^2-1, \alpha-1, \beta-1 \end{matrix} \right] \quad (3.27)$$

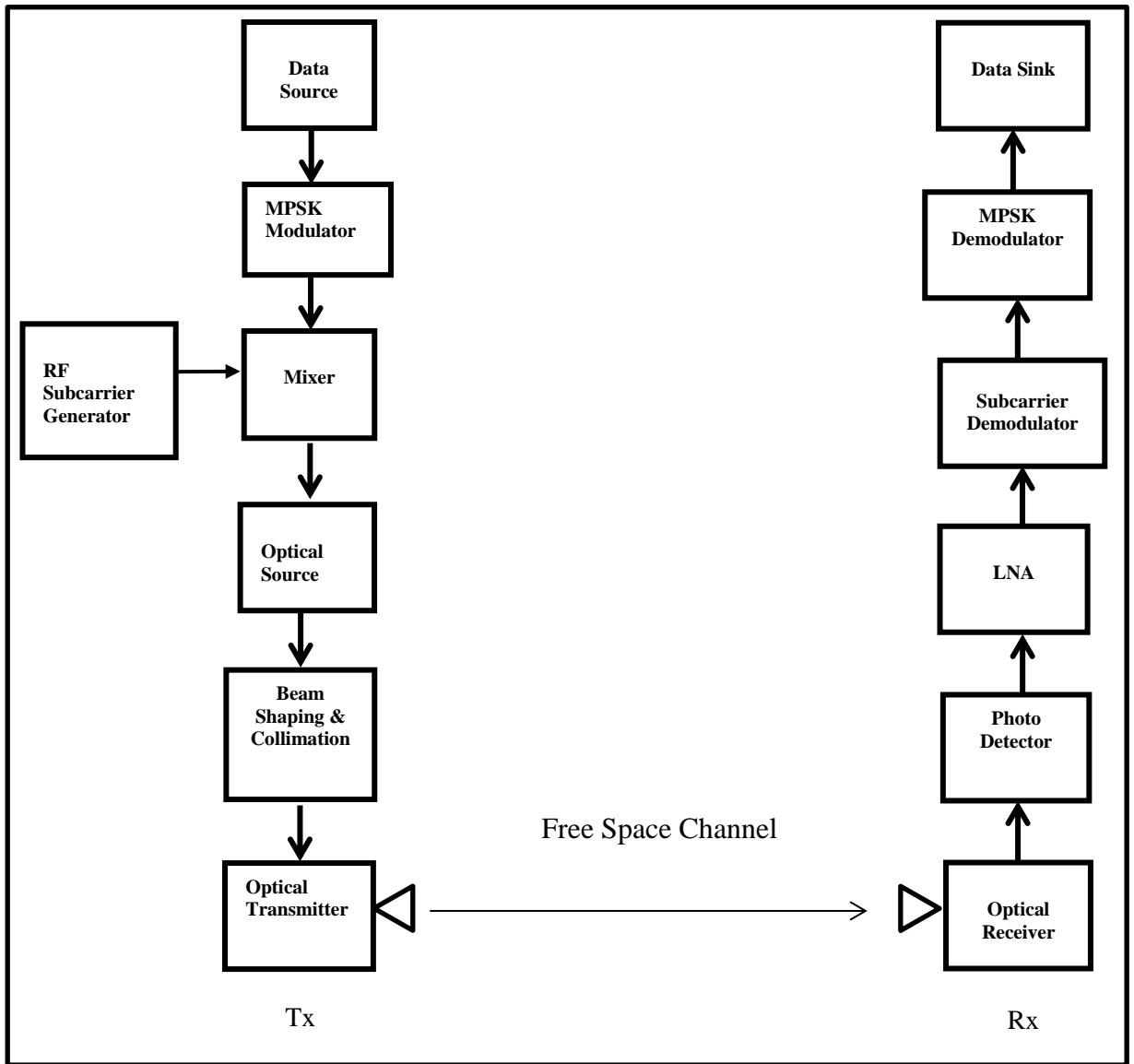


Fig. 3.6: Block Diagram of MPSK SIM based FSO system.

3.3.8 FSO System Performance Model under Selected Modulation Scheme

3.3.8.1 MPSK SIM BER Expression

In MPSK SIM scheme, a subcarrier is modulated with a digital signal using MPSK and then this modulated subcarrier is used to modulate the intensity of optical carrier as shown at figure 3.6. MPSK SIM modulation scheme is very suitable for FSO communications considering its robustness in atmospheric turbulence. Here M is the number of symbols used in modulation scheme.

For a coherent MPSK based SIM-FSO communication system, the probability of conditional BER depending on the intensity fluctuation can be expressed as [5], [36], [40].

$$P_{ec}(h) = \frac{2}{\log_2 M} Q(\sqrt{\log_2(M)SNR(h)} \sin(\frac{\pi}{M})) \quad (3.28)$$

$SNR(h)$ is the signal-to-noise ratio as a function of the channel state h (equation 3.3).

And the average BER is:

$$P_e = \int_0^\infty P_{ec}(h)f_h(h) dh \quad (3.29)$$

Substituting equation 3.27 and equation 3.29 into equation 3.28 and applying Meijer G integral property [41, Eq. (07.34.21.0013.01)], [42] - [44], we get the average BER:

$$P_e = \frac{2^{\alpha+\beta-4}\gamma^2}{\sqrt{\pi^3}\Gamma(\alpha)\Gamma(\beta)} G_{7,4}^{2,6} \left[\frac{16 \log_2(M) \sin^2(\frac{\pi}{M}) SNR_{avg}(A_0^2 h_l^2)}{(\alpha\beta)^2} \left| \begin{matrix} \frac{(1-\gamma^2)}{2}, \frac{(2-\gamma^2)}{2}, \frac{(1-\alpha)(2-\alpha)}{2}, \frac{(1-\beta)}{2}, \frac{(2-\beta)}{2}, 1 \\ 0, \frac{1}{2}, \frac{\gamma^2}{2}, \frac{-\gamma^2+1}{2} \end{matrix} \right. \right] \quad (3.30)$$

3.3.8.2 LPPM BER Expression

In LPPM scheme, data is encoded in the position of a single pulse within one of the L number of slots in each symbol periods. The signal is then used to intensity-modulate the optical carrier to generate FSO signal as shown at figure 3.7. In the receiver the detected signal is converted to electrical signal, amplified and decoded for data sink. LPPM modulation scheme is suitable for FSO communications due to its power efficiency (reduced average power and manageable peak power), simplicity in optical detection, bandwidth efficiency and adaptability to high data rates. Here L is the number of symbols used in modulation scheme.

For a synchronous LPPM based FSO communication system, the probability of conditional BER depending on the intensity fluctuation can be expressed as [28], [45]:

$$P_{ec}(h) = \frac{1}{2} \operatorname{erfc} \left(\frac{1}{2\sqrt{2}} \sqrt{\frac{L}{2} (\log_2(L) SNR(h))} \right) \quad (3.31)$$

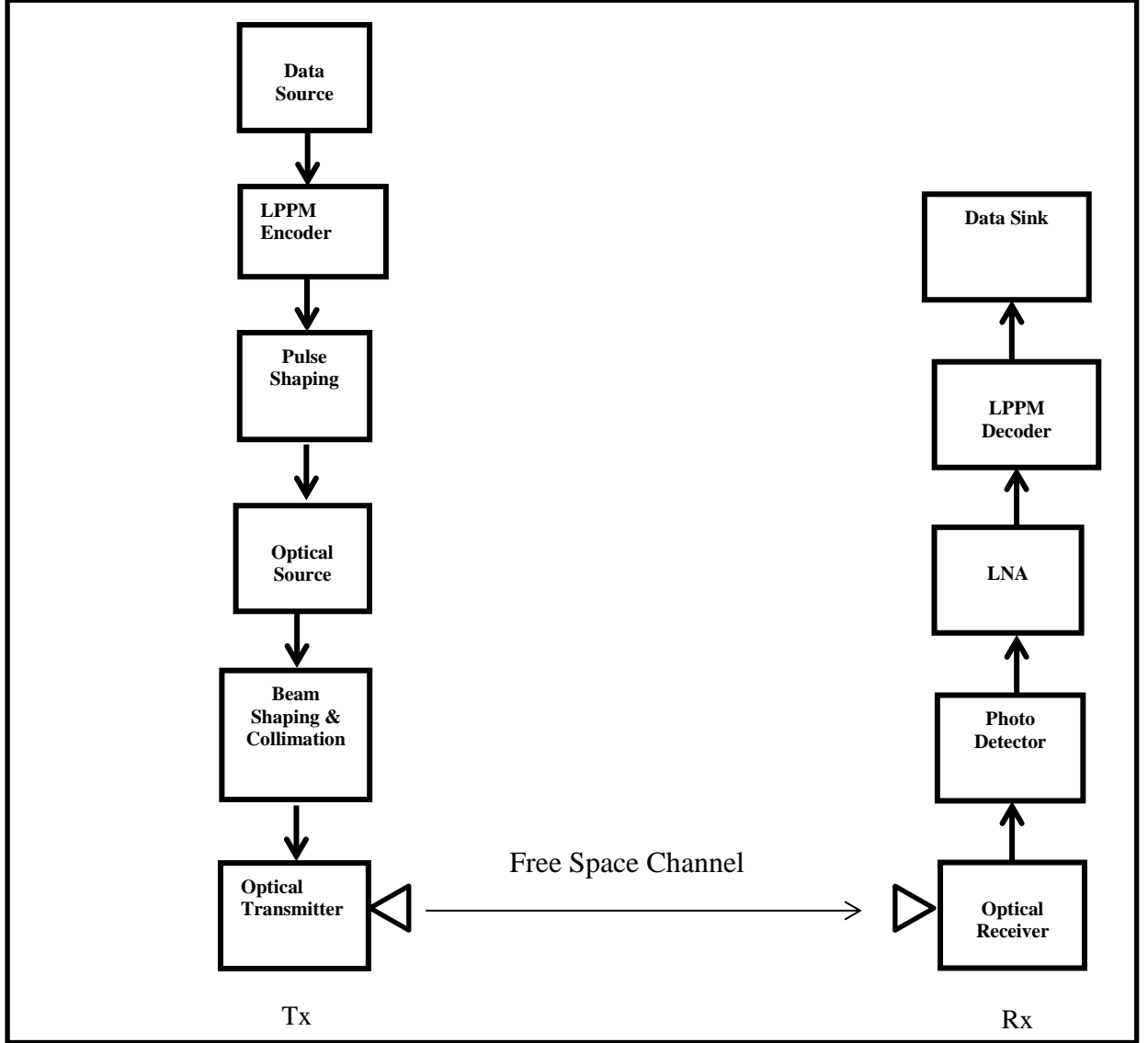


Fig. 3.7: Block Diagram of LPPM based FSO system

Again, substituting equation 3.27 and 3.31 into equation 3.28 and applying Meijer G integral property [41, Eq. (07.34.21.0013.01)], [42] - [44], we get the average BER:

$$P_e = \frac{2^{\alpha+\beta-4}\gamma^2}{\sqrt{\pi^3} \Gamma(\alpha)\Gamma(\beta)} G_{7,4}^{2,6} \left[\frac{16 \left(\frac{L}{2}\right) \log_2(L) SN R_{avg} (A_0^2 h_l^2)}{(\alpha\beta)^2} \middle| \begin{matrix} \frac{(1-\gamma^2)}{2}, \frac{(2-\gamma^2)}{2}, \frac{(1-\alpha)(2-\alpha)}{2}, \frac{(1-\beta)}{2}, \frac{(2-\beta)}{2}, 1 \\ 0, \frac{1}{2}, \frac{\gamma^2}{2}, \frac{\gamma^2+1}{2} \end{matrix} \right] \quad (3.32)$$

3.3.8.3 Consideration of Attenuation due to the Rain Factor

The mathematical expressions to model the combined impacts of deterministic and random atmospheric factors are equation 3.30 and equation 3.32 respectively for MPSK-SIM and LPPM modulation schemes. Here α , β account for atmospheric fluctuations while γ accounts for misalignment factor. The attenuation factors can be represented by h_1 , the value of which varies from 1 to lower value depending upon the level of the signal degradation due to air particle nature and the weather phenomena. Here value 1 represents no signal degradation, value '0' represents full attenuation and fractions are in between. Particularly for the rain factor - the predominant factor in Bangladesh weather - first the relevant signal loss using power law model has been computed using the rain data collected from BMD. Then from the corresponding loss data, value of h_1 can be calculated and applied in the combined impact models (equation 3.30 and 3.32) in order to compute the performance curves.

3.4 Conclusion

This chapter has derived two mathematical expressions in order to model channel characteristics encompassing the relevant factors for each of MPSK-SIM and LPPM based FSO links. The relevant factors considered are random and deterministic factors of the atmosphere. The random factors include parameter related to atmospheric turbulence and receiver alignment with the transmitter. All kinds of atmospheric attenuation factors due to air particles and weather effects – known as deterministic factors – do appear in the models as a scaling factor, whose value of 1 or lower depends on with no atmospheric loss or with atmospheric loss at varying rate. The atmospheric and the random factors have been analyzed mathematically in order to incorporate their impact into the channel model expression. This thesis has worked on plain models without any improvement factors in order to verify the FSO impacts under the variation of relevant factors, which have been graphically computed with MATLAB based programming, and compared with the known or expected performance values. This is the methodology of the thesis work. The chapter concludes with the approach of parameter determination for atmospheric loss factors into the developed channel model equation.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter analyses the data and curves (in the form of results) obtained from the simulation works as well as the secondary sources. It also examines the performance of FSO link system in general and specific to Bangladesh weather condition comparing with available literatures and previous study works. The sections of the chapter have been arranged in relation with the objectives of the research.

4.2 System Configuration

As explained in the first chapter under link configuration, the outdoor FSO communication link system in its simple form has a transmitter, a receiver and in between the propagation media. For MPSK SIM based link (figure 3.6), the intelligence is converted to digital data and then MPSK modulated before intensity modulation on a light carrier. For MCSIM scheme digital data is divided into several blocks where each block is modulated (for a particular order, M) on separate carrier radio and thereafter all modulated signals on different carrier radios are combined, then again modulated on light carrier (intensity modulated) and transmitted into the atmosphere. The system needs to be coherent for reproduction of intelligence. Hence, the local oscillators are required at both ends for MPSK modulation and demodulation functions. The receiver does the opposites to extract the signal.

For LPPM based outdoor FSO communication link (figure 3.7), the data or intelligence needs to be encoded first to LPPM format for a particular order L from baseband signal and then intensity-modulated on a light carrier before transmission into the atmospheric media. The receiver does the opposite. The receiver needs to be synchronous type for synchronizing with the pulse transmission.

4.3 FSO Channel Characteristics in Bangladesh Weather Condition

Although Bangladesh is within the sub-tropical region it experiences a humid, warm climate due to the influence of circulations during pre-monsoon, monsoon and post-monsoon period (figure 4.1). The monthly rainfall data of the selected locations in 2017 (table 4.1) from BMD show the similarity with the figure 4.1. Its warmest months coincide

with the rainy season (April-September). It is very wet land with about 2200 mm yearly average rainfall [46]. The winter is cold and dry (December-February). In regard to local dominant factors affecting FSO communication, Bangladesh experiences heavy monsoon rainfall during significant part of the year. Besides, the high humidity and airborne aerosols (dust, smoke, particles, etc.) also have significant local impact here. Sandstorms from the deserts of the west of Bangladesh during winter season also impact visibility [21].

