PERFORMANCE ANALYSIS OF VARIOUS FSO MODELS FOR NEXT GENERATION COMMUNICATION

DISSERTATION-I

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Requirement for the award of the Degree
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MASTER OF TECHNOLOGY IN

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By

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TOPIC APPROVAL PERFORMA

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Qualitative Assessment of Proposed Topic by PAC		
Sr.No.	**Parameter**	**Rating (out of 10)**
1	Project Novelty: Potential of the project to create new knowledge	6.67
2	Project Feasibility: Project can be timely carried out in-house with low-cost and available resources in the University by the students.	5.33
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Final Topic Approved by PAC: **Investigation of various parameters in Free Space Optics for next Generation Communication.**

Overall Remarks: Approved

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CERTIFICATE

This is to certify that Ramandeep Kaur Gill bearing Registration no. 11614503 have completed objective formulation/Base Paper implementation of the thesis titled, **“Performance analysis of various FSO (Free Space Optics) Models for next generation communication”** under my guidance and supervision. To the best of my knowledge, the present work is the result of his original investigation and study. No part of thesis has ever been submitted for any other degree at any university.

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We are also indebted to all authors of the research papers and books referred to, which have helped us in carrying out the research work.

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DECLARATION

I, Ramandeep Kaur Gill, student of M. Tech under Department of Electronics and Communication of Lovely Professional University, Punjab, hereby declare that all the information furnished in this Dissertation-I report is based on my own intensive research and is genuine.

This report does not, to the best of our knowledge, contain part of my work which has been submitted for the award of my degree either of this University or any other University without proper citation.

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ABSTRACT

In recent years, free space optical (FSO) communication has gained significant importance owing to its unique features: large bandwidth, license free spectrum, high data rate, easy and quick deploy ability, less power and low mass requirement. FSO communication uses optical carrier in the near infrared (IR) and visible band to establish either terrestrial links within the Earth's atmosphere or inter-satellite/deep space links or ground-to-satellite/satellite-to-ground links. It also find its applications in remote sensing, radio astronomy, military, disaster recovery, last mile access, back-haul for wireless cellular networks and many more. However, despite of great potential of FSO communication, its performance is limited by the adverse effects (viz., absorption, scattering and turbulence) of the atmospheric channel. Out of these three effects, the atmospheric turbulence is a major challenge that may lead to serious degradation in the bit error rate (BER) performance of the system and make the communication link infeasible In this thesis report the comprehensive survey of various FSO challenges faced by FSO communication system and different "C^2n" models have been focused to know which would be more efficient to be used in FSO channel models depending on certain parameters. Although there are various FSO channel models that can be used but the more efficient is Gamma Gamma model as it is used in both strong as well as weak turbulences. C^2n i.e. refractive index is the main parameter in Gamma Gamma model that is changing its value in different conditions with respect to various parameters.

LIST OF ABBREVIATION

FSO -Free Space Optical communication

FSP -Free Space Photonics

WOC – Wireless Optical Communication

AFTS - Airborne Flight Test System

LC - Laser Cross-link System

GOLD - Ground/Orbiter Lasercom Demonstration

OCD - Optical Communication Demonstrator

AMOS - Automated Meteorological Observing System

STROPEX - Stratospheric Optical Payload Experiment

MLCD - Mars Laser communications Demonstration

NIR - near infrared

IEC - International Electro technical Commission

OICETS - Optical Inter-Orbit Communications Engineering Test Satellite

HVB - Hufnagel Valley Boundary model

SLC-D - Submarine Laser Communication Day model

IRT - Index of Refraction Turbulence

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CHAPTER-1
INTRODUCTION

1.1 Overview of FSO communication:

FSO is a free space optical transmission system that is a wireless form of connection designed for the interconnection of two points which have a direct line of sight (LOS). FSO sometimes also called FSP (Free Space Photonics). In recent few years, tremendous growth and advancements has been observed in information and communication technologies. With the increase in usage of high speed internet, video-conferencing, lie streaming etc., the bandwidth and capacity requirements are also increasing drastically. This ever growing demand of increase in the usage of data and multimedia services has led to congestion in conventionally used radio frequency (RF) spectrum and arises a need to switch from RF carrier to optical carrier. Unlike RF carrier where spectrum usage is restricted, optical carrier does not require any spectrum licensing and therefore, is an attractive prospect for high bandwidth and capacity applications. Moreover, WOC i.e. 'Wireless Optical Communication' is the technology that uses optical carrier to transfer information from one point to another through an unguided channel that may be an atmosphere or free space. WOC is also considered as next frontier for high speed broadband connection as it offers extremely high bandwidth, ease of deployment, unlicensed spectrum allocation, reduced power consumption (~1/2 of RF), reduced size (~1/10 the diameter of RF antenna) and improved channel security [1]. It can be classified into two broad categories, namely Indoor and Outdoor Wireless Optical Communication. Indoor WOC uses IR or visible light for communicating within a building where a possibility of setting up a physical wireless connection is not possible [2]-[9]. Indoor WOC is classified into four generic system configurations i.e., directed line-of-sight (LOS), non- directed line-of-sight (LOS), diffused and tracked. Outdoor WOC is also termed as Free Space Optical (FSO) communication.

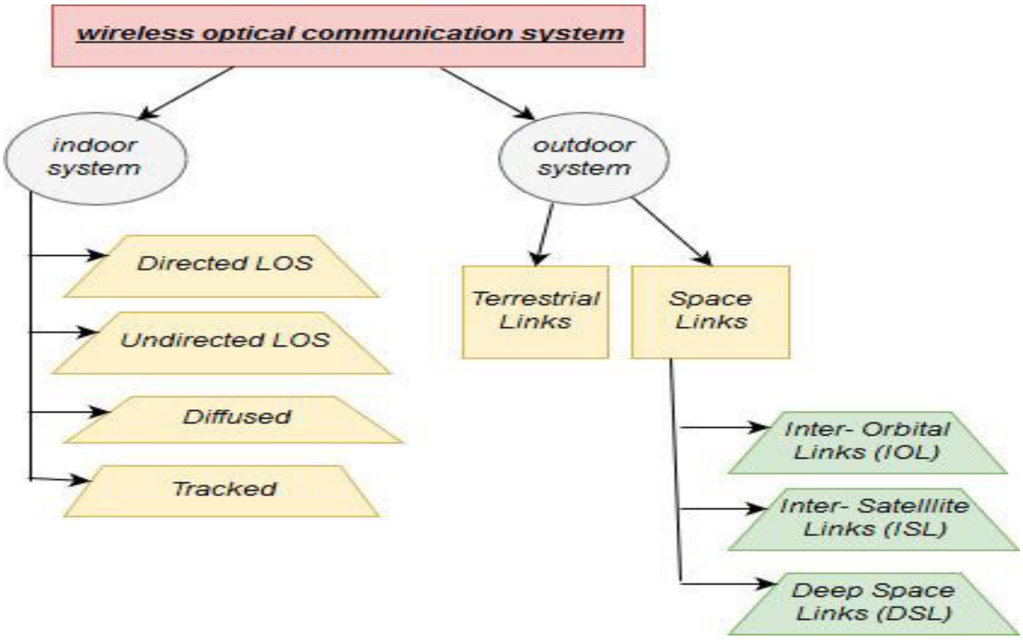


Figure1: classifications of wireless optical communication system

FSO communication systems are further classified into terrestrial and space optical links that includes building-to-building, ground-to-satellite, satellite-to-ground, satellite-to-satellite, satellite-to-airborne platforms (unnamed aerial vehicles (UAVs) or balloons), [10]-[12] etc. Above figure 1 illustrates the classification of WOC system. The basic principle of FSO transmission is similar to the fibre optic communication except that unlike fibre transmission, in this case the modulated data is transmitted through unguided channel instead of guided optical fibre. The initial work of FSO communication started almost 50 years back for defence and space applications where US military used to send telegraphic signals from one point to another using sunlight powered devices. In year 1876, Alexander Graham Bell demonstrated his first wireless telephone system [13],[14] by converting sound waves to electrical telephone signals and transmitted the voice signal over few feet using sunlight as carrier. Thereafter, with the discovery of first working laser at Hughes Research Laboratories, Malibu, California in 1960 [15], a great advancements was observed in FSO technology. Large number of experiments were performed in military and aerospace laboratories that demonstrate ground-to-satellite, satellite-to-ground, satellite-to-satellite, ground-to-ground links. It has also resulted in various successful experimentations like:

(i) Airborne Flight Test System (AFTS)- a link between aircraft and ground station at New Mexico [16],
(ii) Laser Cross-link System (LCS)- full duplex space-to-space link for geosynchronous system [17],
(iii) Ground/Orbiter Lasercom Demonstration (GOLD) – first ground-to-space two way communication link [18],[19],
(iv) Optical Communication Demonstrator (OCD)- laboratory prototype for demonstrating high speed data transfer from satellite-to-ground,
(v) Stratospheric Optical Payload Experiment STROPEX (CAPANINA project)- high bit rate optical downlink from airborne station to transportable optical ground station [20],
(vi) Mars Laser communications Demonstration (MLCD)- provides upto 10 Mbps data transfer between Earth and Mars [21], and
(vii) Airborne laser optical link (LOLA) –first demonstration of a two-way optical link between high altitude aircraft and GEO satellite (ARTEMIS) [22].

Another mission by NASA is laser communication relay demonstration (LCRD) to be launched in this year only that will demonstrate optical relay services for near earth and deep space communication. Due to increase in research area as well as commercial uses of this technology, the FSO was considered a better, reliable medium in telecommunication and its research was enhanced day by day from 1960s to till now. It has drawn an intention in the telecommunication industry, due to its cost effectiveness, easy installation, quick establishment of communication link especially in case of disaster management scenario, high bandwidth provisioning and the wide range of applications. FSO is full duplex that is it can transmit data on both sides. The data rate provided by FSO is 10 Gbps which is very high than RF technology. It is operated mainly between 780-1600 nm wavelength bands [23]. As day by day atmospheric conditions of FSO varies, various factors reduce our visibility to view distant objects, [24]In FSO system for communication especially the laser beam is the only carrier that carries information signal in free space, hence the LOS (Line Of Sight) is mandatory to receive the transmitted information. Although FSO has good networking services still practically it has certain limitation factors also such as **scintillations, scattering,** [25] **Atmospheric losses:** Rain, Snow, Fog or Smog and **misalignment losses:** beam wander or building sway that can easily block transmission path and can affect the network. So to analyse the performance of FSO channels various models have been proposed which comes under channel modelling. To reduce the effect of channel losses various techniques such as modulation, channel coding, and diversity techniques are being used. ITU-Rec.G.640 is a recommendation that provides a procedure for establishing that two co-located FSO transmission systems will not interface each other. Calculations of the conditions have been met to prevent interference in some examples, co-located FSO system is also included in this recommendation. Typically links in FSO are between 30 m and 5 km, although longer distances can be deployed such as 8-11 km are also possible depending upon the speed and required ability. As the demand for high bandwidth is being increased, to fulfill it finally the most viable alternative is FSO. The technology facilitates an optimal solution, Bandwidth scalability, speed of deployment (hours versus week or months), Redeployment and Portability, and Cost effectiveness (one fifth the cost of installing fibre optics). Currently several companies are working on design and manufacturing of FSO systems as outdoor wireless transmission solutions such as canon (Japan), Cassidian (Germany), fsona (Canada), Geodesy (Hungary), Laser ITC (Russia), Novasol (USA), Plaintree System (Canada) and North Hi-tech (UK) among others.