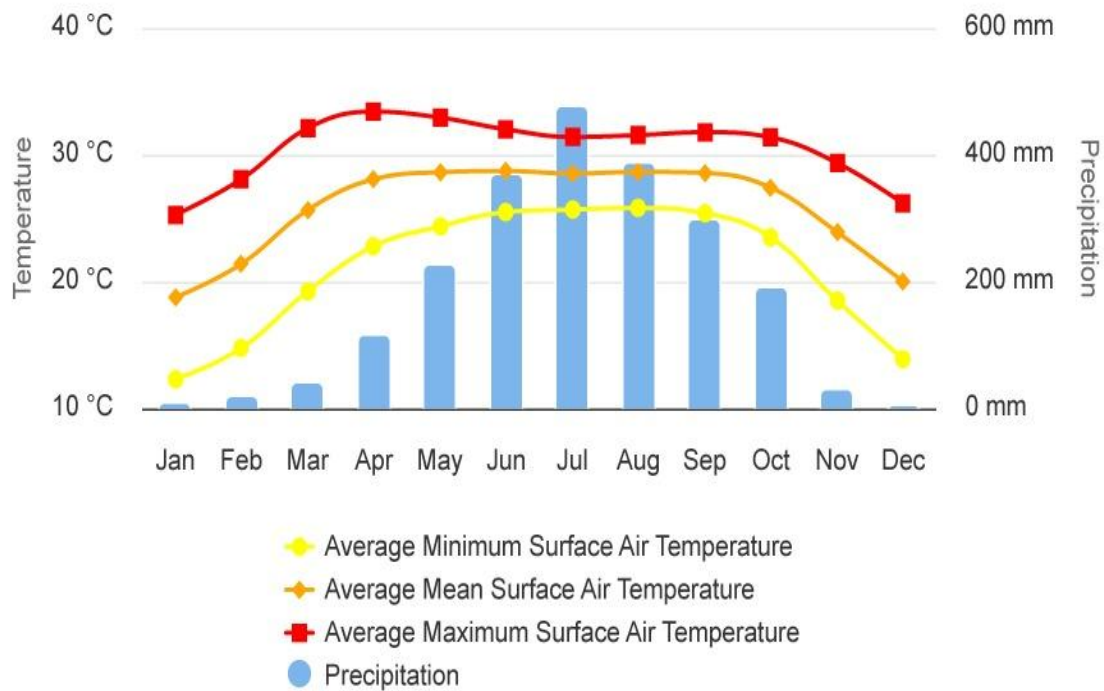


Fig. 4.1: Average Monthly Climatology of Bangladesh for 1991-2020 (Adopted from [46]).

Dense fog can significantly block the FSO signal, making communication impossible. Foggy condition is not a regular event in Bangladesh. It typically occurs during the winter months (December-February) reducing visibility less than 1 km. However, the duration and intensity of fog vary from year to year and from region to region within the country. It may last for several hours in the early morning or dissipate relatively quickly after sunrise. Dense winter fog with longer duration from mid-night to morning is reported as a common phenomenon [47] in Bangladesh. [48] has observed an alarming increase of fog frequency by 118.5% during observation period 1971-2015 in the Indo Gangetic Plains. As a single event, fog causes the highest attenuation in FSO communication.

Because of dominant weather factors (rain, humidity, aerosols and fog) FSO communication typically operates over a short distance. So, these factors have a significant effect on FSO signal similar to atmospheric turbulence, which however become more significant in longer links. So, for longer links, atmospheric turbulence is indeed one of the major factors of signal loss (due to fading) because of local weather effects alongside with atmospheric attenuation. Again, the misalignment issue is also cause of concern for Bangladesh. High winds or occasional storms are not frequent here, but they may occur at any time particularly during hot climate conditions causing serious degradation of FSO signals. High temperature causing distortion of air can occur during Bangladesh hot climate, which can bend light path slightly, but cause misalignment significantly.

Table 4.1: Monthly Rainfall (mm) at Selected Stations in 2017 [with the courtesy of BMD]

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Dhaka	0	2	100	228	188	414	584	544	381	412	6	33
Mymensingh	0	0	164	319	316	530	368	436	309	341	25	34
Srimongal	0	1	237	641	362	925	237	462	463	355	12	118
Sylhet	0	137	344	874	629	1047	774	1155	571	318	3	92
Bogra	0	0	99	164	386	242	504	252	259	239	3	15
Dinajpur	5	0	102	192	175	159	195	655	125	144	0	0
Khulna	0	2	59	99	200	356	690	313	175	322	19	51
Mongla	0	0	81	55	115	335	534	355	207	342	17	59
Barisal	0	0	59	364	118	505	550	342	228	387	14	57
Bhola	0	0	130	315	99	385	551	395	274	238	17	93
Khapupara	0	0	150	84	82	509	1079	344	574	444	23	55
Patuakhali	0	0	119	249	65	368	743	530	272	416	17	52
Chandpur	0	1	147	230	197	435	647	557	379	274	14	125
Chi(Patenga)	0	0	102	296	275	845	1008	523	560	123	2	17
Cox's Bazar	0	0	216	361	143	541	1437	531	524	149	13	36
Hatia	0	0	136	379	192	553	1170	691	650	420	3	41
Kutubdia	0	0	169	270	187	639	1188	444	615	170	9	30
Maijdi Court	0	36	194	318	288	522	994	606	439	415	13	77
Rangamati	0	0	108	388	186	1189	684	629	428	159	18	30
Sandwip	0	0	190	368	331	871	1209	714	994	357	1	37
Teknaf	0	0	128	163	166	856	1409	767	488	164	9	28

In the literature review chapter (chapter 2) the suitability and limitation of various attenuation models (due to air particles and weather effects) and channel models (due to random factors like scintillation and misalignment) have been amply covered. FSO link performance due to rain effect is one concern area of the thesis. One study finds the rain attenuation models (Carbonneau, Japan, Marshal- Palmer and Joss model) do not correctly predict the rain attenuation as evident from the field measurement [29]. One study also

reports that all standard fog induced attenuation models underestimate the experimental field measurement [35].

Power law parameters of rain attenuation model seem to vary location wise. One study in Bangladesh [19] uses Stoke's Law to find attenuation rate due to rain where few parameters like rain drop distribution, rain drop size, etc. are required. The study findings seem to be in the correct range of values compared to other studies. Several channel models are proposed to predict the effects of atmospheric turbulence. The two most commons are log-normal (suitable for weak turbulence) and gamma-gamma (suitable for all kinds of turbulence). One study finds that the empirical models on absorption, scattering, attenuation, turbulence (Kolmogorov model) and beam wander are found to offer a robust analysis of atmospheric propagation. However, there is a need to improve on such models when they are applied for aerospace FSO system [12].

Table 4.2: Design parameters

Parameter	Value		
Link Distance	1 km		
Wavelength	1550 nm		
Transmission Rate	1 Gbps		
Responsivity, R	0.5		
Noise Standard deviation, σ_n	10^{-7}		
Receiver Diameter, 2a	20 cm		
Turbulence Regime			
	Weak	Moderate	Strong
	$(\sigma_r^2 = 0.25)$	$(\sigma_r^2 = 1)$	$(\sigma_r^2 = 3)$
α	11.6	4.367	4.08
β	10.1	2.5636	1.43

4.4 FSO System Performance Analysis

This part of the research thesis has covered the FSO system performance analysis considering the theoretical analysis and the derivation of analytical expressions derived in the preceding chapter. As per the objectives of the paper, the performance analysis has covered MPSK-SIM and LPPM based FSO links under the variation of conditions as well the orders of the modulations., and the similarly the FSO links under the varying rainy

conditions of Bangladesh. The design parameters considered the performance analysis are as per table 4.2. The numbers chosen fall within a normal range of FSO system. The system performance is considered for 1 (one) km link distance. The transmission rate is so chosen that it falls well within the channel capacity and it does not incur additional signal loss coming from signal distortion. Large receiver aperture has been considered for better sensitivity and range. The three types of turbulence weak, moderate and strong are considered.

4.5 Performance of MPSK-SIM based FSO Links

In the MPSK-SIM based link (figure 3.3), the MPSK modulated RF signal is converted to intensity modulated optical signal. At the receiver, signal is amplified, light demodulated and then MPSK demodulated to retrieve data. Here no FEC is applied. In this section of the paper, the link performance has been analysed with simple BPSK under varying conditions, and then various MPSK signals under the similar conditions followed by the comparison among the MPSK links.

4.5.1 BPSK link under varying Conditions

BPSK is one of the simplest and most robust digital modulation schemes in which phase of a carrier signal is shifted between two distinct states. Here number of symbols used in this modulation scheme is 2 as $M=2$ as per figure 3.6.

As per the graph (figure 4.2), the BPSK link suffers about 20 dB penalty in SNR at BER of 10^{-4} from low to moderate or moderate to strong turbulence condition. The huge SNR penalty at strong turbulence causes deep fading and link-break condition. The invisible factor, even during clear weather condition, is one of the challenges of FSO system, that the designer needs to address through several improvement techniques. Pointing Error too can cause a SNR penalty of 20 dB at BER value of 10^{-4} when the jitter spread becomes four times as much as the receiver aperture (figure 4.3). These two factors together may cause huge signal fade that must be compensated, otherwise general benchmark standard of 99.99% availability cannot be ensured.

Controlling beam radius is likely to compensate the signal loss, but not at the same rate of loss due to strong turbulence or pointing error condition as evident in figure 4.4 where the

gain becomes 10 dB at BER value of 10^{-4} when the ratio of beam waist at the receiver to the receiver aperture is lowered from 26 to 10. It may be noted that in weak turbulence condition, BPSK performance is just 1(one) dB less than that of OOK based link [5]. The same study also shows about 19 dB SNR penalty at BER value of 10^{-4} when BPSK based link changes from low turbulence to moderate turbulence in a GG turbulence model condition. Here however, the difference between moderate to high turbulence condition is about 3 dB, far less than of the current study findings.

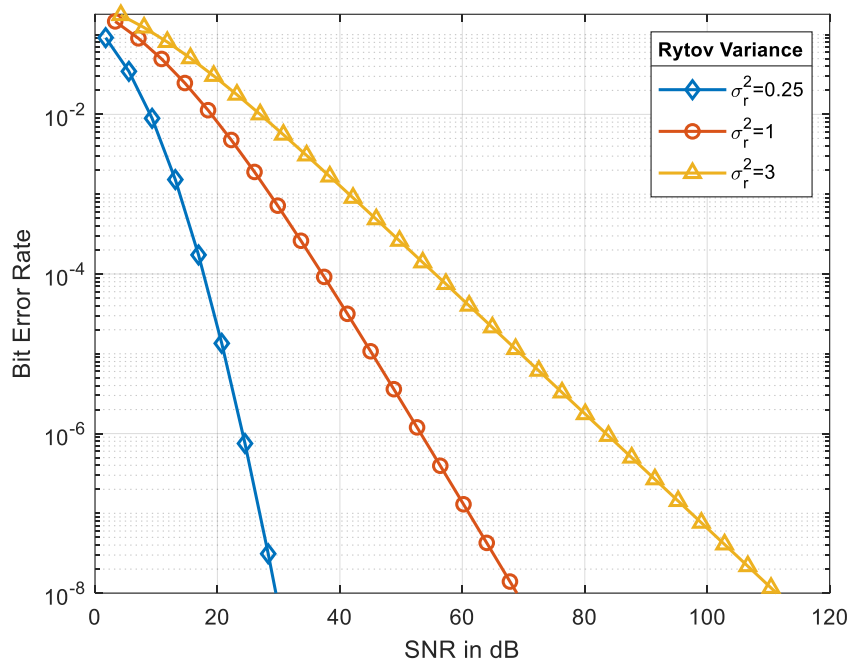


Fig. 4.2: BPSK FSO Link under varying turbulence without Pointing Errors.

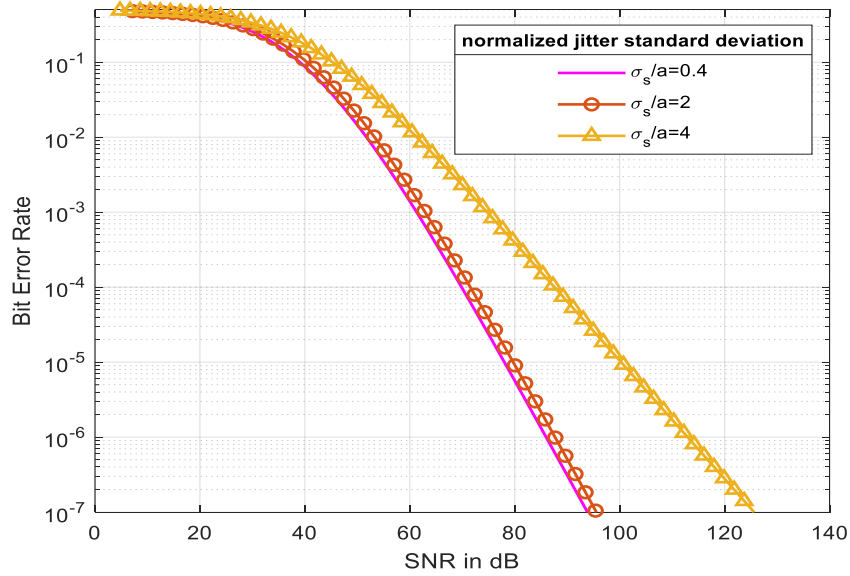


Fig. 4.3: BPSK FSO Link under varying Pointing Error.

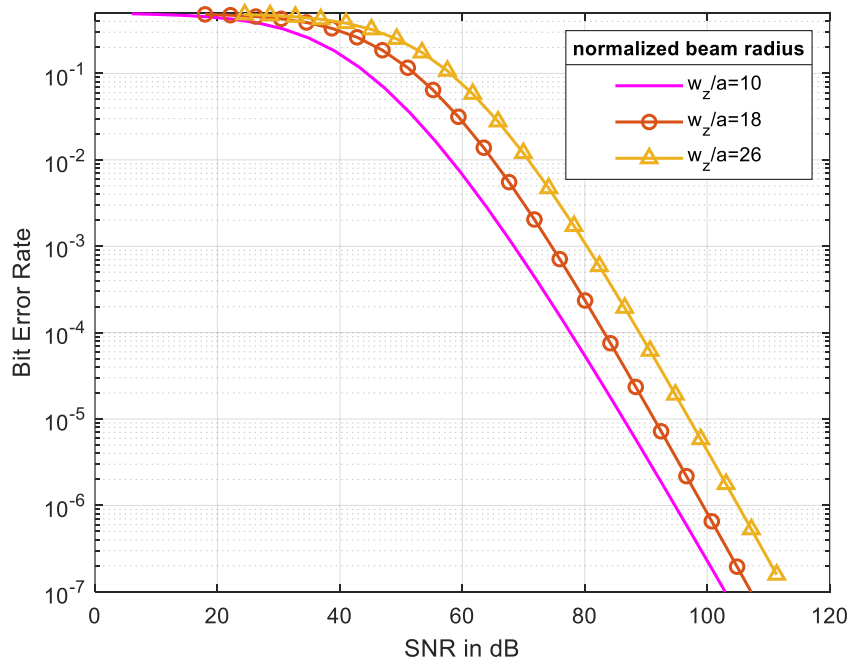


Fig. 4.4: BPSK FSO Link for varying Beamwidth.