1.2 FSO block diagram:

The major three block of FSO block diagram are Transmitter, communication channel and Receiver that are discussed and shown below in figure 2.

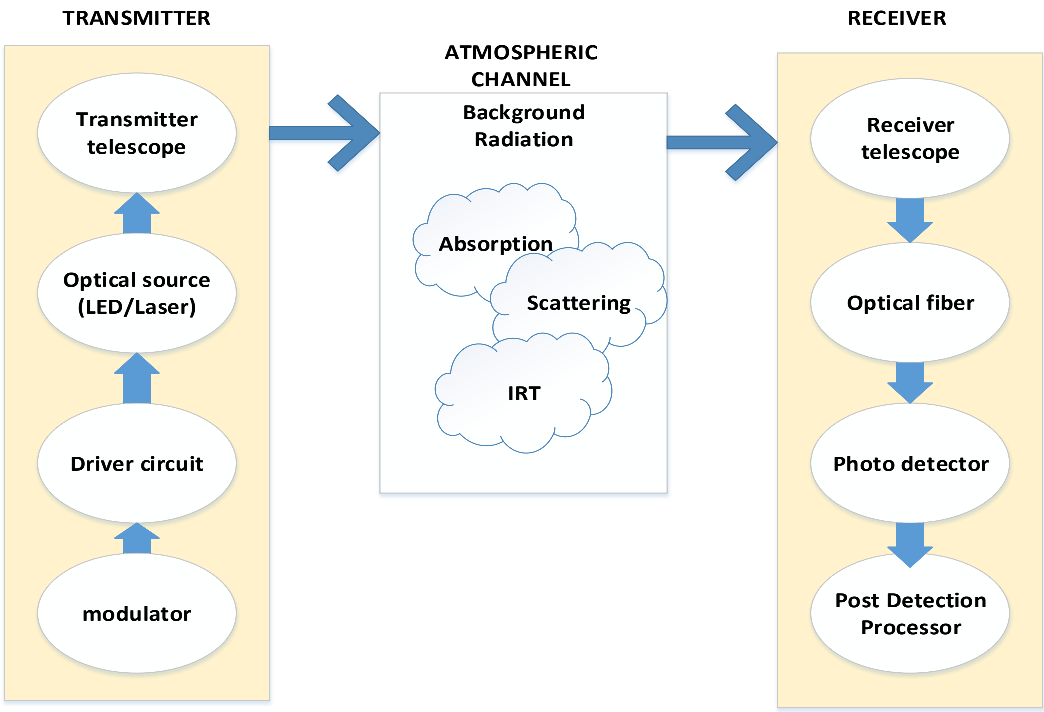


Figure 2: FSO block diagram

- **TRANSMITTER**: The transmitter has a primary task of modulating the source message onto the optical carrier for propagation through the atmosphere to the receiver end of the communication channel [26-28]. The transmitter is made up of modulator, driver circuit, optical source and transmitter telescope. The modulator is responsible for modulating the source message onto optical carrier. OOK i.e. On off Keying modulation scheme is most common used in FSO communications. OOK is very sensitive to distortions in signal amplitude. Atmospheric conditions such as clouds and fog can significantly affect its performance by attenuating the received signal. The exact wavelength and the phase of optical carrier are however irrelevant for the demodulation of received signal. The source has modulated output on an optical carrier, laser or LED which is then transmitted as an optical field through the atmospheric channel. The modulated light source, which is typically a Laser or Light Emitting Diode (LED), provides the transmitted optical signal and determines all the transmitter capabilities of the system. For telecommunication purposes, only lasers that are capable of being modulated at 20 Mbit/s to 2.5 Gb/s can meet current marketplace demands. In addition, how the device is modulated and how much modulated power is produced are both important to the selection of device. Lasers in the 780nm-850nm and 1520nm-1600nm spectral bands meet frequency requirements and are available as off-shelf products. Within these two wavelength windows, FSO systems should have the following characteristics:

- Ability to operate at higher power levels (important for longer-distance FSO systems).
- High-speed modulation (important for high-speed FSO systems).
- Small footprints and low-power consumption (important for overall system design and maintenance).
- Ability to operate over a wide temperature range without major performance degradation (important for outdoor systems).
- Mean Time between Failure (MTBF) that exceeds 10 years.

To meet the above all requirements, FSO manufacturers generally use VCSELs for operation in the shorter- IR wavelength range and Fabry-Perot (FB) or Distributed Feedback Lasers (DFB) for operation in the longer-IR wavelength range. Several other types of lasers are not suitable for high-performance FSO systems. Some of the other Optical aspects that should be considered important in optical transmitter system are size, power and beam quality, which determines laser intensity and minimum divergence obtainable from the system.

- **ATMOSPHERIC CHANNEL:** FSO technology uses atmospheric channel as a propagating medium whose properties are random function of space and time. It makes FSO communication a random phenomenon that is dependent on weather and geographical location. Various unpredictable environmental factors like clouds, snow, fog, rain, haze etc., cause strong attenuation in the optical signal and limit the link distance at which FSO could be deployed some of other parameters such as scattering, absorption, IRT etc. may effects the FSO link design badly. **Scattering** is basically defined by the process where light, sound or other moving particles are forced to deviate from a straight trajectory by one or more paths due to localized non uniformities in the medium through which they pass. It is of two types: Rayleigh and Mie scattering. The atmospheric **absorption** is a wavelength dependent phenomenon. There are some typical values of molecular absorption coefficients for clear weather conditions. The wavelength range of FSO communication system is chosen to have minimal absorption i.e. atmospheric transmission window. In this window, the attenuation due to molecular or aerosol absorption is less than 0.2 dB/km. There are several transmission windows within a range of 700-1600nm. Majority of FSO systems are designed to operate in the windows of 780-850nm and 1520-1600nm. These wavelengths have been chosen because of readily availability of transmitter and detector components at these wavelengths. **IRT** is Index of Refraction turbulence effect that mainly occurs in long range communication links. It causes fading resulting in phase- perturbations which evolves in far- field speckle patterns and distorted wave fronts.

- **RECEIVER:** At the receiver, the field is optically collected and a photo-detector transforms the optical field to an electrical current. The receiver processes the detected electrical current to recover the original transmitted information. There are number of factors to consider when examining the effectiveness of the receiver in an FSO system; these include the type of detector used, the sensitivity rating and size of the detector, the size and design of the receiver optics, and the operating wavelength itself. In order to correctly assess the efficiency of the overall system, one must also take into account the number and the power of the laser being used to generate the signal. Types of FSO equipment come in two basic types: PIN and APD. The PIN detector is a lower cost detector that has no internal gain, while APD is more expensive but more sensitive detector with internal gain. The size of receiver optics is also important; a large area receive optic contributes to reducing errors due to scintillation. Scintillation is atmospheric turbulence due to solar loading and natural convection, causing temporally and spatially varying refractive index changes in air. As a laser beam propagates through atmosphere, there is a time-varying intensity at the receiver due to this phenomenon; this is referred to as scintillation. This is quite similar to the apparent twinkling of the stars or distant city lights, which is due to same effect. The result is that an FSO communications receiver can experience error bursts due to surges and fades in received signal strength. A collecting aperture i.e. much larger than the spatial scale of scintillation provides an averaging effect of the localized surges and fades, thus improving the error rate. The large-aperture approach is more effective for scintillation reduction than multiple smaller apertures, which perform less averaging at each lens. Another way to mitigate this problem is to use multiple transmitters, each of which takes a slightly different path through the atmosphere, which also contributes an averaging effect. Another problems that may takes place at receiver side are interferences, signal distortion, etc. The operating wavelength of an FSO system also contributes to the performance of the receiver. It is generally true that high-quality photodiodes at both 800nm and 1500 nm achieve comparable quantum efficiencies. However, the sensitivity of a 1550 nm receiver is generally lower due to noise floor. So it all comes down to “usable real-world link margin”.

1.3 Advantages and Applications of FSO:

FSO systems are used for high data rate communication between two fixed points i.e. source and destination over the distances up to several kilometres. In comparison to RF, the FSO link has high optical bandwidth availability and much higher data rates. Recently 10 Gbps transmission rate is already achieved in the market with terrestrial OWC products and is expected to achieve more in coming years. FSO system also provides high reuse factor, more secure, robustness to electromagnetic interference and frequency used in this technology is above 300 GHz i.e. unlicensed worldwide [29]. Moreover, it is easy to deploy and reinstall the FSO systems without the cost of any dedicated fibre connection. FSO systems are also used in wide range of applications, some of them are elaborated below: [29-33]

- **Campus/Enterprise connectivity:** FSO can bridge the multiple buildings in a campus or a corporate network supporting ultrahigh speeds without the cost of dedicated fibre links.
- **Video Surveillance and Monitoring:** Surveillance cameras are widely deployed in commercial, public safety, law enforcement and military applications. For all these applications FSO is preferred more than any other wireless technology due to its high QOS, it can support high -quality video transmission.
- **Back- Haul for Cellular systems:** As the number of users is increasing day by day, the requirements of bandwidth utilization are also increased, so to achieve a better quality or throughput FSO technology is used.
- **Redundant link and Disaster Recovery:** FSO can be also helpful in case of a natural disaster where local infrastructure could be damaged**.**
- **Security:** It provides a secure connection.
- **Broadcasting:** In Broadcasting, live events such as sports and ceremonies or TV reporting from remote areas or war zones, signals from the camera are sent to a broadcasting vehicle i.e. connected to the central office via satellite uplink.