4.5.2 MPSK Link under varying Conditions

Like the performance analysis of BPSK, this part of the section has analyzed the performance of various MPSK links with each under the variation of turbulence strength with low pointing error condition. The BPSK link (figure 4.5) is similar to the BPSK link (figure 4.2) except fixed pointing error condition, although both graphs are almost similar, which is the usual case. For the performance curves (figure 4.5, 4.6, 4.7 & 4.8) the PSK

modulation order, M (figure 3.6) has been varied with four values (2, 4, 8 and 16). As seen in the graphs, the curves have gradually shifted to right meaning increasing signal losses in terms of SNR penalty. That means, increasing modulation order of MPSK links is associated with SNR penalty.

Comparing to first two orders (figure 4.5 and figure 4.6), the SNR penalty is at the BER value of 10^{-4} and low turbulence is negligible when switched from BPSK link to 4-PSK link. The deterioration becomes about 5 dB at similar condition when the link is switched from 4-PSK (figure 4.6) to 8-PSK (figure 4.7) system or from 8-PSK (figure 4.7) to 16-PSK (figure 4.8) system. Similar degradation of signal strength occurs at medium as well as strong turbulence condition on switching of links. Coming to individual link, each link shows similar signal loss when turbulence condition is changed. Like, for example, for 8-PSK link (figure 4.7), the signal loss becomes about 20 dB at BER value of 10^{-4} when turbulence strength changed from low to medium or medium to strong condition. Similar value is noticed for other MPSK based links (figure 4.5, 4.6 and 4.8). So, it may be said that the increasing order of modulation of MPSK-SIM links inherently improves bandwidth efficiency, but at the cost of performance.

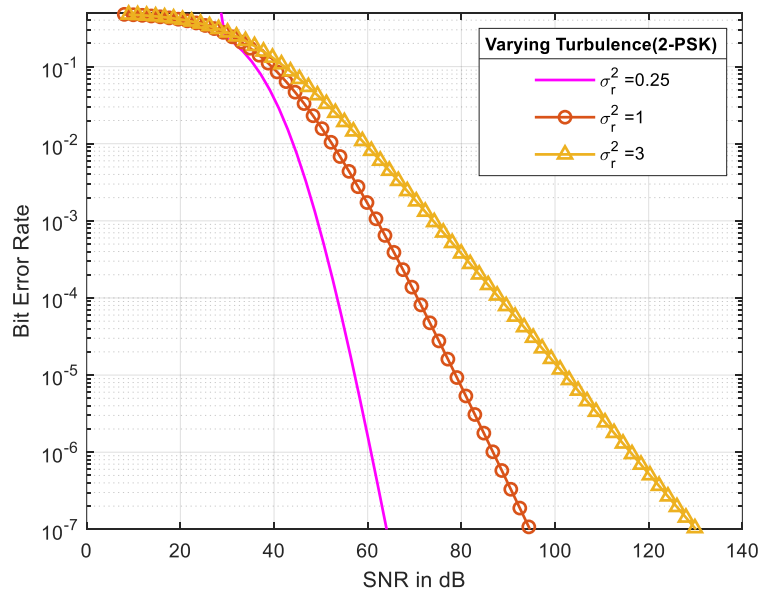


Fig. 4.5: BPSK Link under varying Turbulence, with Pointing Error

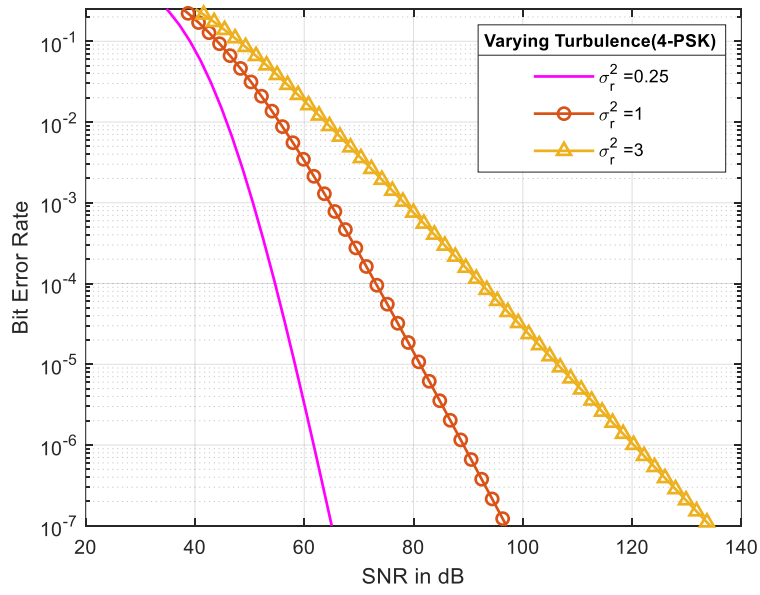


Fig. 4.6: 4-PSK Link under varying Turbulence.

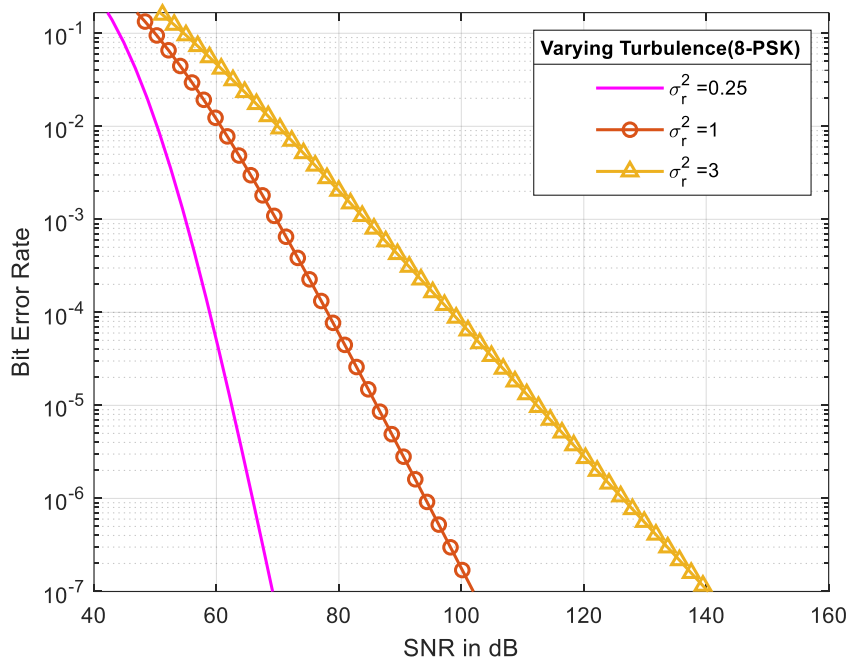


Fig. 4.7: 8-PSK Link under varying Turbulence.

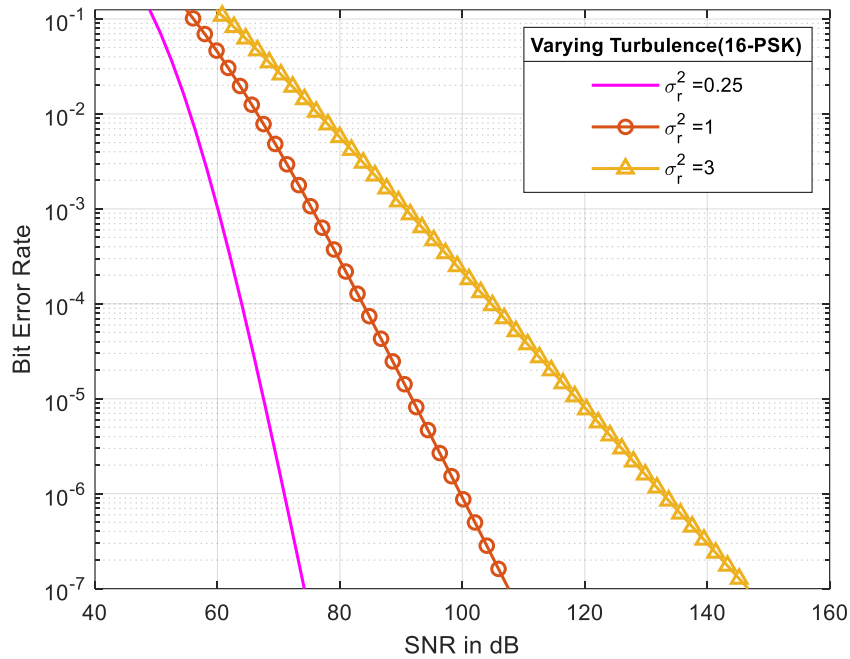


Fig. 4.8: 16-PSK FSO Link under Turbulence.

4.5.3 Comparison among various MPSK Links

The comparison among the various order MPSK FSO links is at figure 4.9 and figure 4.10. Performance deterioration switching from lower order to higher order is not uniform, rather becomes progressively higher at the increasing orders of modulation scheme. The conditions considered here as low turbulence and low misalignment condition. The SNR loss penalty (figure 4.10) is 2.5, 7.5 and 13 dB respectively for switching to 4-PSK, 8-PSK and 16-PSK link from BPSK link at BER value of 10^{-8} . The results are also same at BER value of 10^{-4} . As a result, when switching is done from BPSK to 16-PSK link, the SE is increased by a factor of 4 while the signal deterioration or SNR loss becomes significantly very high at 13 dB approximately. One study however shows a degradation of 4 dB performance when switching from BPSK to 16-PSK link [5].

This performance deterioration with the increase of modulation order of MPSK complies with the general principle that by increasing M the detection decision margin reduces leading to the higher probability of symbol error or BER. It also complies with one study [47] on performance of MPSK FSO link which shows about 5 dB degradation with the switching of the link from BPSK to 8-PSK at the BER value of 10^{-3} . Under clear weather

condition, the link may operate at higher order modulation scheme with complexity of electronics. It may dynamically or adaptively shift to lower modulation schemes to compensate the losses (as much as 13 dB as explained above) of bad weather condition in order to maintain the standard of 99.99% link reliability. It may be noted that for MPSK modulation schemes, the symbol is decoded by the estimation of phase states of the signal by MPSK demodulator. Therefore, the receiver needs to be coherent for the phase estimation. Its detection and recovery algorithm becomes very complex at the higher order of modulation.

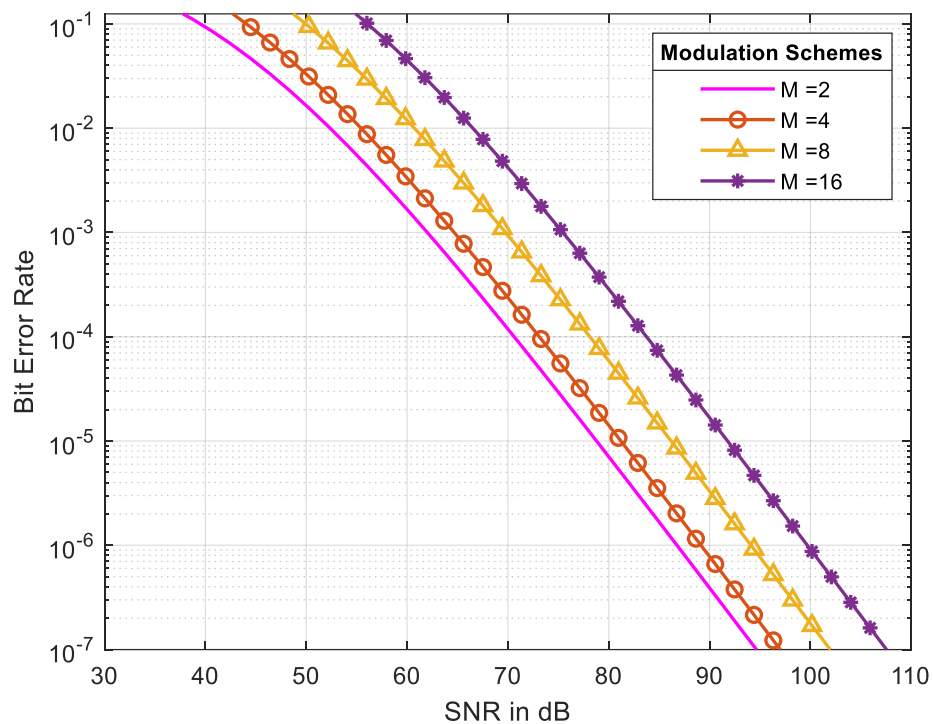


Fig. 4.9: Comparison among MPSK Links under moderate Condition.

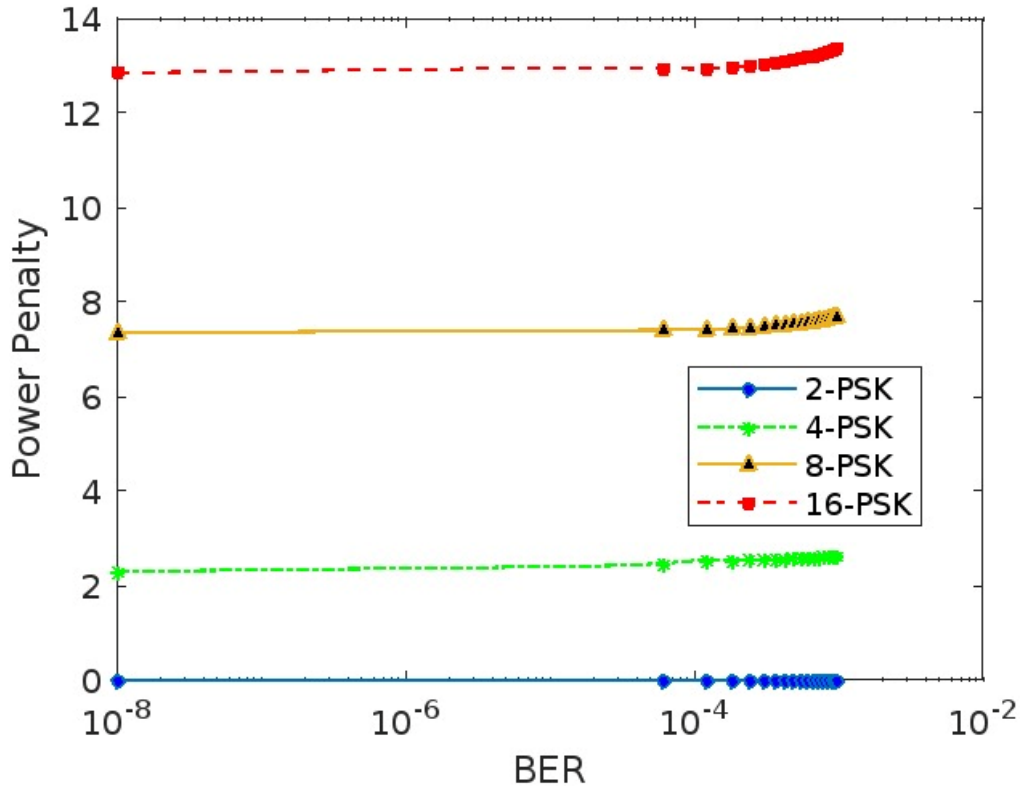


Fig. 4.10: Power Penalty Curve of MPK Links under moderate Condition.