1.4 Choice of wavelength in FSO communication:

Wavelength selection is very important in FSO communication, design parameters as it affects link performance and detector sensitivity of the system, since antenna gain is inversely proportion to operating wavelength, therefore, it is more beneficial to operate at lower wavelengths. However, higher wavelengths provides better link quality and lower pointing induced signal fades [34]. Therefore, a careful optimization of operating wavelength in the design of FSO link helps in achieving better performance. The choice of wavelength strongly depends o
n atmospheric effects, attenuation and background noise power. Further, the availability of transmitter and receiver components, eye safety regulations and cost deeply impacts the selection of wavelength in FSO design process.

The International Commission on Illumination [35] has classified optical radiations into three categories:

- IR-A (700nm to 1400nm),
- IR-B (1400nm to 3000nm) and
- IR-C (3000nm to 1mm).

It can be sub classified into:

(i) near infrared (NIR) ranging from 750nm to 1450nm is a low attenuation window and mainly used for fibre optics,

(ii) short infrared (SIR) ranging from 1400nm to 3000nm out of which 1530nm to 1560 nm is a dominant spectral range for long distance communication,

(iii) mid-infrared (MIR) ranging from 3000nm to 8000nm is used in military applications for guiding missiles,

(iv) long infrared (LIR) ranging from 8000nm to 15µm is used in thermal imaging, and

(v) Far-infrared (FIR) is ranging from 15 µm to 1mm.

Almost all commercially available FSO system are using NIR and SIR wavelength range since these wavelengths are also used in fibre optic communication and their components are readily available in market. The wavelength selection for FSO communication has to be eye and skin safe as certain wavelengths between 400nm to 1500nm can cause potential eye hazards or damage to retina [36]. Under International Electro technical Commission (IEC), lasers are classified into four groups from class 1 to class 4 depending upon their power and possible hazards [37]. For same safety class, FSO system operating at 1500nm can transmit more than 10 times optical power than system operating at shorter wavelengths like 750nm or 850 nm. It is because cornea, the outer layer of eye absorb energy of the light at 1550 nm and does not allows it to focus on retina. Laser power level up to which person can be exposed without any hazardous effect on eye or skin. Table I summarize various wavelengths used in practical FSO communication for space applications. [38-53]

Mission	***Laser***	***Wavelength***	***Other parameters***	***Applications***
Semi-conductor Inter-satellite Link Experiment (SILEX)	AlGaAs laser diode	830 nm	60mW, 25 cm telescope size, 50 Mbps, 6μrad divergence, direct detection	Inter- satellite communication
Ground/Orbiter Lasercom Demonstration (GOLD)	Argon-ion laser/GaAs laser	Uplink:514.5 nm Downlink:830 nm	13W, 0.6 m and 1.2 m tx. And rx. Telescopes size, respectively, 1.024 Mbps, 20 μrad divergence.	Ground-to-satellite link
RF Optical System for Aurora (ROSA)	Diode pumped Nd:YVO4 laser	1064 nm	6W, 0.135 m an 10m tx, and rx. Telescopes size, respectively, 320 kbps	Deep space fade
Deep space Optical Link Communication Experiment (DOLCE)	Master Oscillator Power Amplifier (MOPA)	1058 nm	1 W, 10-20 Mbps	Inter-satellite/ deep space mission
Mars Orbiter Laser Altimeter (MOLA)	Diode pumped Q	1064 nm	32.4 W , 420 μrad divergence,	Altimetry

	switched Cr:Nd:YAG		10 Hz pulse rate, 618 bps, 850 µrad receiver field of view (FOV)	
Altair UAV to ground Lasercomm Demonstration	Laser diode	1550 nm	200mW, 2.5 Gbps, 19.5 µrad jitter error, 10 cm and 1 m uplink and downlink telescope size , respectively.	UAV-to-ground
Mars Polar Lander	AlGaAs laser diode	880 nm	400 nJ energy in 100 nsec pulses, 2.5 khz rate, 128 kbps.	Spectroscopy
Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation(CALIPSO)	Nd:YAG	532nm/1064nm	115 mJ energy, 20 Hz rate, 24 ns pulse	Altimetry
KIrari's Optical Downlink to Oberpfaffenhofen (KIODO)	AlGaAs laser diode	847nm/810nm	50 Mbps, 40 cm and 4m tx. And rx. Telescopes size, respectively, 5 µrad divergence	Satellite-to-ground downlink
airborne laser optical link (LOLA)	1.umics fibre laser diode	800 nm	300 mW, 50 Mbps	Aircraft and GEO satellite link
Tropospheric Emission Spectrometer (TES)	Nd:YAG	1064 nm	360 W, 5 cm telescope size, 6.2 Mbps	Interferometry
Galileo Optical Experiment (GOPEX)	Nd:YAG	532 nm	250 mJ, 12 ns pulse width,110	Deep space mission

			μrad divergence, 0.6 m primary and 0.2 m secondary transmitter telescope size, 12.19 ×12.19 mm CCD array receiver	
Engineering Test Satellite VI (ETS-VI)	AlGaAs laser diode (downlink) Argon laser (uplink)	Uplink:510 nm Downlink:830 nm	13.8mW, 1.024 Mbps bidirectional link, direct detection, 7.5 cm spacecraft telescope size, 1.5 m earth station telescope	Bidirectional Ground-to-satellite link
Optical Inter-orbit Communications Engineering Test Satellite (OICETS)	Laser diode	819 nm	200 mW, 2.048 Mbps bidirectional link, direct detection, 25 cm telescope size	Bidirectional Inter-orbit link
Solid States Laser Communications in Space (SOLACOS)	Diode pumped Nd:YAG	1064 nm	1 W, 650 Mbps return channel and 10 Mbps forward channel, 15 cm telescope size, coherent reception	GEO-GEO link
Short Range Optical Inter-satellite Link (SROIL)	Diode pumped Nd:YAG	1064 nm	40mW ,1.2 Gbps, 4cm telescope size, BPSK homodyne detection	Inter-satellite link

Mars Laser Communications Demonstrations (MLCD)	Fibre laser	1064nm and 1076nm	5W,1-30 Mbps, 30 cm tx. Telescope size and 5 m and 1.6 m rx. Telescope size, 64 PPM	Deep space mission

Table1: various wavelengths used in practical FSO communication for space applications

CHAPTER-2
LITERATURE SURVEY

This chapter concentrates on the literature review for Free Space Optical systems, FSO based systems, comparison of various channel models, Different channel models, and their effects by atmospheric turbulence with their estimated parameters are discussed. By studying and analysing data through various sources, I focused my work towards the improvement and analysing various c^2n models i.e. refractive index models of FSO. Over last two decades, FSO has become more and more interesting as an adjunct or alternative to radio frequency communication. Although FSO is a medium with high bandwidth having maximum data rates and security issues in present era. But still the turbulent atmosphere affects the performance of the link [54]. Humidity, water vapour, signal absorption, beam scintillation, spreading and wandering are some factors which causes laser beam degradation. Maintaining a free space optical link between two junctions is a tough challenge and need enhancement in its features. The optical fibre was first developed in 1970 by corning glass works. At the same time, GA As semiconductor lasers were developed for transmitting light through fibre optic cables. The first generation fibre optic system was developed in 1975, it used GA As semiconductor lasers, operated at a wavelength of 0.8 μm and bit rate of 45Mb/s with 10 Km repeater spacing [55]. Below figure 2 discusses the optical fibre data rates enhancements w.r.t time.

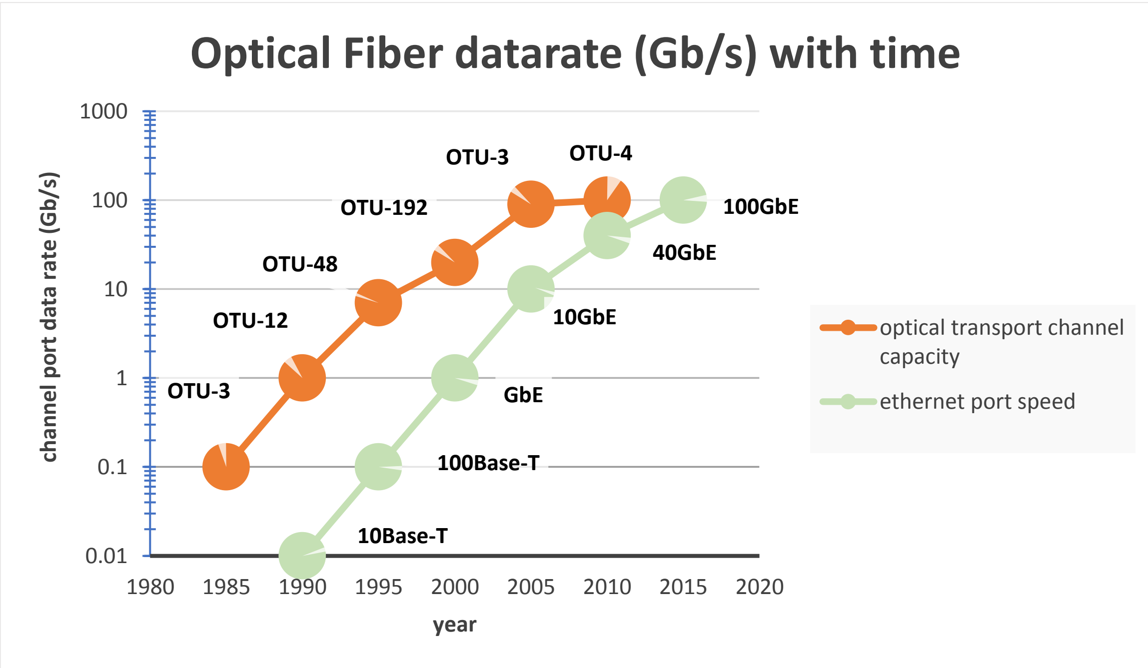


Figure 3: optical fibre data rate with time

Moreover the following table 2 showcase the papers or the evolution came in free space optics with a new technology.