4.6 Performance of LPPM based FSO Links

As shown at figure 3.7, the LPPM encoder encodes the data bits into the PPM signal. It involves the position of pulse among time slots designed for one symbol period. The signal is then converted to optical signal through intensity modulation. The received signal then converted back into electrical signal, amplified and decoded by LPPM decoder into original data. In this section of the paper the link performance has been analyzed for several orders of modulation schemes under varying conditions.

4.6.1 LPPM Links under varying Turbulence

This section deals with the performance analysis of several LPPM links under varying conditions of scintillation and for various values of order of modulation, L (2,4,8 and 16) as per figure 3.7. Now specific to 2-PPM link, the performance graph for example for 2-PPM link (figure 4.11) has spread to the right with the increase of the turbulence strength meaning SNR penalty of about 20 dB from low to moderate and about 27 dB from moderate to strong turbulence condition at BER value of 10^{-4} .

The individual plot for turbulence comes closer to the left with the increase of order of modulation schemes (figure 4.12, 4.13, & 4.14) meaning SNR gain. For example, at the BER value of 10^{-6} and low turbulence strength, the 2-PPM link requires 58 dB SNR. For 4-PPM signal it is 56 dB meaning 2 dB gain. For 8-PPM and 16-PPM signal it equates to 53 dB and 51dB respectively meaning successive gain of 3 and 2 dB when switched immediate higher link. Under strong turbulence the LPPM links (figure 4.11 to 4.14) at same BER value require SNR of 110, 105, 100 and 95 dB respectively for the four orders of modulation schemes meaning SNR gain of about 5 dB at successive switching of links and 15 dB at the switching of 16-PPM link from 2-PPM link. It is therefore inferred that the performance of LPPM links degrades under the increasing strength of turbulence. It, though, performs better with the higher order of modulation schemes. From weak to moderate turbulence condition, the 4(four) links show respectively the SNR penalty of 20, 26, 25 and 26 dB at BER value of 10^{-6} . Again, the SNR penalty of the 4(four) links become respectively 28, 26, 27 and 28 dB from moderate to strong turbulence condition at similar BER value.

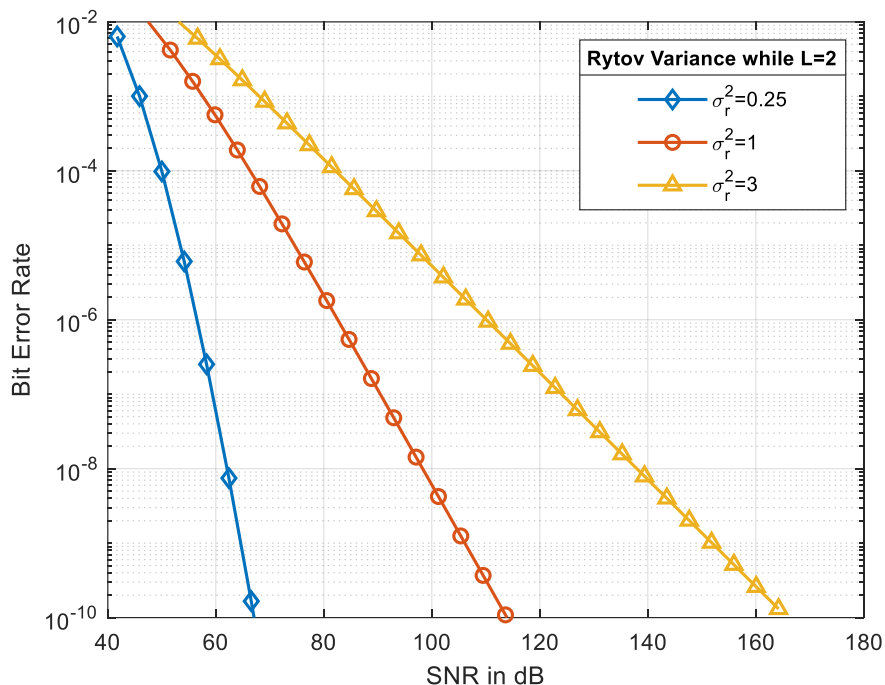


Fig. 4.11: 2-PPM links under varying Turbulence strengths.

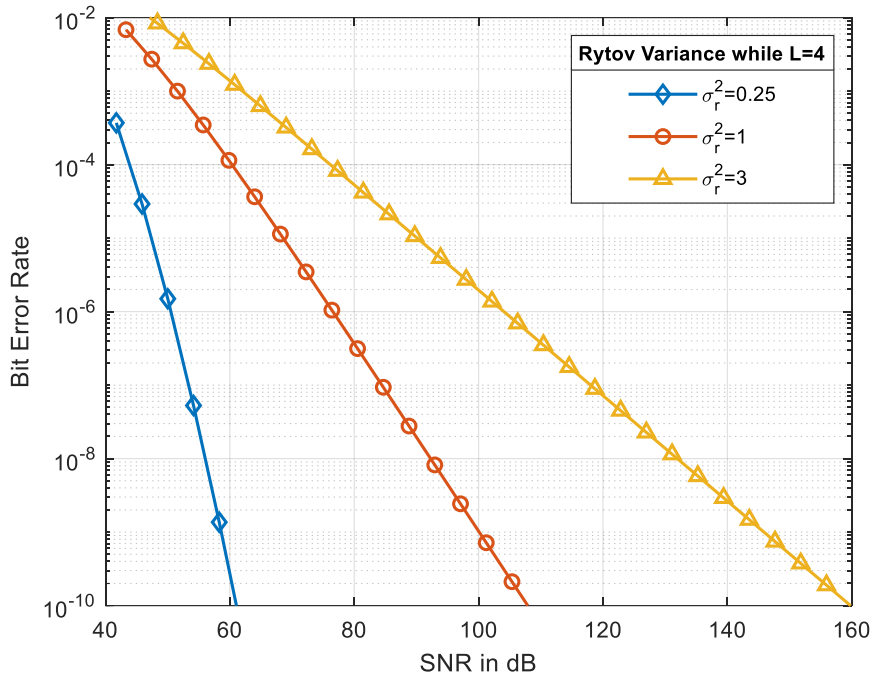


Fig. 4.12: 4-PPM links under varying Turbulence strengths.

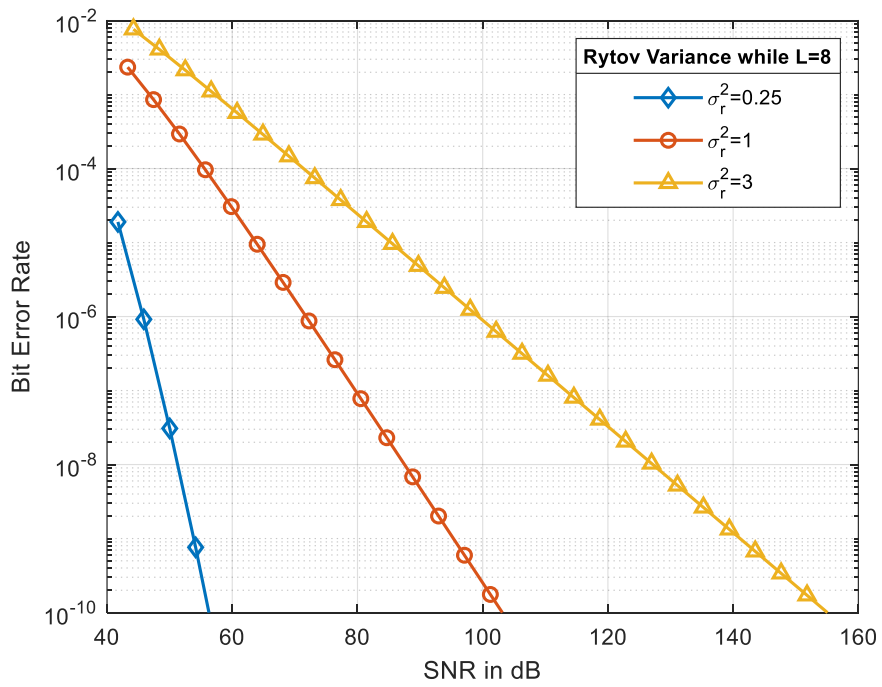


Fig. 4.13: 8-PPM links under varying Turbulence strengths.

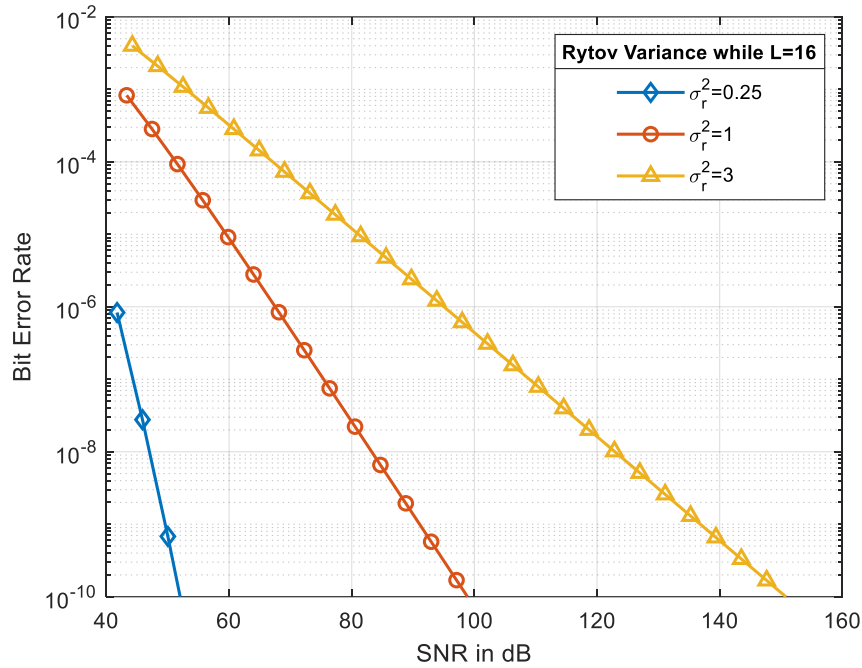


Fig. 4.14: 16-PPM links under varying Turbulence strengths.

4.6.2 LPPM Links under varying Pointing Error

Under variation of pointing error with moderate turbulence and also the order of modulation L , the LPPM FSO links (figure 4.15 to 4.18) show similar behavior like the turbulence situation covered in the previous section. For small deviation, and at BER value of 10^{-4} , the 2-PPM link (figure 4.15) needs about 69 dB of SNR. The figure stands for 70 dB and 87 dB for respectively moderate and strong deviation meaning about 18 dB SNR penalty at strong deviation. For 4-PPM, 8-PPM and 16 PPM links, the SNR value at weak deviation and the BER value of 10^{-4} stands at 63, 57 and 52 dB respectively showing progressive gain (figure 4.16, 4.17 & 4.18). The signal degradation of these 4(four) links due to strong deviation at same BER value are 18, 18, 18 and 19 dB respectively. Hence, it may be said that LPPM links perform better at the higher order of modulation schemes, but degrades as the deviation increases.

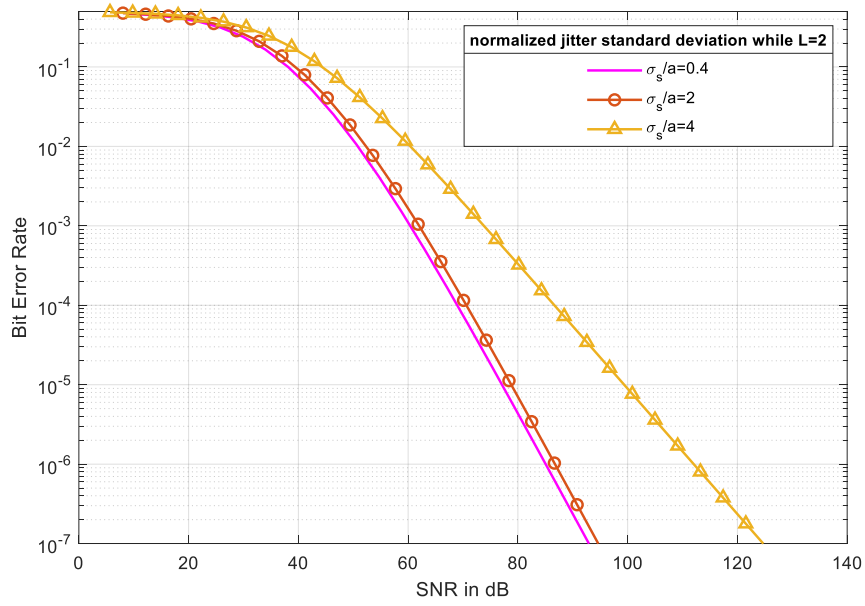


Fig. 4.15: 2-PPM Links under varying Pointing Errors.

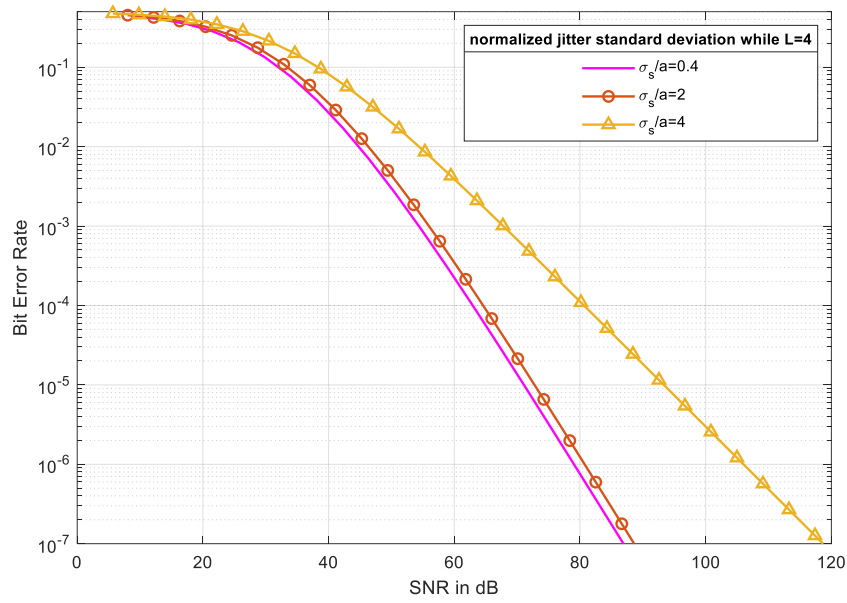


Fig. 4.16: 4-PPM Links under varying Pointing Errors.