REFERENCES	*OBJECTIVE*	*OBSERVATION*
[56]	The main focus is on OWC in unguided propagation media	To fulfil the demand of larger bandwidth and higher data

	through use of some optical carriers. Although FSO has vast number of advantages and applications but still FSO signal can be affected by certain regimes.	rates, FSO needs to support the requirements by overcoming the major problems in PHY layer design. Major issues to be considered are regimes in atmosphere.
[57]	In this paper the effect of fog & snow on FSO and radio communication is being discussed according to the droplet size and other conditions.	The BER for FSO system due to these two factors is more than the BER of RF system. So RF is used as backup link. So that signal can be switched to RF when FSO is blocked due to atmospheric conditions.
[58]	By using 3 optical transmission windows, 850nm, 1310 nm and 1510nm, the link having range 500 meters upto attenuation of 70 dB/km is analysed.	From all the three windows the 1310 nm gives more efficient result as transmission is in higher levels of attenuation.
[59]	The FSO system having range 1km and data rate 2.5 Gb/s is analysed with clear weather and fog conditions.	It is analysed that as we move from clear weather to heavy fog the Q factor decreases immensely.
[60]	FSO attenuation model for visibilities range from 9 to 12 km with the help of Kruse attenuation model.	The comparison of Q factor is being discussed with a new proposed model whereas in old the Q factor was constant.
[61]	Scintillation index (SI) of FSO channel with Phase screen modelling is discussed with help of some experimental values.	SI for three different sizes of aperture under moderate turbulence condition is discussed. Also observed that simulation gives consistently higher values than the experimental measured parameters.
[62]	Gamma Gamma fading model is reviewed under all types of regimes and is also better under correlation than other fading channel models.	As gamma Gamma can be used for all regimes, it can also work under sub-channel correlation effect where other

		simple channels are unable to perform better.
[63]	Calculation of impact on atmospheric turbulence conditions on FSO communication links using gamma Gamma model.	The two separate regions with low height (2m to 10m with difference 2m) and high height (15m to 35m with difference 5m) are being observed, from both its concluded that at high height performance is more better.
[64]	Performance of FSO system with BPSK & QPSK modulation. FSPL (Free Space Path Loss) and SI is also considered.	It is observed that choice of modulation technique depends on the achieved value of SNR i.e. if SNR value is more than 20 dB then QPSK is used as it provides higher data for signal transmission. (OOK can be also used due to its higher efficiency)
[65]	Error rate in performance of coded FSO links over Gamma Gamma turbulence channel model.	In this paper the investigation of the error rate performance of coded FSO system operating over atmospheric turbulence channel i.e. gamma Gamma model, which is used under all type of regimes has been discussed. Also the transfer function technique is employed to obtain upper bounds on BER performance of coded FSO link with OOK modelling.
[66]	Challenges & Mitigation techniques of Free Space Optical communication.	In this paper the various challenges & mitigation techniques have been discussed in order to have high link availability & reliability of FSO system.
[67]	Survey of Gamma Gamma model	In this paper the Gamma-gamma fading model is reviewed which gives impressive results under all

		types of turbulence conditions. The Gamma-gamma channel model statistics and its performance with spatial diversity techniques under correlation are reviewed. It has been shown that the Gamma-gamma channel model is able to perform better under correlation than other fading channel model
[68]	Using Historic Models of C^2n to predict r0 and regimes affected by atmospheric turbulence for horizontal, slant and topological paths	This paper depicts the Use Historic Models of C^2n to predict r0 and regimes affected by atmospheric turbulence for horizontal, slant and topological paths.
[69]	On the Performance of Free-space Optical Wireless Communication Systems over Double Generalized Gamma Fading Channels	In this paper, the PDF of the irradiance under the impact of pointing errors over double GG channel model is being analysed and derived.
[70]	Comparison in Behaviour of FSO System under Clear Weather and FOG Conditions	This paper discusses that as we move from clear weather to heavy fog Q factor decreases. In this paper the FSO system whose maximum transmission range is 1 km at attenuation 0.4 dB/km which is clear weather conditions is taken. But as the weather conditions changes from clear to fog it effects the transmission in our FSO systems very badly. The Q factor decreases as the Fog conditions occur more immensely i.e. when changes from light to heavy Fog.

Table2: Research papers with their objectives and observations.

CHAPTER-3
OBJECTIVES

3.1 VARIOUS CHALLENGES IN FSO COMMUNICATION:

FSO technology uses atmospheric channel as a propagating medium whose properties are random function of space and time. It makes FSO communication a random phenomenon that is dependent on weather and geographical location. Various unpredictable environmental factors like clouds, snow, fog, rain, haze etc., cause strong attenuation in the optical signal and limit the link distance at which FSO could be deployed. Below figure 4 depicts some of the FSO challenges that are being faced. Furthermore, the system designers also faced some of the challenges that they observed highly affects the FSO link are discussed below in detail.

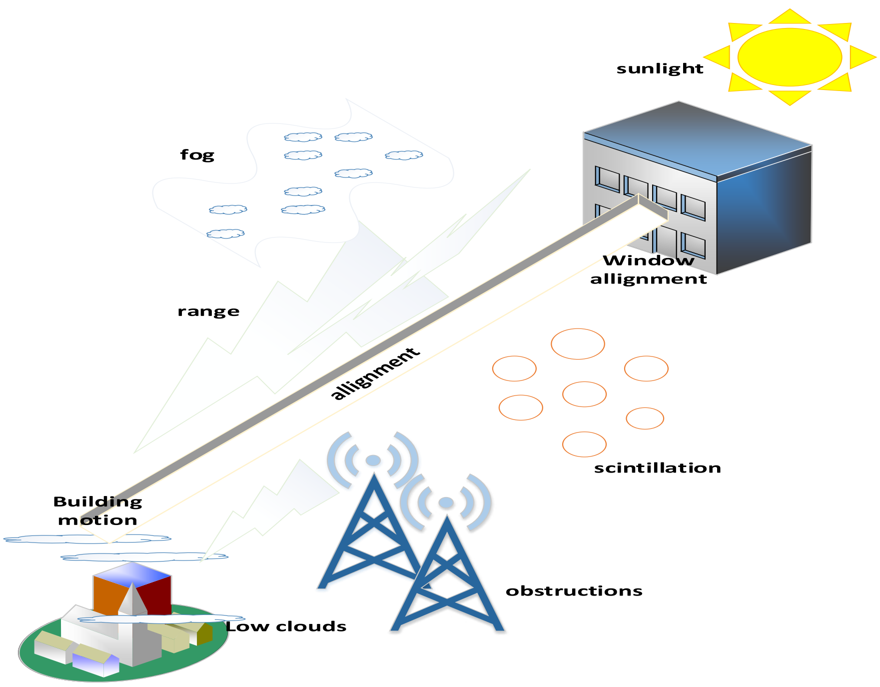


Figure 4: FSO challenges

A. Terrestrial Links:

The communication between building-to-building, `mountain-to-mountain or any other kind of horizontal link between two ground stations is included in terrestrial links. These network links can be deployed with point-to-point or point-to-multipoint or ring or mesh topology as shown below in figure 5. When a laser beam propagates through atmosphere, it experiences power loss due to various factors and a role of system design engineer is to carefully examine the system design requirements in order to combat with the random changes in the atmosphere. For reliable FSO communication, the system design engineer need to have atmosphere and its associated losses.

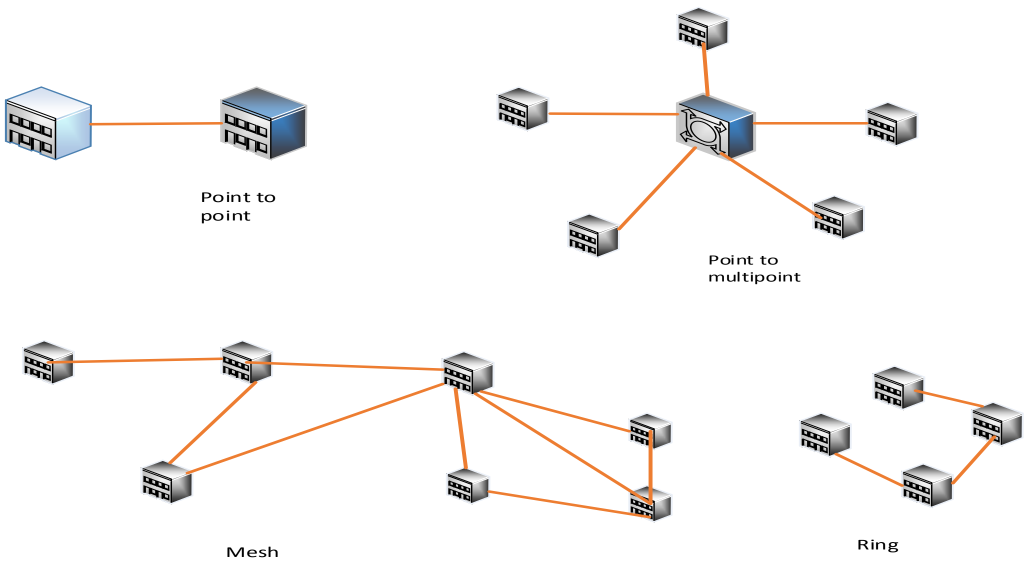


Figure 5: Terrestrial FSO link

The various losses encountered by the optical beam when propagating through atmospheric channel are:

I. ***Absorption and scattering loss:*** The loss in the atmospheric channel is mainly due to absorption and scattering process and it is described by Beer's law [71]. At visible and IR wavelengths, the principal atmospheric absorbers are the molecules of water, carbon-dioxide and ozone [72], [73]. The atmospheric absorption is a wavelength dependent phenomenon. Some typical values of molecular absorption coefficients are given in table 3 for clear weather conditions. The wavelength range of FSO communication system is chosen to have minimal absorption i.e. atmospheric transmission window. In this window, the attenuation due to molecular or aerosol absorption is less than 0.2 dB/km. There are several transmission windows within a range of 700-1600nm. Majority of FSO systems are designed to operate in the windows of 780-850nm and 1520-1600nm. These wavelengths have been chosen because of readily availability of transmitter and detector components at these wavelengths. The wavelength dependence of attenuation under different weather conditions is commonly available in databases like MORTAN [74], LOWTRAN [75] and HITRAN.