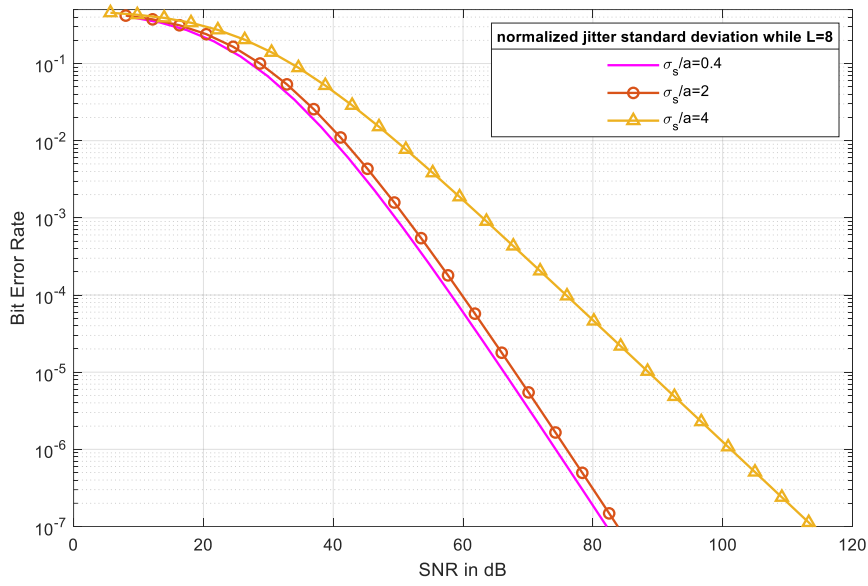


Fig. 4.17: 8-PPM Links under varying Pointing Errors.

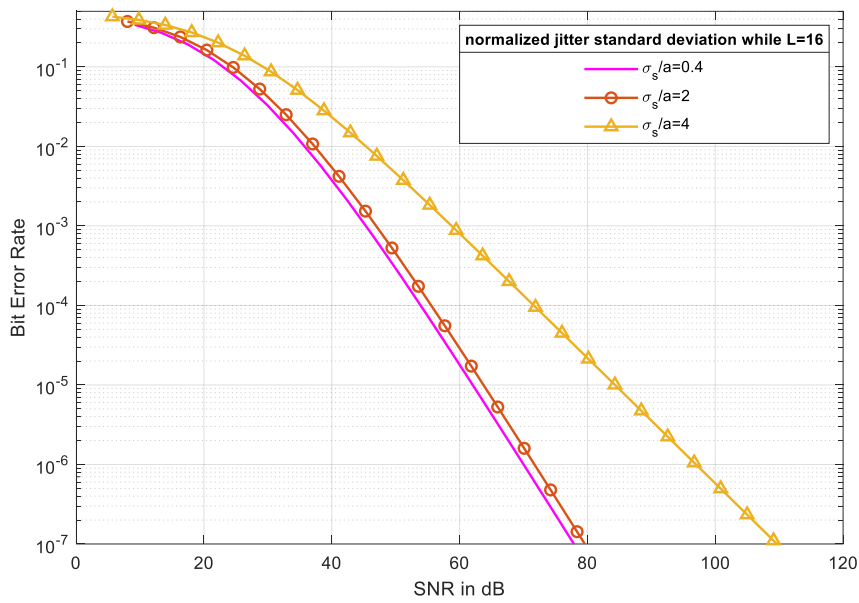


Fig. 4.18: 16-PPM Links under varying Pointing Errors.

4.6.3 LPPM Links under varying Beamwidth

Here the performance of the FSO links under varying beam radius have been analyzed. At the specific BER value (10^{-2}) and normalized beamwidth of 10, 2-PPM link (figure 4.19) requires a SNR of 55 dB, which increases to 62 dB with a degradation of 7 dB at the higher beam radius. However, the 4-PPM link (figure 4.20) shows a SNR of 48 dB at the same beamwidth meaning 7 dB gain. The other links (figure 4.21 & 4.22) of LPPM show a SNR

value of 44 dB and 40 dB respectively with a gain of 4 dB each. The trend is that with the increase of transmitting beamwidth the LPPM links suffer degradation of SNR penalty due to lower value of power per unit area or called power density. The degradation can be offset with the higher order of LPPM modulation schemes.

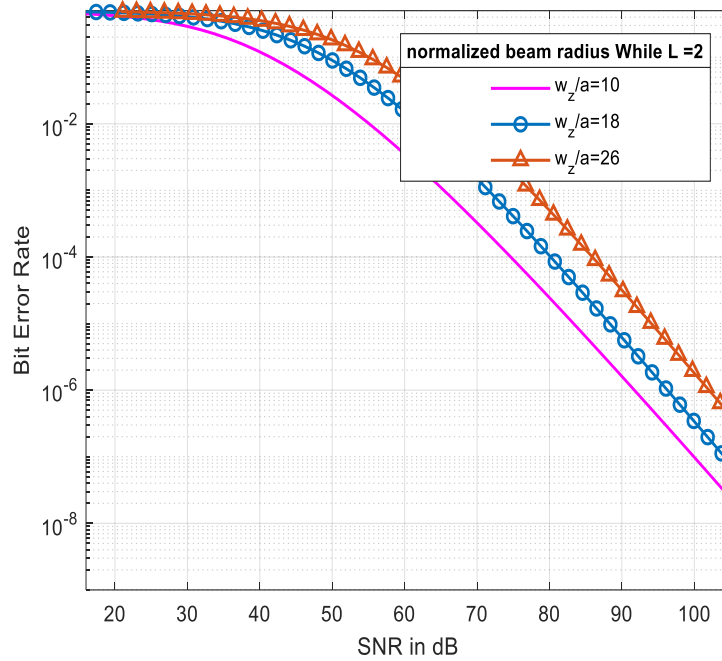


Fig. 4.19: 2-PPM Links under varying Beamwidth.

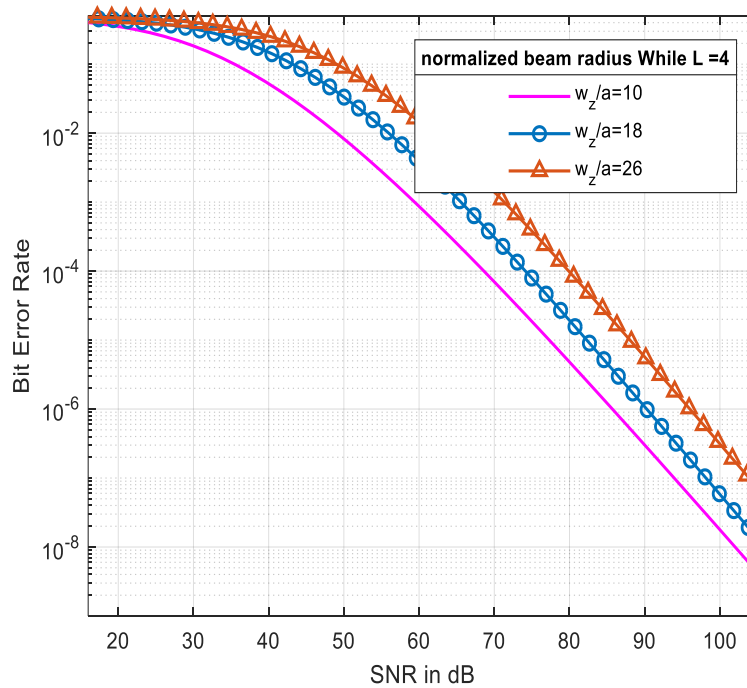


Fig. 4.20: 4-PPM Links under varying Beamwidth.

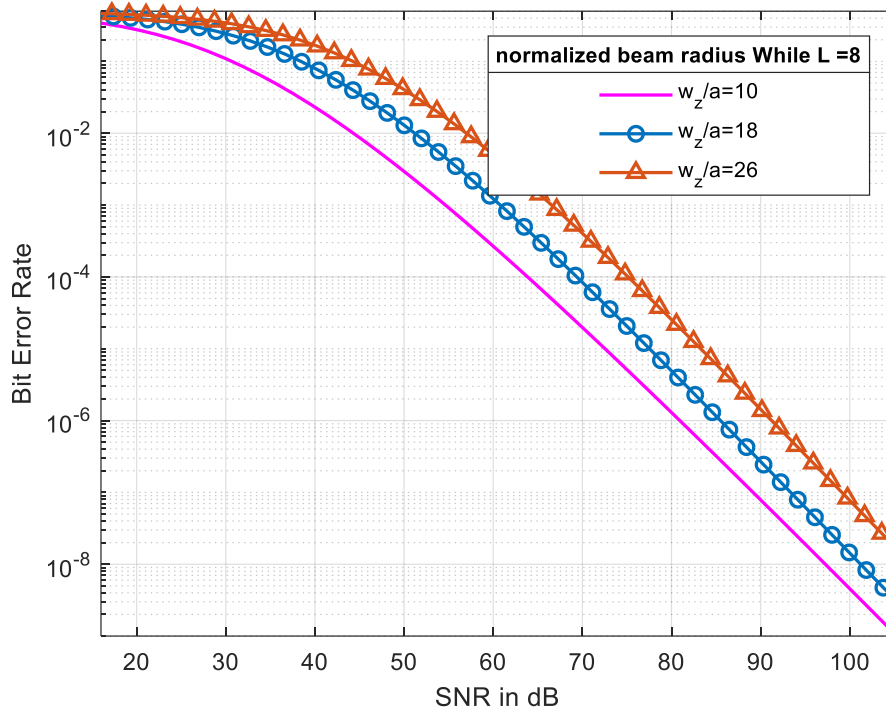


Fig. 4.21: 8-PPM Links under varying Beamwidth.

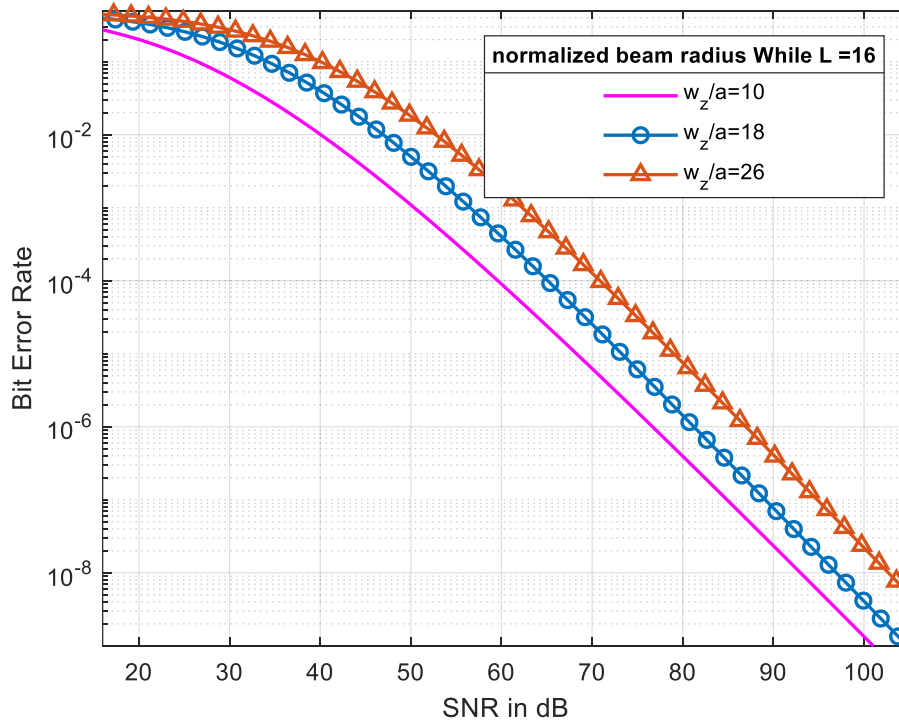


Fig. 4.22: 16-PPM Links under varying Beamwidth.

4.6.4 Comparison among various LPPM Links

The figure 4.23 here shows the comparison of LPPM links of increasing orders of modulation, L (2, 4, 8 and 16). The conditions applied are fixed moderate conditions of turbulence and deviation. As explained before, LPPM link shows better performance with the increase of order of modulation. Specific to the comparison graph (figure 4.23), at the specified BER value, the plot of higher order squeezes to the left meaning progressively better performance. As the link switches to the immediate higher order, to 4-PPM, there shows a SNR gain of 4 dB at BER value of 10^{-2} . For other two links it shows a SNR gain of 4 dB and 7 dB respectively. There is a net gain of 15 dB when switched from 2-PPM to 16-PPM link under moderate conditions of turbulence and misalignment. One study [50] on the LPPM FSO link performance investigation under the variation of the order of modulation shows about 11 dB gain with such switching at strong turbulence and misalignment condition. So, it shows that by increasing the order of modulation of LPPM scheme, the SNR gain can be achieved. This complies with the general principle of LPPM modulation features that with the increase of modulation order (L), the average power requirement decreases hence leading to the increase of SNR. It may be noted that however, with strong turbulence, this reduction in average power is not significant, but for weak or moderate turbulence, the impact of L is high.

As a result, at the higher order of modulation, LPPM schemes provide better energy efficiency, spectral efficiency, and enhance transmission capacity. This is the great feature of LPPM modulation format that attracts its application in space, where energy efficiency is highly desirable. However, for terrestrial application, it is less attractive due to its strict requirement of slot and symbol synchronization. At turbulent region, it is really problematic due to signal fade and pulse widening effects, that easily break the synchronization chain. Even during high turbulence, the reduction of average power and increase of peak power due to higher order modulation application is not significant.

From the power penalty curve of LPPM link signals (figure 4.24) it is evident that 16-PPM signal has the best performance over other link signals. At a BER value of 10^{-8} the 8-PPM, 4-PPM and 2-PPM links have a penalty of 4, 9 and 15 dB respectively when switched from 16-PPM link. It has almost similar penalty value at BER value of 10^{-4} . It is evident that the lower order PPM signal should not be a suitable option of FSO applications because of low

performance and low bandwidth efficiency. The higher the order of LPPM schemes the better is the performance and the bandwidth efficiency. This higher order modulation scheme based FSO link is widely used for indoor application where there is no issue of turbulence condition. Because of its superior energy efficiency and better EMI resistance, it has great potentials for terrestrial applications where environmental conditions can be controlled and where power consumption is a big factor for consideration (like battery).

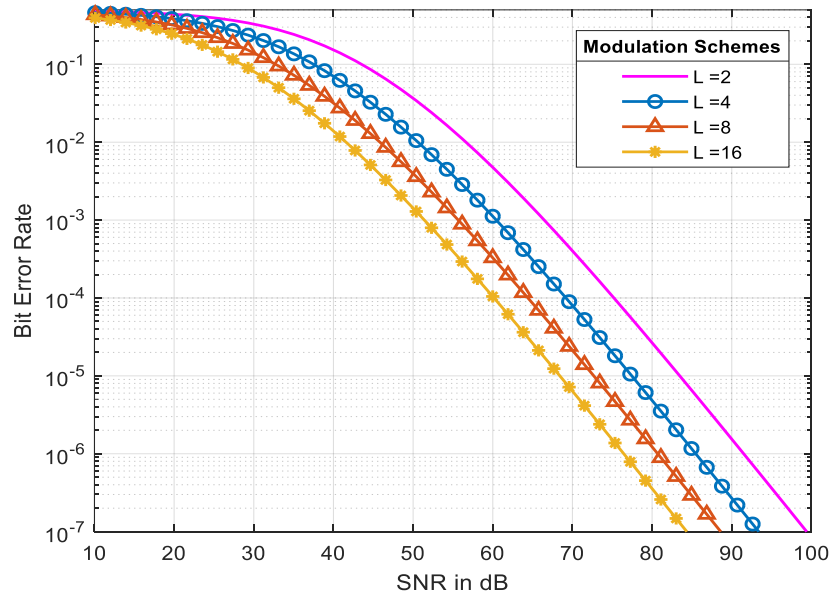


Fig. 4.23: Comparison among LPPM FSO Links of different Order.

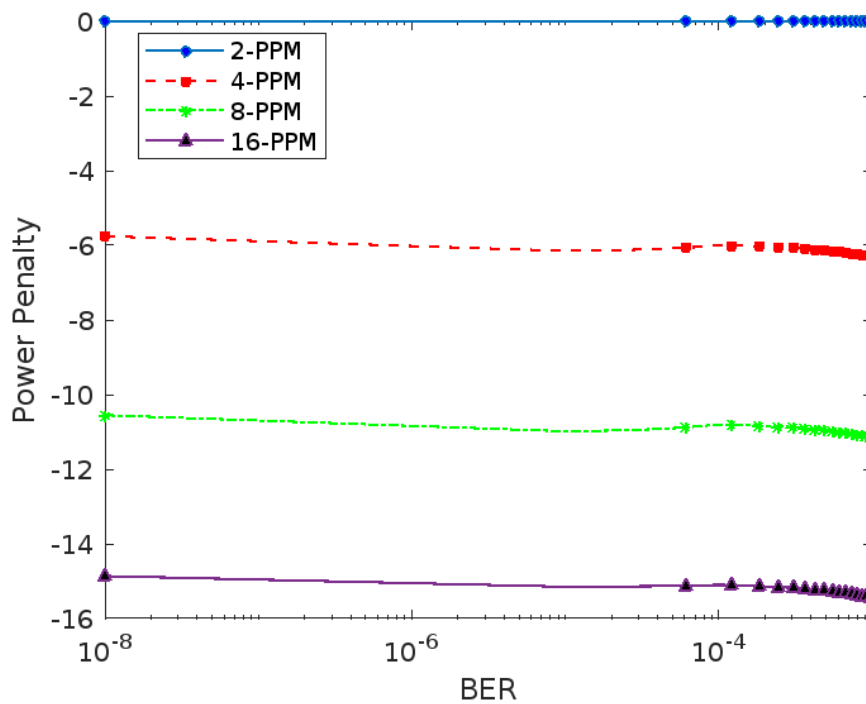


Fig. 4.24: Power Penalty Curve for LPPM Links.

4.7 Performance Comparison among various MPSK and LPPM Links

So long, the performances of MPSK-SIM and LPPM based FSO links have been considered separately under varying conditions of turbulence, pointing error, beamwidth and also the orders of modulation schemes. It has been seen that the performance of MPSK based FSO links deteriorates with the increase of order of modulation whereas conversely for LPPM system the performance improves with the increasing order of modulation schemes. Now here, the comparison between the two sets of plots for each multi-order schemes have been shown through a combined plotting into one (figure 4.25) in order to understand the individual link performance position compared to others. Here the moderate conditions in respect of turbulence and misalignment have been considered. Here the value of h_1 has been considered 1(one) meaning that attenuation loss due to atmospheric particles is considered zero.

Among the total 8 FSO links, BPSK provides the best BER performance against all points of transmitted power, whereas the 2-PPM has the worst performance. Again, 4-PSK is the second best followed by the 16-PPM link, which is then followed by 8-PSK. Thereafter comes 8 PPM followed by 16 PSK. The second worst performer is the 4-PPM links. It is evident from this discussion that higher order PPM links are comparable to the best performer links of MPSK (the lowest ones). So, 16-PPM link provides very suitable BER performance comparable to BPSK link (the best one) while this PPM link provides higher data rates or bandwidth due to its higher order. For the case of MPSK modulation schemes, the link can be switched to the higher order link with high data rate potentials, but with BER penalty as well. It may be mentioned that [41] compares LPPM (from 2-ary to 64-ary PPM) with BPSK and shows that BPSK link has lower performance than that of 8-PPM and 16-PPM links while the current study shows BPSK based link is the best performer among LPPM based links (from 2-ary to 16-ary link). The difference may be attributed to the environmental conditions considered in the model evaluation. The example one is for strong turbulence and misalignment conditions while the current study for moderate conditions.

From the power penalty curve (figure 4.26), it is seen that BPSK has the best performance. At BER value of 10^{-9} the 4-PSK link suffers about 1 dB penalty compared with BPSK, followed by 16-PPM link which suffers about 2 dB. Here 8-PSK has coincided with 16-PPM. Here 8-PPM has a penalty of 3 dB from BPSK link level, followed by 16-PSK with

about 5 dB penalty. The 4-PPM penalty curve has initial high followed by a dip and then again high penalty value. At the specified point, it has a penalty of over 4 dB. The 2-PPM link has the highest penalty of 15 dB.

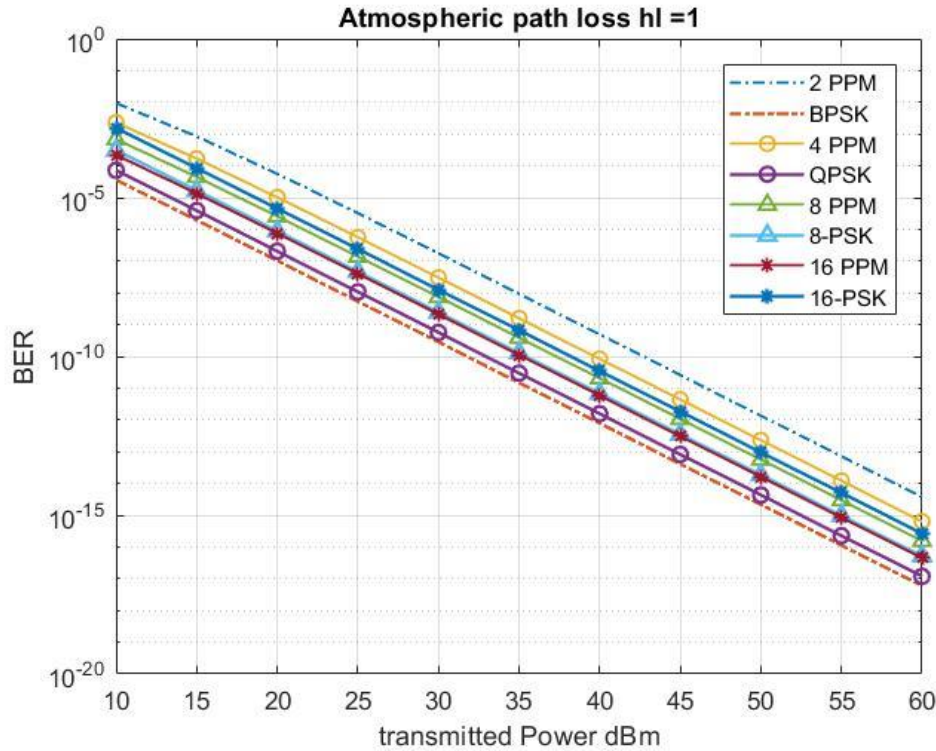


Fig. 4.25: Comparison among multi-mode MPSK, LPPM based Links.

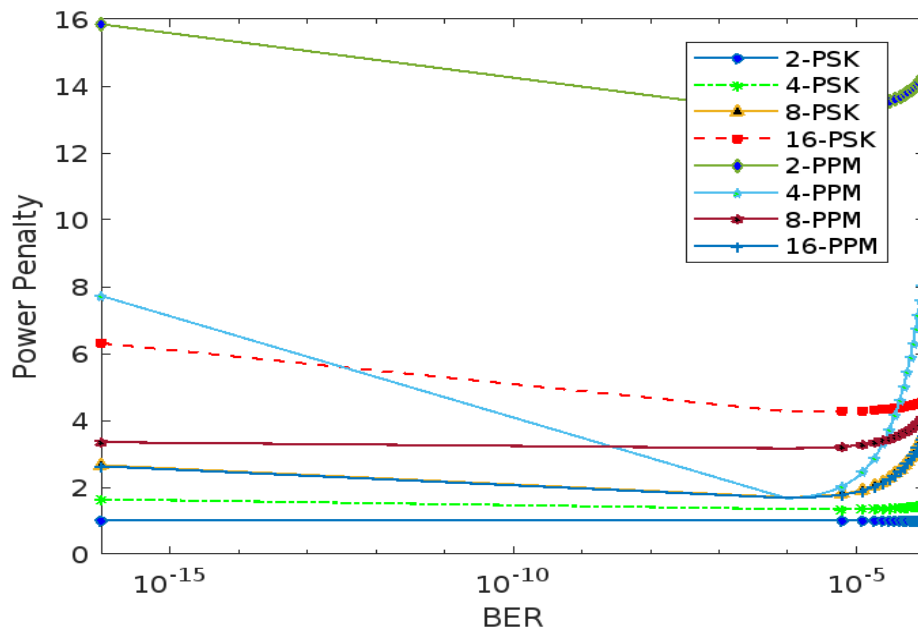


Fig. 4.26: Power Penalty Curve for MPSK and LPPM Links

4.8 Bangladesh Rain Data Rate and Its Impact on FSO Links

4.8.1 Rain Intensity Data of Bangladesh Weather Condition

There are several empirical formulas on finding rain data related attenuation rate. But there is less material found on how to compute them from a comprehensive model that incorporates other random and deterministic factors of FSO performance in terrestrial environment, and allows BER performance computation and analysis analytically taking into account all degrading factors including rain effect. The models can be used for the said purposes varying h_1 parameters of the analytical expressions (equation 3.30 & 3.32). This part of the thesis depends on the approach as explained. First, the rain rate data collected from BMD is converted for one-hour based rate. Then the attenuation is calculated from the empirical formula based on the particular value of rain rate chosen. Thereafter value of h_1 parameter is computed accordingly from attenuation corresponding the rain rate chosen. The link performance is then analysed under the variation of h_1 parameter of the analytical expressions (equation 3.30 and 3.32).

The rain data was collected from BMD for 5 years period (2015-2019) recorded at different locations of the country: main land, costal locations and island spots. Since BMD does not record rain drop size, the analysis has to depend on rain rate-based power law equation to find the rain attenuation in Bangladesh. Furthermore, the data collected is of 3-hour period interval, which gives a broad overview of rain rate situation in the country. Although the equation necessitates one-minute interval rain data, the thesis needs to depend on the data available which surely provides more optimistic result (less degradation) than the actual. In fact, the actual rain rate should be higher than the recorded data. The thesis considers the highest rain rate data recorded in the particular month of the spot. Accordingly, a set of rain rate data of maximum value per month recorded are shown for 3 (three) specific locations (table 4.3, 4.4 & 4.5).

Table 4.3: Max Rain Intensity (mm/3 Hr.) Recorded, Dhaka 2014-2018 [BMD database]

Month	2014	2015	2016	2017	2018
Jan	0	1.4	2.8	0	0
Feb	3.4	5.4	6.4	1.8	13.6
March	9.8	1.2	17.2	32	13.8
Apr	33.6	21	16	33.2	50.4
May	23	35.2	26.2	49	81
Jun	34.4	66	38.2	44	54
July	51.4	42	24.6	54	52
Aug	40	36	29	54	20.4
Sep	22	43	20.2	66	15.4
Oct	25	17	25.6	35.6	22.4
Nov	0	0	11.2	1.6	13
Dec	0	1	0	9.6	5.8

Table 4.4: Max Rain Intensity (Mm/3 Hr.) Recorded, Chattogram 2014-2018 [BMD database]

Month	2014	2015	2016	2017	2018
Jan	0	1.2	1.8	0	11.6
Feb	8	0	2	0	0
March	8	44.2	30.6	23.2	20
Apr	21	38	12	37	32
May	52	20.2	65	67	60
Jun	88	93.1	24.6	69	50
July	32	68.6	55	98	47
Aug	46.6	30	38	60	44.5
Sep	52.2	66.2	54	78	21
Oct	40	25	78.4	37	36.8
Nov	0	1.2	36	1.5	2
Dec	0.3	7.4	0	4.2	4.2

Table 4.5: Maximum Rain Intensity (Mm/3 Hr.) Recorded, Hatia 2014-2018 [BMD database]

Month	2014	2015	2016	2017	2018
Jan	0	3	1	0	0
Feb	7	5	19	0	0.3
March	7.6	53	24	25	11
Apr	1	67	9	75	32
May	24	29	36	49	51
Jun	89	75	60	53	45
July	73	88	82	96	54
Aug	45	31	52	42	30
Sep	34	84	65	46	30
Oct	34	83	94	84	50
Nov	1	20	56	0	4
Dec	1	7.5	0	0	3

4.8.2 Rain Rate vs Attenuation Loss Factor

Rain attenuation in FSO communication is severe and it usually happens during monsoon season in Bangladesh. Although fog attenuation can be more severe than rain attenuation, but its geographical extent and duration is far less than that of rain in Bangladesh. Again, both issues appear as a scaling factor in the BER expressions (equation 3.30).

There are many empirical methods on modeling of rain attenuation prediction. The two specific empirical models recommended by ITU-R are: Carbonneau and Japan model. One study [28] involving data measured in Malaysia rain-affected FSO link finds both models overestimate the practical measurement, but Japan model more severely. This study has followed Carbonneau model ($k=1.076$, $\alpha=0.67$). The target is to find the values of h_l , that can be applied to the BER expressions. First the rain rate data chosen are the average values of the data recorded (table 4.3, 4.4 & 4.5) during no-rain, dry season, pre-monsoon, monsoon and post-monsoon respectively. According to common meteorological principles [51], these correspond to the conditions of no, light (below 2.5 mm/hr), moderate (between 2.5 to 7.6 mm/hr), and heavy (between 7.6 to 50 mm) rain rate or intensity conditions. Bangladesh does experience violent or very heavy rain condition (above 50 mm/hr), but its

frequency is very low. However, heavy rain condition occurs from April to October for about 7 months duration and this may affect heavily the FSO links unless mitigation technique is applied.

As per table 4.6, the rain attenuation in dB is computed from rain intensity data chosen using Carbonneau model. Then the corresponding values of h_l are computed from the attenuation data in dB using anti-logarithm operation. For example, for rain attenuation ‘A’ (dB per km), and $10 \log h_l = -A$, then h_l becomes $h_l = 10^{-A/10}$

Table 4.6: Variations of h_l under different rain intensity

Recorded intensity (mm/3hr)	Converted intensity (mm/hr)	Rain Classification	Attenuation (dB/km)	h_l
0	0	No	0	1
3	1.67	Light	1.5	0.7
10	3.3	Moderate	2.4	0.57
45	15	Heavy	6.6	0.22
75	25	Heavy	9.3	0.12

4.8.3 Performance of MPSK based FSO Links under varying Rain Conditions

The performance of various MPSK links (with different order of modulation as 2, 4, 8 and 16) under various rain intensity conditions has been presented here. The other conditions assumed are moderate values of turbulence and misalignment. The performance curves are at figures (4.27, 4.28, 4.29 & 4.30). The curves spread to the right meaning SNR penalty with the increase of rain rate. The BPSK link (figure 4.27) shows a SNR of 70 dB at 10^{-4} BER value with no rain condition. However, it with respect to no rain condition suffers about 2 dB, 3 dB, 15 dB and 20 dB of SNR penalty respectively under light, moderate, heavy 1 and heavy 2 rain conditions. These values are found to be higher than the corresponding values (table 4.6) calculated directly from power law theory as explained before. The other loss factors considered in the analytical expression (equation 4.29 and 4.31) account for such differences in attenuation rate.