S.No	Wavelength (nm)	Molecular Absorption (dB/km)
1.	550	0.13
2.	690	0.01
3.	850	0.41
4.	1550	0.01

Table 3: molecular absorption at typical wavelengths [76]

Scattering of light is responsible for degrading the performance of FSO system. Like absorption, scattering is also strongly wavelength dependent. Scattering is basically defined by the process where light, sound or other moving particles are forced to deviate from a straight trajectory by one or more paths due to localized non uniformities in the medium through which they pass. It is of two types:

RAYLEIGH SCATTERING: If the atmospheric particles are small in comparison with the optical wavelength, the Rayleigh scattering is produced. It occurs in air molecules and aerosols particles like fine soil particles, cosmic dust and smoke when the size of particle is much smaller than wavelength i.e.(radii<1µm). It effect is very small. The main feature of this scattering is that, it equally forward and backward the scattered portions of optical signals.

MIE SCATTERING: Mie scattering, dominant in smog, smoke, mist, haze and fog; occurs when the size of particles is comparable to incident wavelength i.e. (radii>1µm). In this optical signal is scattered more in forward direction as compared to backward, thereby preventing the receiver of detecting the minimum required power.

Total atmospheric attenuation is represented by atmospheric attenuation coefficient which is expressed as combination of absorption and scattering of light. It is therefore expressed as sum of four individual parameters given as:

$$\Gamma = \alpha_m + \alpha_a + \beta_m + \beta_a ,$$

Where, α_m and α_a are molecular and aerosol absorption coefficients, respectively and β_m and β_a are molecular and aerosol scattering coefficients, respectively.

Various factors that cause absorption and scattering in FSO system are as follows:

Rain: It has distance reducing the impact on FSO although its impact is significantly less than fog. This is because the radius of raindrops (200-2000 µm) is significantly larger than the wavelength of typical FSO light source. Typically rain attenuation is moderate in value.

Snow: Snowflakes are ice crystals that come in a variety of shapes and sizes. It has a larger impact as compared to rain due to its larger droplet size. The impact of light snow to blizzard and whiteout condition falls approximately between light rain to moderate fog with link attenuation of approximately 3dB/km to 30dB/km.

Fog:[77] Fog has the most impact on the FSO because it is composed of small weather droplets with radii about the size of near infrared wavelengths. The particle size distribution varies for the different degree of fog. In fog mostly 830, 740, 1550 nm are durable wavelengths used.

Haze:[78]When the particle is in order of wavelength, the resulting scattering coefficient is high, i.e. the most severe environmental conditions Fog and Haze occur as both of their radii is close to the size of near infrared wavelengths.

Below table 4 shows the different visibility range for different atmospheric conditions:[79]

Atmospheric conditions	***Visibility Range***
Thick Fog	200mm
Moderate Fog	4500mm

Light Fog	800mm
Heavy Rain (30mm/hr)	1600mm-1900mm
Medium Rain (15mm/hr)	2400mm-3800mm
Drizzle (0.25mm/hr)	16000mm-18000mm
Very Clear	19000mm-40000mm

Table 4: different visibility range for different atmospheric conditions

II. ***Atmosphere Turbulence Induced Fading:*** Under the clear atmospheric conditions, atmospheric losses are negligible but still, we faced to another adverse effect known as scintillation or fading. Inhomogeneities in temperature and pressure of atmosphere caused by solar heating and the wind lead to variations of air refractive index along transmission path [80]. The resulting atmospheric turbulence causes random fluctuations in both amplitudes as well as the phase of a received signal. The atmospheric turbulence is basically characterized by three parameters: the inner and outer of turbulence i.e. lo and Lo respectively and c^2n i.e. refractive index structure parameter. The c^2n parameter is altitude dependent and is larger at lower altitudes due to more significant heat transfer between air and surface [81]. Generally, it is also dependence on link distance and its value varies from 10^{-17} to 10^{-13} [82]. Moreover, the values of c^2n vary with sunrise, sunset, day-time, night-time, mid-day. During night-time the c^2n is constant and height decreases more instantly whereas at day-time the height decreases slowly with c^2n .At near ground levels, c^2n has its peak value during mid-day hours whereas minima occur near sunrise and sunset. To discuss various regimes there are various models such as Gamma Gamma, I-K, K, Negative Exponential and lognormal model have been proposed.

III. ***Beam Divergence:*** In this beam is spreaded approximately 1m/km of distance. If no environmental factors were present, beam spread would be the only distance limiting variable

IV. ***Geometric and Misalignment Losses:*** Geometric losses occur due to the divergence of a beam when propagating through an atmosphere. It can be calculated by using divergence angle, link distance, and receiver lens aperture size. For horizontal FSO transmission, a good approximation is to consider a Gaussian profile for beam intensity with a relatively large divergence, its statistical properties are close to the case of a point source [83], [84]. In these cases, the approximations of plane or spherical wave can effectively be used. The degree of beam divergence also effects the transmitter receiver alignment and beam tracking at receiver.

Misalignment occurs due to Beam wander, Building Sway or errors in the tracking system. Due to the Beam wander the large scale atmosphere eddies takes place that can cause deflection of the optic beam and may result in the beam deviation from its original path [85]. On the other hand, Building Sway is the result of a variety of factors including thermal expansion, wind loads, small earthquakes, and vibration .Because of the narrowness of transmitted beam and usually small receiver field of view, Building sway can effectively cause a communication interrupt [86].

B. Space Links:

Space links include both ground-to-satellite/ satellite-to-ground links, inter-satellite links and deep space links. Links between LEO to GEO are used for transmitting gathered data from LEO to GEO which in turn transmits data to other part of the earth as shown in figure 6. Many researchers in US, Europe and Japan are investigating space-to-ground links using LEO (Mobile FSO link). Optical Inter-Orbit Communications Engineering Test Satellite (OICETS) was the first successful bi-directional optical link between KIRARI, the Japanese satellite and ESA's Artemis in 2001 [87]. Also, successful operational inter-satellite optical link was established between Artemis and Spot4 via SILEX system [88]. An optical link between two LEO orbiting satellites, Terra SAR-X and NFIRE at 5.5 Gbps on a total distance of 5500km and at a speed of 25,000 km/hr has been established in 2008. A 2.5 Gbps experiment was performed successfully between LEO satellite and ground station at 1 W laser power, 1064nm wavelength using BPSK modulation scheme [89]. An optical link at 2.5 Gbps was demonstrated by NASA between ground station and UAV achieving a BER of 10^{-9} at 1550nm wavelength [43].

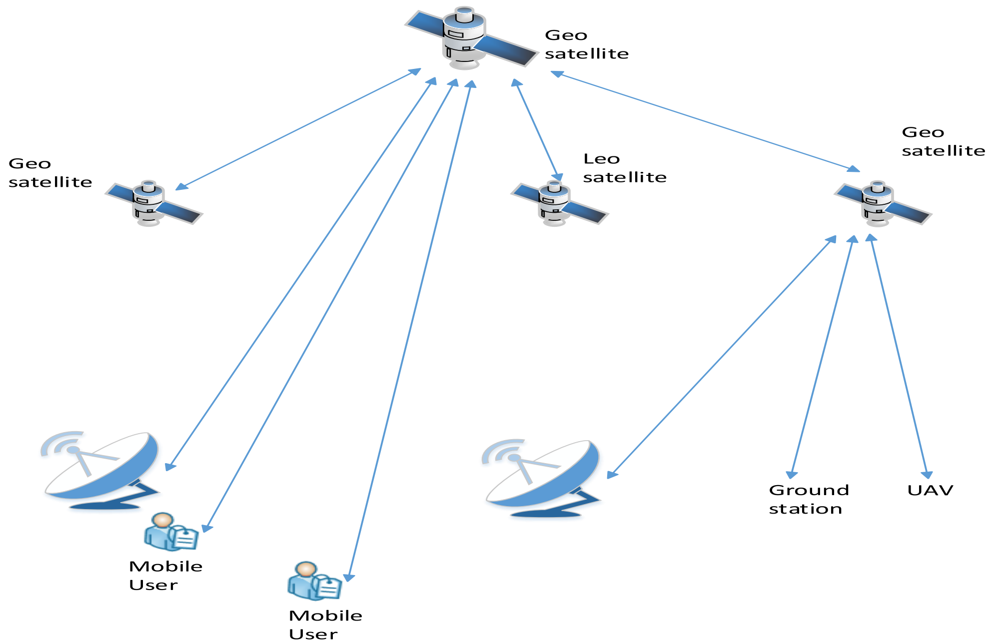


Figure 6: Space FSO Links

These space links have to face severe challenges due to adverse atmospheric effects (in case of ground-to-satellite/satellite-to-ground links) as discussed in previous section as well as very tight acquisition, tracking and pointing owing to its narrow beam width.

I. **Pointing loss:** Pointing error is one of the major challenge in FSO communication that can result in link failure. It is very essential to maintain pointing & acquisition throughout the duration of communication. It could arise due to the many reasons such as satellite vibration or platform jitter or kind of stress in electronic or mechanical devices. The effect of satellite vibrations in FSO systems is described in [90-92]. Pointing error can also be caused due to atmospheric turbulence induced beam wander effect which can displace the beam from its transmit path [93]. In any of the case, Pointing error will increase the chances of link failure or can significantly reduce the amount of received resulting in high probability of error.

II. **Atmospheric turbulence-vertical links:** For vertical links, the value of C^2n changes with altitude h unlike horizontal link where its value is assumed to be constant. With the increase in the altitude, the value of C^2n decreases at the rate of $h^{-4/3}$. Therefore, for vertical links, the value of C^2n has to integrated over the complete propagation path extending from height of the receiver above sea level to top of the atmosphere (roughly up to 40 kms). Due to this reason the effect of atmospheric turbulence from ground-to-satellite (uplink) is different from satellite-to-ground (downlink). Various empirical models of C^2n have been proposed in [94],[95] that describes the strength of the atmospheric turbulence with respect to altitude that are discussed in table. The most widely used model for vertical link is Hufnagel Valley Boundary (HVB) model[96] given by:

$$C^2n(h) = 5.94\times10^{-53} [v/27]^2 h^{10} e^{-(h/100)} + 2.7\times10^{-16} e^{(-h/1500)} + Ae^{(-h/100)}$$

This model was basically defined with two variables: A, which represents relative strength of turbulence near the ground that is approximately 1.7×10^{-14} and v, which represents the high altitude wind speed that is approximately 21 m/s (also may be 57m/s sometimes for stronger conditions). The value of e used in this is 2.718 that is the value of e from constant logs.

III. Background Noise: The main sources of background noise are: (a) diffused extended background noise from the atmosphere, (b) Background noise from the sun and other stellar (point) objects and (c) scattered light collecting receiver [97]. This noise can be only controlled by limiting the receiver optical bandwidth. Single optical filter with very narrow bandwidth in order of approx. 0.05 nm can be used to control the amount of background noise. In addition, the other sources of noise in FSO system are detector dark current, signal shot noise and thermal noise. Total noise contribution is sum of background noise and noise due to other sources.

IV. Atmospheric Seeing: The perturbations of the optical beam associated with coherence length of the atmosphere, r_o is referred as atmospheric seeing effect. When r_o is significantly smaller than the receiver aperture diameter D_R, then it leads to the blurring of received signal which is known as astronomical seeing which is given as λ/ r_o [98]. For a perfect optical collection system, the spot size of the received signal in the focal plane of the receiver is expressed as
($2.44\ F\ \lambda/ D_R$) where F is the focal length of receiver collecting optics. When the optical beam propagates through atmosphere, then D_R is replaced by r_o and therefore, the related signal spot size at the focal plane is increased by the ratio
D_R/ r_o which effectively leads to increase in the background noise. Also, larger FOV at the receiver can limit the electrical bandwidth of the receiver thereby limiting the data rate. This problem can be taken care of bye use of adaptive optics or array detectors.

V. **Angle of arrival fluctuations:** Due to the presence of turbulence in the atmosphere, the laser beam wave front arriving at the receiver will be distorted. This will lead to spot motion or image dancing at the focal plane of the receiver. This effect is called angle of arrival fluctuations. However, this effect can be compensated by use of adaptive optics or fast beam steering mirror. For plane wave, the variance of angle of arrival fluctuations, $(\beta)^2$ is expressed as: [99]

$$(\beta)^2 = \begin{cases} 1.64C^2n\ Llo - \frac{1}{3}, & Dr \ll lo \\ 2.91C^2n\ L\ Dr - \frac{1}{3} & Dr \ll lo \end{cases}$$

Where Dr is the diameter of collecting lens and lo is the inner scale of turbulent eddy.

3.2 VARIOUS REFRACTIVE INDEX MODELS OF FSO:

C^2n is basically a measure of the intensity of optical turbulence. The refractive index parameter (C^2n) depends on altitudes, geographical location & time of day. Different locations have different characteristics of temperature distribution that are reflected on the values assumed by C^2n. Below tropopause, the target gradient of temperature associated with largest value of atmospheric pressure & air density are close to ground, at sea level there is largest value of C^2n to be expected. As altitude decreases resulting in smaller values of C^2n until the tropopause where strong wind shear occur producing a new C^2n. During sunset and dawn, due to equilibrium along the atmospheric vertical profile, one should expect C^2n to have lower values. Considering the temperature dynamics, during day closer to ground, the turbulence is stronger around noon. Below are various C^2n models discussed with their expressions:

1. **KAIMAL TYPE MODELS**: It is the simplest model of c^2n that was developed by Walters and Kunkel [100], on similarity theory description of boundary layer turbulence in order to predict the dependence of c^2n with height. The daytime altitude fall off is as -4/3 power and range of validity extends up to approximate one-half the height of boundary layer inversion. The model is expanded in the following form:

$$\frac{c^2n(h)}{c^2n(ho)} = \begin{cases} \left(\frac{h}{ho}\right)^{-\frac{4}{3}} & ho, h \le 0.5hi \\ \left(\frac{0.5hi}{ho}\right)^{-\frac{4}{3}} & 0.5hi \le h \le 0.7hi \\ 2.9\left(\frac{0.5hi}{ho}\right)^{-\frac{4}{3}} \left(\frac{h}{hi}\right)^{3} & 0.7hi \le h \le h \end{cases}$$

Where hi is the height of inversion layer above ground and ho is a reference altitude(often taken to be tower level) and assumed to be above surface layer. The region of validity for this model extends to the height of the inversion layer.

This model was further again developed by Kukharets and Tsvang by adding exponential fall off for c^2n above the inversion layer.

$$\frac{c^2n(h)}{c^2n(ho)} = \frac{k1\left(\frac{h}{hi}\right)^{-\frac{4}{3}} + k2\; e^{-k3\left(\frac{h}{hi}-1.1\right)^2}}{k1\left(\frac{ho}{hi}\right)^{-\frac{4}{3}}}$$

In above-given model ho is a reference height, hi is the height of inversion layer, k1(a warmer inversion)=4.6×10^{-2}, k2(less dense air mass move over cooler)=0.6 and k3(denser air mass)=12. This model assumes heights at or above some observing stations.

2. **HUFNAGEL VALLEY MODEL OR PARAMETRIC MODEL:** It is another popular model of c^2n developed by Hufnagel and augmented with a boundary layer term extending the model to surface as suggested valley[101]. The Hufnagel valley model is given as:

$c^2n(h) = 5.94\times10^{-53}\,[v/27]^2\, h^{10}\, e^{-(h/100)} + 2.7\times10\text{-}^{16}\, e^{(-h/1500)} + Ae^{(-h/100)}$

This model was basically defined with two variables: A, which represents relative strength of turbulence near the ground that is approximately 1.7×10^{-14} and v, which represents the high altitude wind speed that is approximately 21 m/s (also may be 57m/s sometimes for stronger conditions). The value of e used in this is 2.718 that is the value of e from constant logs.

3. **SLC-D MODEL:** This is commonly used model with no parameters is Submarine Laser Communication Day model [102]. It is basically based on data collection from AMOS telescope site at the top of Mt. Haleakala, Hawaii. Care needs to be taken in this model because of its unique topology of the site and subtropical climate. The SLC-D model of version 1 has following terms:

$$C^2n(h)=\begin{cases} 1.70\times10^{-14} & h<18.5m \\ 3.13\times\frac{10^{-13}}{h} & 18.5m<h<240m \\ 1.30\times10^{-15} & 240m<h<880m \\ 8.87\times\frac{10^{-7}}{h^3} & 880m<h<7{,}200m \\ 2.00\times\frac{10^{-16}}{h^{0.5}} & 7{,}200m<h<20{,}000m \end{cases}$$

Similar model i.e. SLC-D version 2 is available for the night time conditions.

$$C^2n(h)=\begin{cases} 0 & 0m<h<19m \\ 4.008\times10^{-13}h^{-1.054} & 19m<h<230m \\ 1.300\times10^{-15} & 230m<h<850m \\ 6.352\times10^{-7}h^{-2.966} & 850m<h<7{,}000m \\ 6.209\times10^{-16}h^{-0.6229} & 7{,}000m<h<20{,}000m \end{cases}$$

3.3 VARIOUS CHANNEL MODELS OF FSO:

There are various FSO models which are used for different regimes in different conditions. . To discuss various regimes there are various models such as Gamma Gamma, I-K, K, Negative Exponential and lognormal model have been proposed that are being that are being discussed in below table 5. [103] The lognormal model is used for weak turbulence conditions only. So if long propagation path is considered another model i.e. K distribution is used because of its strong turbulence conditions [104]. The Negative distribution is used for very strong turbulence conditions as its PDF (Probability Distribution Function) gives appropriate results in negative regimes.[105] The Gamma Gamma is used for all types of regimes, due to its quality of describing fluctuations of irradiance of optical signal distorted due to atmospheric factors, this model is preferred more among all another model.

Channel Model	***Turbulence***
Lognormal [103]	Simple, tractable but only for weak regimes.
K [104]	Strong regimes only
I-K	Weak to strong turbulence regimes
Gamma Gamma [105]	All regimes
Negative Exponential [105]	Saturation regimes only

Table 5: channel regimes with the various models

GG model was proposed by Andrew et al, in 2001, is based on modulation process where fluctuations of light radiation trans versing a turbulent atmosphere is assumed to consist of small scale i.e. scattering and large scale i.e. refraction effects. This model basically models the shadowing/ fading channels as well as in wireless system, it describes the fluctuations of irradiance of optical signals distorted by atmospheric turbulence. In this model the large fluctuations are being generated by turbulent eddies larger than that of first Fresnel zone or scattering desk. Small scale eddies are assumed to be modulated by large scale eddies. Consequently the normalized received Irradiance (I) is defined as product of two random processes i.e I_x and I_y .

Where, I_x is large scale eddies and I_y is small scale eddies.

$$I = I_x I_y$$

Their pdf 's are given by:

$$P(I_x) = \frac{\alpha(\alpha Ix)^{\alpha-1}}{\Gamma(\alpha)} \exp(-\alpha I_x)$$

$$P(I_y) = \frac{\beta(\beta Iy)^{\beta-1}}{\Gamma(\beta)} \exp(-\alpha I_y)$$

Irradiance PDF given by Andrew is:

$$P(I)=\frac{2(\alpha\beta)^{\alpha+\beta/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{(\alpha+\beta/2)-1} K_{\alpha-\beta} (2\sqrt{\alpha\beta I}) \qquad ,(I > 0)$$

Where, α is for large scale eddies, β is for small scale eddies, K is modified Bessel function of second kind of order n and Γ is Gamma function.

$$\alpha = \left\{ exp\left[\frac{0.49\ \sigma_R^2}{\left(1 + 1.11 + \sigma_1^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right] - 1 \right\}^{-1}$$

$$\beta = \left\{ exp\left[\frac{0.51\ \sigma_R^2}{\left(1 + 0.69d^2 + \sigma_1^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right] - 1 \right\}^{-1}$$

Where, σ_R^2 Rytov variance that represents the variance of log intensity function.

$$\sigma_R^2 = 0.5\ c^2n\ k^{7/6} L^{11/6}$$

Where, c^2n is a index of refraction structure parameter and it is altitude dependent, k is 2π/λ is optical wave number (λ is wavelength), L is the distance between transmitter to receiver. There are several c^2n models available but mostly preffered is hufnagel valley model. The hufnagel valley model is given as:

$c^2n(h) = 5.94 \times 10^{-53} [v/27]^2\ h^{10}\ e^{-(h/100)} + 2.7 \times 10^{-16}\ e^{(-h/1500)} + Ae^{(-h/100)}$

This model was basically defined with two variables: A, which represents relative strength of turbulence near ground that is approximately 1.7×10^{-14} and v, which represents the high altitude wind speed that is approximately 21 m/s (also may be 57m/s sometimes for stronger conditions). The value of e used in this is 2.718 that is value of e from constant logs.