Similarly, the SNR value of 4-PSK link (figure 4.28) under the same BER value and no-rain-condition is 72 dB. At the other rain conditions, the link suffers about 3 dB, 5 dB, 15 dB and 18 dB respectively with respect to no rain condition. At 8-PSK and 16 PSK links, the plot has shifted to the right by 5 dB and 10 dB respectively from 4-PSK link with similar SNR penalty with respect to no rain condition. Following the similar approach, it is found that BPSK link suffer more than 30 dB penalty at very heavy rain condition (above 50 mm/hr), which however becomes more at the higher order modulation schemes.

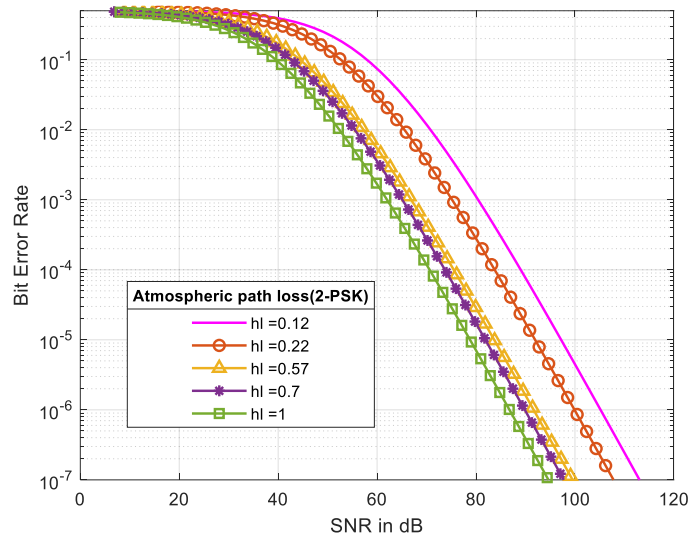


Fig.4.27: BPSK Link under varying Rain Condition.

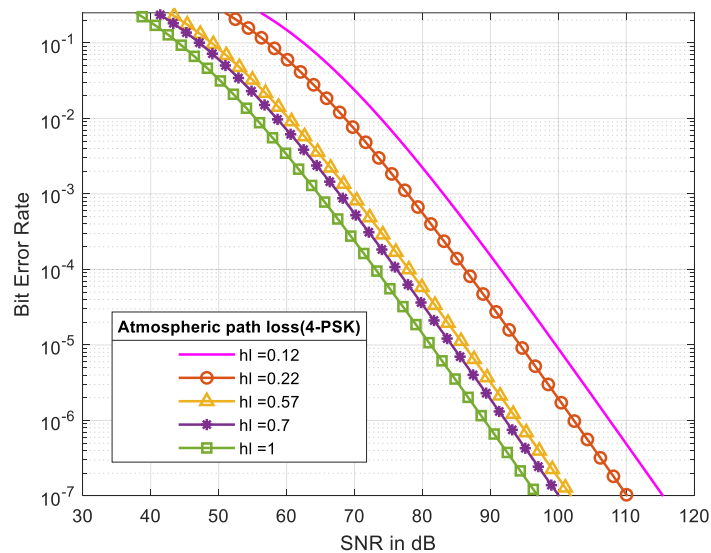


Fig.4.28: 4-PSK Link under varying Rain Condition.

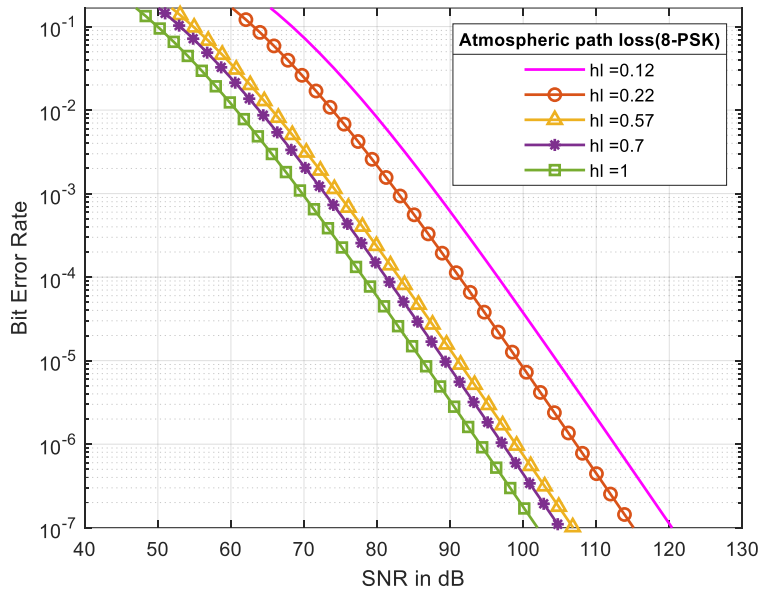


Fig.4.29: 8-PSK Link under varying Rain Condition.

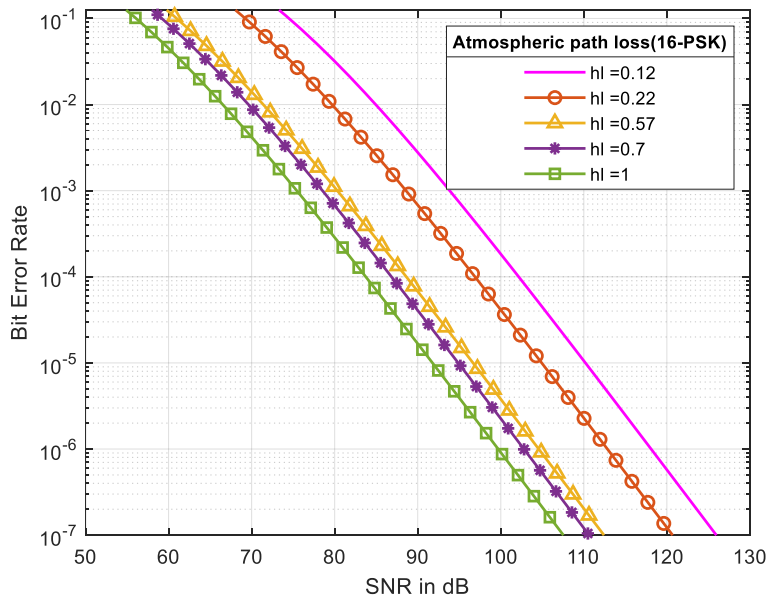


Fig.4.30: 16-PSK Link under varying Rain Condition.

4.8.4 Performance of LPPM based FSO Links under varying Rain Conditions

The performance of various LPPM links (with different order of modulation, L as 2, 4, 8 and 16) under various rain intensity conditions has been presented here. The other conditions assumed are moderate values of turbulence and misalignment. The performance curves are figure 4.31, 4.32, 4.33 and 4.34. The curves spread to the right meaning SNR penalty with the increase of rain rate. The 2-PPM link (figure 4.31) shows a SNR of about

57 dB at 10^{-2} BER value with no rain condition. However, it with respect to no rain condition suffers about 3 dB, 5 dB, 15 dB and 25 dB of SNR penalty respectively under light, moderate, heavy 1 and heavy 2 rain conditions. These values are found to be higher than the corresponding values (table 4.6) calculated directly from power law theory as explained before. The other loss factors considered in the analytical expression (equation 3.31) account for such differences in attenuation values. This rain attenuation related performance deterioration matches with one study of rain attenuation figure during pre-monsoon, monsoon and post-monsoon condition of Bangladesh weather [19].

Similarly, the SNR value of 4-PPM link under the same BER value and no-rain-condition is 50 dB. At the other rain conditions, the link suffers about 3 dB, 5 dB, 14 dB and 18 dB respectively with respect to no rain condition. At 8-PPM and 16-PPM links, the plot has shifted to the left meaning SNR gain by 4 dB and 8 dB respectively from 4-PPM link with similar SNR penalty with respect to no rain condition. Following similar approach, it is found that 2-PPM based FSO link suffer more than 30 dB penalty at extreme rain-rate condition (above 50 mm/hr), which however becomes less at the higher order modulation schemes.

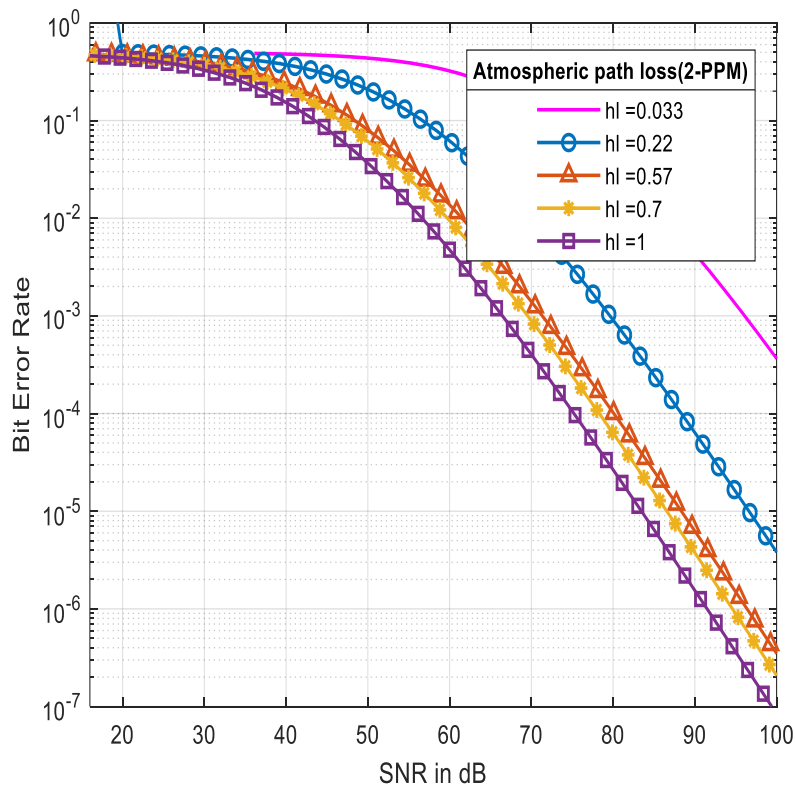


Fig.4.31: 2-PPM Link under varying Rain Condition.

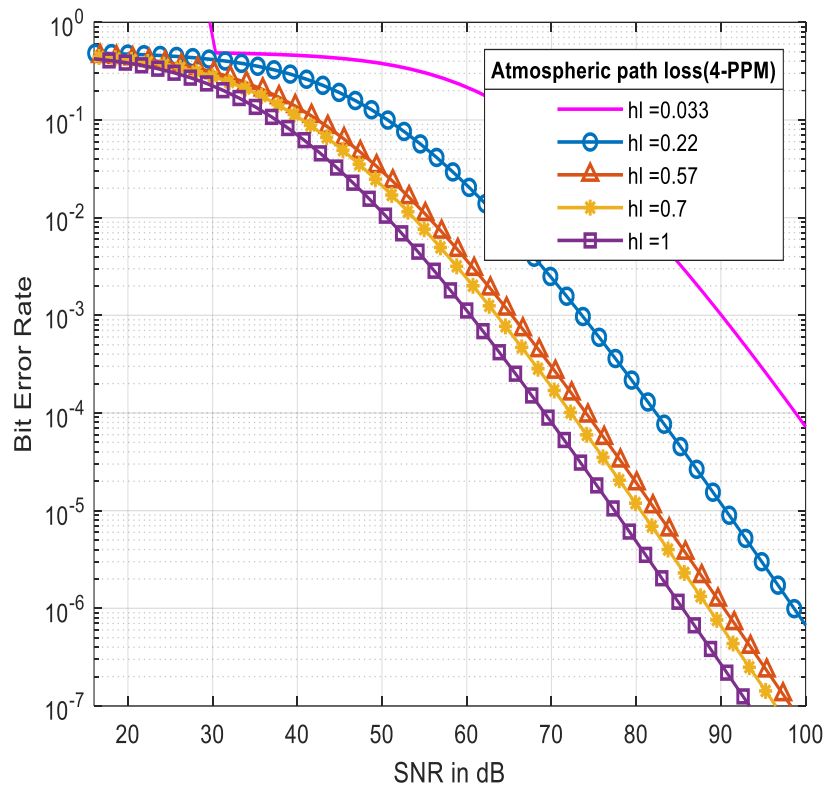


Fig.4.32: 4-PPM Link under varying Rain Condition.

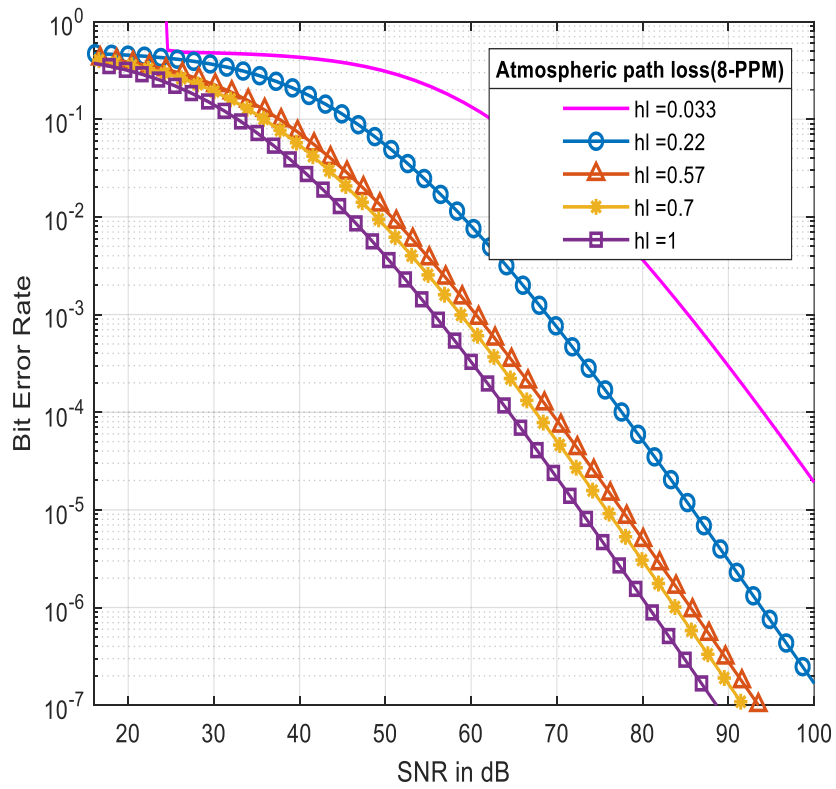


Fig.4.33: 8-PPM Link under varying Rain Condition.