3.4 OBJECTIVES AFTER STUDYI NG ALL CHANNELS AND MODELS:

By studying various atmospheric challenges and literature survey of FSO I found three objectives. Those objective are discussed below:

- PERFORMANCE ANALYSIS OF VARIOUS (C^2N) REFRACTIVE INDEX MODELS OF FSO
- PERFORMANCE ANALYSIS OF VARIOUS CHANNEL MODELS OF FSO
- PERFORMANCE ENHANCEMENT IN FSO MODELS

CHAPTER-4
RESEARCH METHODOLOGY

This chapter has a basic flow diagram which show the procedure of how the data is being collected with the help of different research papers and software is being used to analyse and obtain the c^2n models implementation i.e MATLAB.

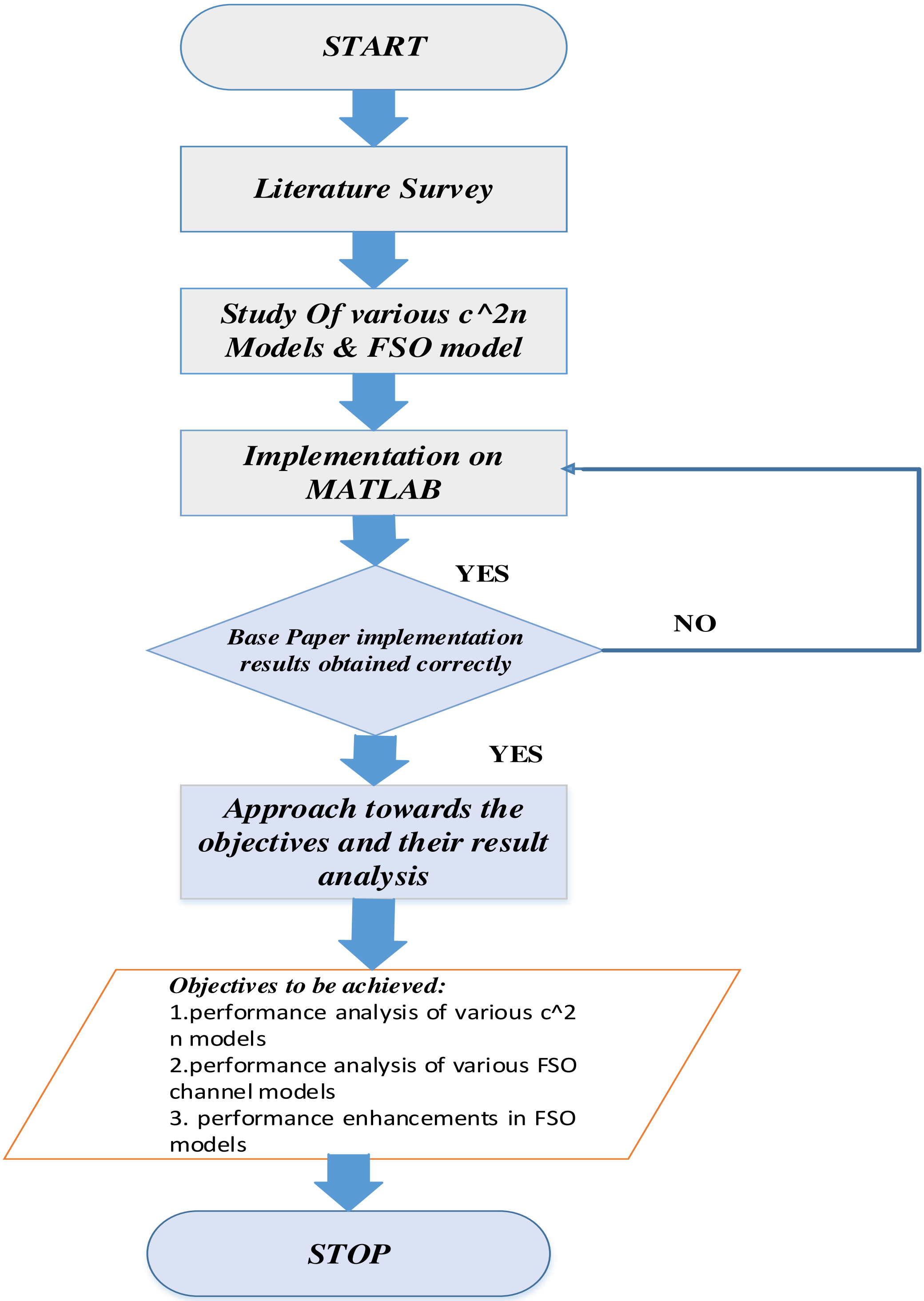


Figure 7: flow diagram of research methodology

4.1 HOW DATA IS COLLECTED?

By studying and analysing data through various sources such as research papers and with the help of my mentor I collected data of my thesis topic "Performance Analysis of various FSO (Free Space Optics) models" and later analysed some of the improvement that could be done in FSO models. Over last two decades, FSO has become more and more interesting as an adjunct or alternative to radio frequency communication. So, by concentrating on the literature review for Free Space Optical systems, FSO based systems, comparison of various channel models, Different channel models, and their effects by atmospheric turbulence with their estimated parameters such as c^2n i.e. refractive index, I found three main objectives that could be improved in this topic:

- PERFORMANCE ANALYSIS OF VARIOUS (C^2N) REFRACTIVE INDEX MODELS OF FSO
- PERFORMANCE ANALYSIS OF VARIOUS CHANNEL MODELS OF FSO
- PERFORMANCE ENHANCEMENT IN FSO MODELS

First objective of thesis is to find the results of all c^2n models of FSO. After that to put all the c^2n values in Gamma Gamma model to analyse which c^2n model gives efficient results. The enhancement i.e. observed after doing literature survey can be done is that there are various models of c^2n present but mostly everyone till now is using Hufnagel Valley model. So, main focus of thesis work is to put all the c^2n models one by one in the Gamma Gamma model to analyse which one is more better.

4.2 WHICH SOFTWARE IS USED IN RESEARCH WORK?

The software that I have used in my research work is MATLAB i.e. matrix laboratory is a multi-paradigm numerical computing environment that means it helps us in plotting graphs, process signals and can even helpful in sampling a signal. It was initially released in 1984 i.e. 33 years ago and now used by almost 2 million people .A proprietary programming language developed by MathWorks, MATLAB allows matrix manipulations, plotting of functions and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other languages, including C, C++, C#, Java, Fortran and Python. Although MATLAB is intended primarily for numerical computing, an optional toolbox uses the MuPAD symbolic engine, allowing access to symbolic computing abilities. An additional package, Simulink, adds graphical multi-domain simulation and model-based design for dynamic and embedded systems. MATLAB is a proprietary product of MathWorks, so users are subject to vendor lock-in.

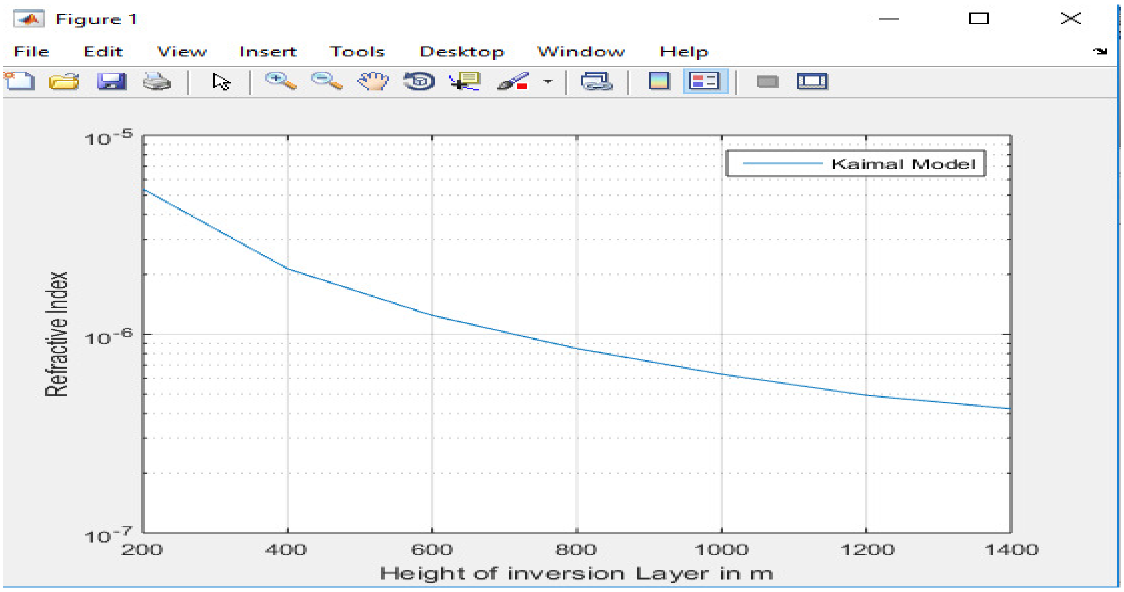
4.3 WHICH RESEARCH IDEAS HAS BEEN PROPOSED?

The enhancement that could be done after doing literature survey is that there are various models of c^2n i.e. refractive index present but mostly everyone till now is using Hufnagel Valley model. So, main focus of my thesis work is to put all the c^2n models one by one in the Gamma Gamma model to analyse which one is more better.