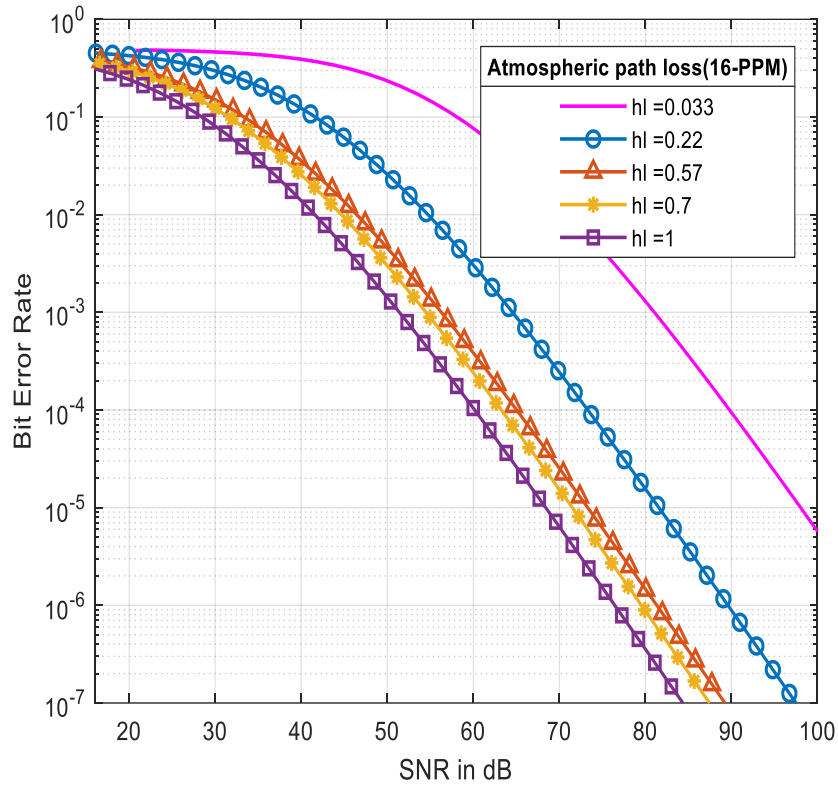


Fig.4.34: 16-PPM Link under varying Rain Condition.

4.9 Comparison with the Findings of the Existing Literatures

The current study has focused on the evaluation of the performance of MPSK-SIM and LPPM based FSO links under different factors of system parameters and environmental conditions through the analytical form of expressions. For doing so, the study has defined statistical channel models, which take into account the random and deterministic factors of the environment. The performance parameter of the link in respect of any other parameter depends not only on their relationships but also on the state of other independent parameters or conditions. Each literature on the FSO schemes has varied approaches of the study and varied states of conditions and other parameters. Unless any two studies follow similar approaches, the findings of each may have some differences. However, the comparison may provide certain ideas and confidence on the outcome and quality of the study under consideration. The table 4.7 shows the comparison between the findings of the current study and those of the existing literatures with some similarities as well as some differences.

Table 4.7: Comparison between the findings of the current study and the few literatures

Criteria	The Current Study	The Selected Literatures
BPSK link performance at different conditions	<p>The BPSK link shows 70 dB SNR at low turbulence and at BER value of 10^{-4}.</p> <p>The link suffers 20 dB penalty at same BER when changed from low to moderate or moderate to high turbulence.</p> <p>The link suffers the same penalty at similar pointing error conditions</p>	<p>[5] The OOK link shows SNR of 69 dB at same BER.</p> <p>BPSK link suffers about 19 dB penalty when changed from low to moderate and 3 dB penalty from moderate to high turbulence condition.</p>
Link degradation under switching from BPSK to higher order MPSK link	<p>Degradation of 10 dB when switched from BPSK to 8-PSK link at BER value of 10^{-4}.</p> <p>Degradation of 13 dB when switched from BPSK to 16-PSK link at same BER</p>	<p>[47] Degradation of 5 dB when switched from BPSK to 8-PSK link at BER value of 10^{-3}.</p> <p>[5] Degradation of 4 dB at switching from BPSK to 16-PSK link</p>
SNR gain at switching from low order to higher order PPM links	<p>A gain of 15 dB SNR when switched from 2-PPM to 16-PPM link at moderate conditions of turbulence and misalignment and at BER value of 10^{-4}.</p>	<p>[50] A gain of 11 dB in similar switching at strong conditions of turbulence and misalignment.</p>
Rain attenuation under the variation of rain-rate intensity condition at Bangladesh weather condition.	<p>The 2-PPM based link suffers 3, 5, 15 and 25 dB at light, moderate, heavy 1 (15mm/hr) and heavy 2 (25 mm/hr) rain conditions respectively from no-rain condition at BER of 10^{-2}.</p> <p>The 4-PPM, 8-PPM and 16-PPM each suffers about 3, 5, 14, and 18 dB at similar conditions.</p> <p>Here turbulence and misalignment are at moderate conditions.</p> <p>At similar conditions, for BPSK link the numbers are 2, 3, 15 and 20 dB. For other 4-PSK, 8-PSK and 16-PSK links the figure are same as 3, 5, 15, 18 dB.</p>	<p>[19] Pre-monsoon (moderate rain): 6.5 dB/km Monsoon (heavy rain): 23 dB/km Post-monsoon (light rain): 3 dB/km</p>

Comparison among MPSK and LPPM based links	The comparison shows the descending order of performance: BPSK, 4-PSK, 16-PPM, 8-PSK, 8-PPM, 16-PSK, 4-PPM, 2-PPM at moderate conditions of turbulence and misalignment. Here BPSK shows better performance compared to 16-PPM link by 2 dB.	[50] The comparison was done among LPPM links (2-64 modulation order) with BPSK at strong conditions of turbulence and misalignment. It shows that PPM links show better performance with the increase of modulation order. However, the BPSK link has lower performance with respect to 16-PPM by 4 dB.
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4.10 Conclusion

The chapter has computed the results, analysed the data (obtained from the secondary sources) and discussed in length about the underlying reasons of what the results are and why they are so. The chapter has been divided into several sections based on the objectives of the thesis – the review of the existing FSO channel models, the performance of the defined channel models under varying conditions and finally the same under Bangladesh rain condition. The chapter has concluded with the detailed rain-rate data obtained from BMD including the data processing, the findings on the local rain-pattern condition and its pattern generation and finally its impact on link performance.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Introduction

This is the last chapter of the thesis paper. It discusses the summary of findings, limitation of the study and recommendations on future research works.

5.2 Summary of Findings

One of the main objectives of the thesis is to define analytical models in respect of the FSO channel taking into account all atmospheric degradation factors in Bangladesh weather condition while analyzing the performance of the model with two modulation schemes under various degrading conditions according to the other objectives. The analytical expressions with the two separate modulation schemes (MPSK SIM and LPPM modulation schemes as per the objectives) have considered local rain data in addition of the random and deterministic factors that affect the performance of FSO channels. The findings of the thesis work are summarized as follows:

- The outdoor FSO communication system in Bangladesh weather condition is highly vulnerable to local conditions including its weather factors. The high humidity and airborne aerosols like dust, smoke, particles, black carbon (pollution from urbanization, especially during winter season), etc. have significant local impacts. The rain is almost a whole-the-year weather phenomenon, that affects FSO communication links. Bangladesh experiences heavy rainfall during significant part of the year with consequently heavy signal loss experienced by the link. As a single factor, fog has the highest degrading impact on the link. The fog occurrences, though, are significantly lower many times compared to the rain events in Bangladesh weather. Besides these deterministic factors, the random factors like the atmospheric turbulence and receiver misalignment (also called deviation or pointing error) cause significant SNR penalty. Overall, the FSO link operates over a short distance unless planned for a long-distance link incorporating appropriate mitigation techniques and improvement factors.

- The FSO system empirical models on absorption, attenuation, scattering, turbulence and beam wander are found to offer a robust system of analysis of outdoor atmospheric propagation. However, the challenges lie with the finding out of the appropriate values of the parameters (of each model) that correspond with the field realities. Although there are standard values for tropical/ sub-tropical weather conditions, but they may not always fit well to the local condition. They need to be validated through experimentation and measurement under the local conditions.
- BPSK FSO link suffers heavily (about 20 dB SNR penalty) at the change of turbulence condition from low to moderate or from moderate to strong at the BER value of 10^{-4} . Similar degradation is also observed at strong misalignment condition at same BER value. The performance again deteriorates with the higher order of modulation of MPSK-SIM based FSO link. The 4-PSK, 8-PSK and 16-PSK links also show similar performance reduction as BPSK link when subject to strong turbulence as well as strong misalignment condition. The 16-PSK link improves its SE efficiency by a factor of four, but suffers about 13 dB SNR penalty when switched from BPSK link at weak turbulence, weak misalignment and BER value of 10^{-8} .
- The 2-PPM FSO link at BER value of 10^{-4} suffers about 20 dB SNR penalty at the change of turbulence from low to moderate and about 27 dB penalty from moderate to strong turbulence as well as strong misalignment condition. The higher order links such as 4-PPM, 8-PPM and 16-PPM show almost similar performance at the change of turbulence condition. However, they show better performance compared to 2-PPM link. The 16-PPM link at BER value of 10^{-6} improves its SE by a factor of four and also shows 7 dB gain when switched from 2-PPM link at low turbulence condition, and 15 dB gain at strong turbulence condition. These 4 (four) LPPM links show a degradation of 18 dB due to strong misalignment condition. Finally at weak turbulence, weak misalignment and BER value of 10^{-8} the switching of 2-PPM link to 16-PPM link results in SNR gain of 15 dB.
- Comparing BER performance of the various MPSK-SIM and LPPM FSO links (with each having 4 types of links with the modulation order 2, 4, 8 and 16) at moderate turbulence, moderate misalignment and negligible path loss, it is found that BPSK shows the best performance while 2-PPM is the worst among them. Here 4-PSK link is

the second best with 1 dB difference. The 8-PSK and 16-PPM based links are at the third performance level trailing BPSK by 2 dB. Then the order is 8-PPM, 16-PSK, 4-PPM and 2-PPM. It is worth noting that comparing between individual performance levels, 8-PSK link shows similar BER performance level as with 16-PPM link.

- Bangladesh experiences heavy rain intensity from the month of May to October (which coincides with the hot weather condition). The MPSK links suffer about 15-20 dB loss due to heavy rain during this period at moderate turbulence, moderate misalignment and BER value of 10^{-4} . The LPPM links show similar performance degradation (14-25 dB loss) due to rain events during the same period at similar condition and at BER value of 10^{-2} . As per BMD rain data – on 14 locations along coastal lines from Mongla to Teknaf including Dhaka inland point - collected from BMD database for 2015-2019, there are no violent or very heavy rain occurrences. Bangladesh, though, experiences extreme rain condition (also called very heavy or violent rain condition) occasionally during this period, which cause instant flooding in the affected areas. According the signal degradation of these links would be much higher than the values shown here above.
- From the findings above, both MPSK-SIM and LPPM based links suffer heavily from strong turbulence, strong misalignment and heavy rain condition. The degradation value depends on many factors like the state of other conditions, path loss, BER value, the modulation schemes, the order of modulation, etc. In general, the SNR degradation due to change of turbulence conditions is 20 dB for MPSK and 20-27 dB LPPM links at BER value of 10^{-4} . The strong misalignment causes a degradation of 20 dB for MPSK and 18 dB for LPPM schemes. Lastly, the heavy rain conditions of Bangladesh cause a signal loss of 15-20 dB for MPSK and 14-25 dB for LPPM schemes.
- The higher modulation order based FSO links provide better SE with disadvantage of SNR penalty for MPSK, but with the advantage of SNR gain for LPPM schemes. The penalty of MPSK schemes becomes as high as 13 dB when switched from BPSK to 16-PSK link. On the other hand, the gain for LPPM schemes becomes as high as 15 dB when switched from 2-PPM to 16-PPM link. To overcome the heavy loss factors due to turbulence, misalignment and rain condition it is very essential to apply modulation

schemes with higher gain factors and appropriate mitigation schemes in the FSO link system.

- Both higher order MPSK-SIM and LPPM based FSO links have their individual merits and demerits relative to each other. Higher order MPSK is beneficial for band-width efficiency and high data rate applications. But it is more sensitive to phase noise and atmospheric turbulence. Considering the requirement of coherent detection, its system is more complex and expensive. On the other hand, higher order LPPM is better power efficient and more advantageous in turbulent environment due to its strong resilience against amplitude jitters, although it has sensitivities to delay or timing jitters. Its system has some complexities due to slot and timing synchronization requirement. It is less complex than MPSK system as no phase tracking is required. However, it requires more bandwidth and provides lower data rate compared to PSK. Considering Bangladesh environment with unfavorable conditions, both schemes are subject to link degradation and even link break due to extreme conditions. The high-speed high-order FSO link with either modulation scheme fits better for short distance application in Bangladesh environment. The link needs to have adaptive modulation schemes and suitable improvement factors to maintain the standard continuity of the link during adverse weather conditions. The FSO link is also suitable for hybrid application or mixed link configuration with radio and FOC signal.

5.3 Limitation of the Study

The study is analytical research which has defined the FSO channel models based on MPSK and LPPM modulation schemes. These models have been used to analyse BER performance of the link systems under the varying parameters of the atmospheric conditions. The parameters have been assumed according to the general standard values. The rain parameters, however, have been defined based on the rain data obtained from BMD. Although the variation of BER performance of both types of links complies with the general concept and theory of FSO communication including its modulation schemes, such results could be more credible if it could be validated and verified with the performance of real FSO links or through an experimental one. This is simply a theoretical study and the results have been verified through MATLAB software-based coding output.

5.4 Scope on future Research

The following further researches could be undertaken based on the proposed models of FSO links and on the findings of this thesis:

- One real FSO system or one experimental system may be used to evaluate various FSO system parameters under Bangladesh weather condition and compare the results with the performance of the models of this thesis work. The wind data of BMD may be incorporated into the model of atmospheric turbulence to determine its parameters in Bangladesh weather condition. Performance of the outdoor FSO system in respect of link budget analysis may be done using the proposed FSO models of the study, particularly in the rain-affected environment. Again, from the local monthly accumulated rain data of BMD, the statistics of rain attenuation may be estimated taking into account the effects of drop size distribution.
- The defined FSO models of the current study could be modified to extend them to define other advanced or hybrid modulation schemes. Again, the expressions of the existing modulation schemes may need to be evaluated and small modification be made to avoid simplified assumptions and incorporate the new parameters where applicable. Similar approach may be taken for performance evaluation of MFSK-SIM and MQAM-SIM based FSO links.
- The proposed models may be expanded to accommodate various mitigation techniques or improvement factors of the FSO system in order to counteract the losses encountered in Bangladesh weather condition. Advanced modulation schemes with appropriate error control codes may be introduced into the proposed models of the current study. The proposed models may be used to design and evaluate the hybrid FSO system with RF link or the mixed link like RoFSO link or multi-hop FSO link.
- High data rate FSO system may be designed and evaluated using the proposed models. Again, the security features of FSO links may be assessed and compared with the other link systems.

5.5 The Concluding Remarks

This study has mainly focused on the performance analysis of MPSK and LPPM based FSO links defining the FSO channel model for each case. The BER performances of these models under increasing order of modulation, and also the variation of pointing error, turbulence and local rain intensity comply with the general concept and theory of FSO link system. The study analysis has confirmed that FSO links degrade heavily under turbulence, misalignment and local rain condition. The higher modulation order based FSO links provide better SE with disadvantage of SNR penalty for MPSK, but with the advantage of SNR gain for LPPM schemes. The high speed, high order FSO link along with its environment impairments fits better for a short distance application in Bangladesh weather condition and needs to be modulation-adaptive with added improvement features to maintain its link continuity. It can adaptively switch to lower order modulation scheme with reduced data-rate from higher order scheme to address worsening weather condition. The study is expected to provide very valuable insights into the impact of local conditions in FSO system under Bangladesh environment and its findings would be very helpful for the system designer, operator and maintainer. The thesis work may be extended to evaluate other link configurations, add mitigation techniques and investigate the performance of MFSK-SIM and MQAM-SIM based FSO links.

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