CHAPTER-5
DISCUSSION AND ANALYSIS

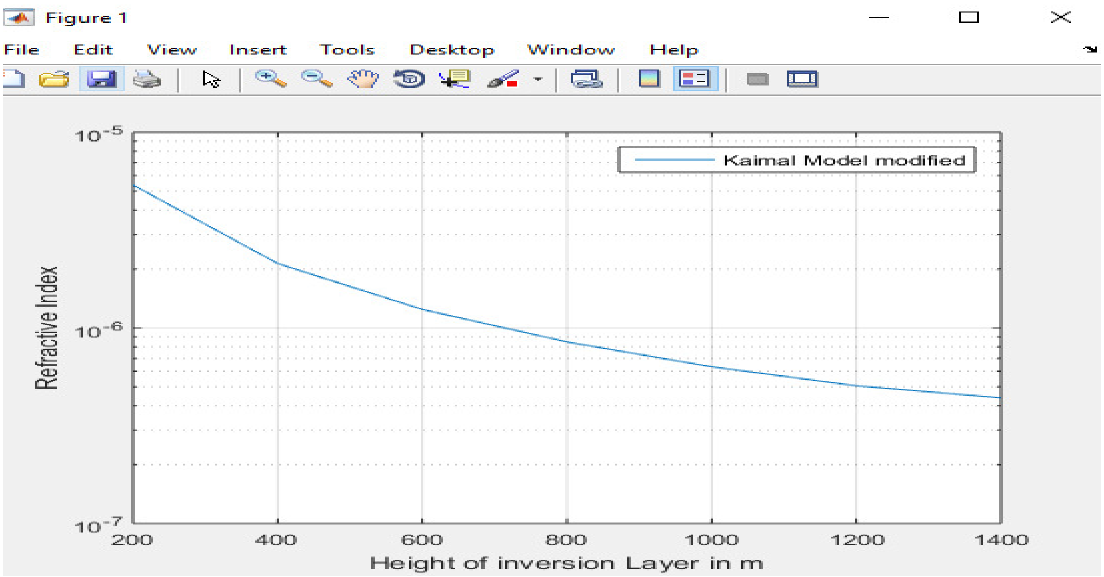
1. KAIMAL MODEL:

Version1:



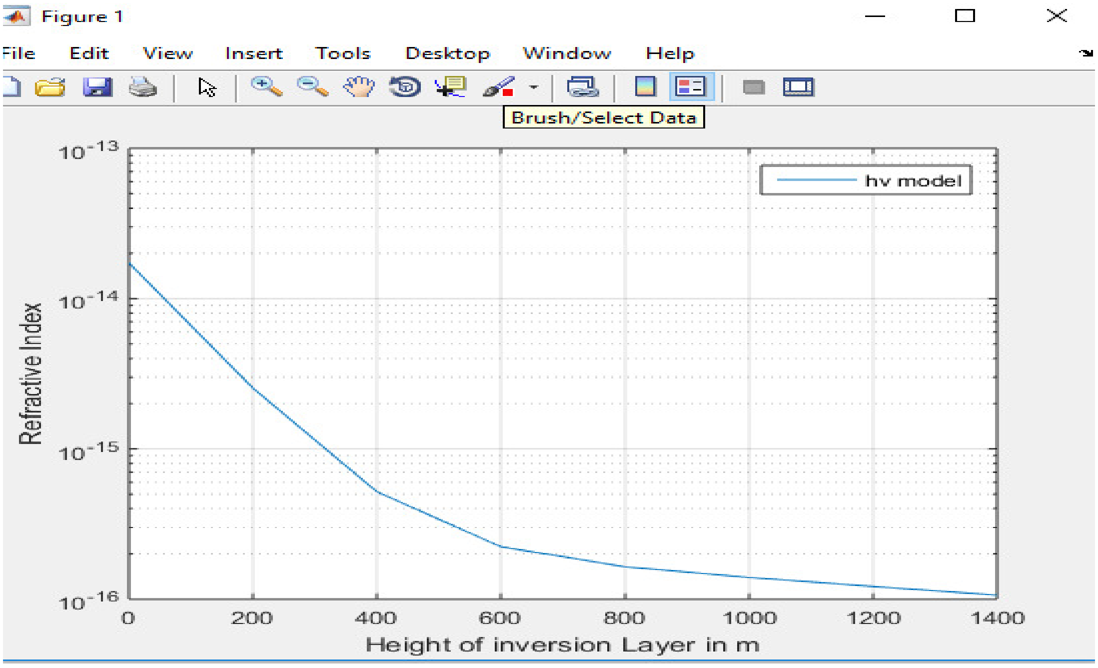
- As we move to higher altitudes we have lower pressure & lower temperature. So as a result the value of c^2n falls with height. Close to ground, there exists the largest gradient of temperature associated with largest values of atmospheric pressure. Therefore, larger value of c^2n is expected at sea level.
- As the altitudes increases the temperature gradient decreases, resulting in smaller values of c^2n.

Version2:



- This model is basically used for rain attenuation model.
- The value of k1 & k2 is depended upon rain drop size & rain temperature.
- In this modified version also the c^2n value decreases with increasing height.

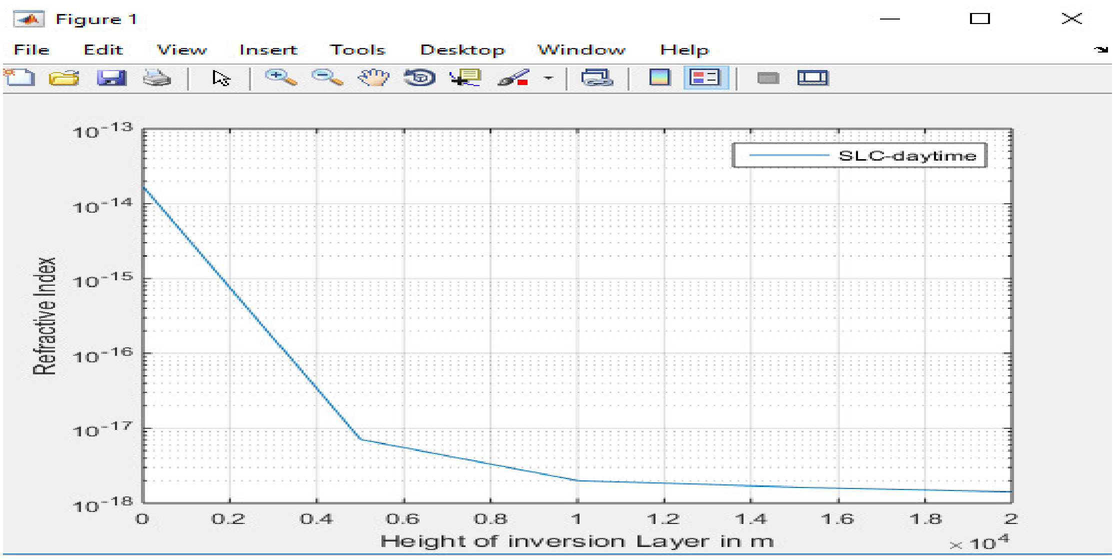
2. HUFNAGEL VALLEY MODEL:



- It was basically applicable for inland scene.
- It is the most popular model as it easily allows easy variation of daytime & nightime profile by varying various site parameters like wind speed, iso-planatic angle and altitude.
- Best suited model to ground-to-satellite uplink.
- Here the value of A i.e. relative strength of turbulence near the ground is 1.7×10^{-14} $m^{-2/3}$ for daytime and 8.4×10^{-15} $m^{-2/3}$ for nighttime.
- HV 5/7 is generally used to describe c^2n profile during daytime. HV 5/7 yields a coherence length of 5cm & isoplanatic angle of 7μrad at 0.5μm wavelength.

3. SLC MODELS:

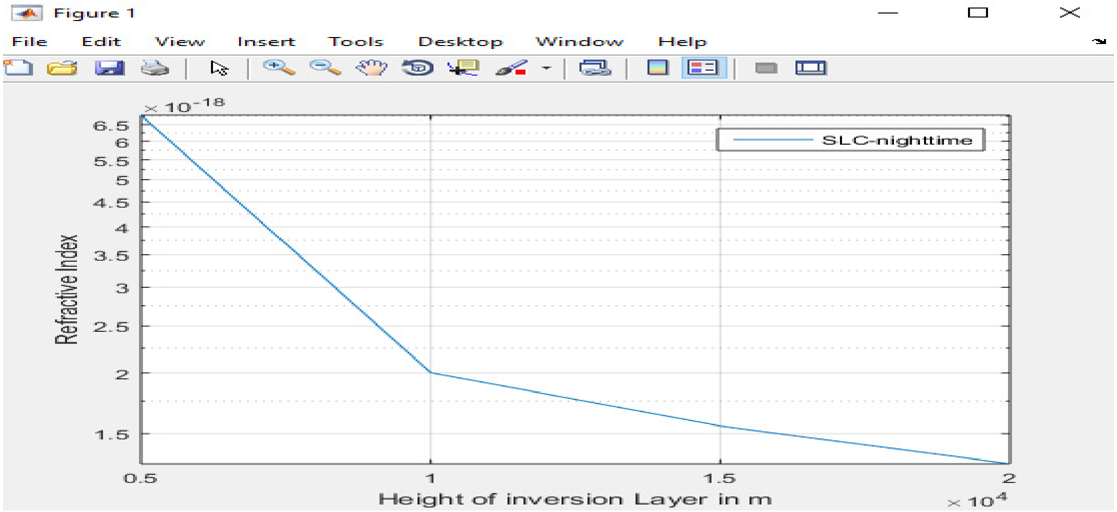
Daytime conditions(version 1):



- SLC-D version 1 or SLC- daytime have long range approximately to tens of kms.

- This model is well suited for daytime turbulences.
- Developed for AMOS observatory in Maui Hawaii.

nighttime conditions(version 1)::



- This model is not suitable for nigh time conditions. It is only applicable to the daytime turbulences.

Moreover, below table shows all the discussion regarding the c^2n models precisely:

MODELS	RANGE	COMMENTS
Kaimal type models (i) By Walters and kunkel (ii) By Kukharets & Tsvang	Long (few tens of kms)	➢ In this c^2n varies with height means if we are moving to higher altitudes we have lower pressure & lower temperature. Due to this the c^2n falls with height. ➢ Rain attenuation model i.e. the value of k1 & k2 is depended upon rain drop size & rain temperature.
Parametric fits to experimental data by **Hugnagel : Hufnagel Valley Model.**	Long (few tens of kms)	➢ Most popular model as it allows easy variation of daytime & nightime profile by varying various site parameters like wind speed, iso-planatic angle and altitude. ➢ Best suited to ground-to-satellete uplink. ➢ HV 5/7 is generally used to describe the c^2n profile during daytime. HV 5/7 yields a coherent length of 5cm &

		isoplanatic angle of 7µm at 0.5 µm wavelength.
SLC-D (Submarine Laser Communication-Day Model) (i) SLC-D version 1 (for daytime) (ii) SLC-D version 2 (for night time)	Long (few tens of kms)	➢ SLC-D version 1 model was basically developed for AMOS observatory in Maui Hawaii. ➢ It is well suited for daytime turbulence. ➢ As the high altitude behaviour is very similar between two versions, the ground layer behaviour of c^2n is absent in second version of profile model. This makes second version unsuitable for modelling of ground based observations.

Figure6: discussion regarding various c^2n models precisely

CHAPTER-6
SUMMARY AND CONCLUSIONS

In order to attain the desired research objectives, study of various c^2n models i.e. refractive index models has been studied. After the literature review was carried out, all the c^2n models has been plotted with the help of Matlab. From the results it has been concluded that different c^2n models are used for different weather conditions and almost in every the parameter c^2n varies with height means if we are moving to higher altitudes we have lower pressure & lower temperature. Due to this the c^2n falls with height.

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