Performance of FSO Communication in the Atmospheric Turbulence for Various Modulation Schemes

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Abstract*— *With the growing population there has been a demand for highly efficient communication link owing to the rapid advancement of broadband wireless communications. Optical fibre had grown in the last few decades due to its low loss and high capacity. In the present communication era, Free Space Optical (FSO) communication has gained significant importance and is replacing radio communication owing to its unique features: large bandwidth, high data rate, license free spectrum, less power, low mass requirement and last but not the least easy and quick deploy ability. All these can be achieved by using FSO and because of this it has therefore become need of the hour. Due to this there has been tremendous advancement in the technical side and available components under free space laser communication. In spite of that, Turbulence manifests in the performance of FSO in the atmosphere due to increased Bit Error Rate(BER) leading to degradation in the link performance. It happens because a portion of the atmosphere always includes turbulence and multiple scattering effects. Now this paper provides detailed survey of FSO system, its advantages, disadvantages and different applications. The modulation techniques used in FSO like OOK, BPSK, DPSK etc. have also been listed along with advantages. It also provides a comprehensive analysis of the degradation in performance of FSO in atmosphere. Different channel models have also been listed along with atmospheric scintillation.

Keywords— *FSO, atmospheric turbulence, modulation techniques, lazers, los (line-of-sight), optical wireless, scintillation, Bit Error Rate (BER), OOK, BPSK, DPSK.*

I. INTRODUCTION

With the increase in demand for high speed internet, live streaming, video conferencing etc., there has been tremendous advancement and growth in information and communication technologies. Because of the increasing demand of data, the Radio Frequency (RF) spectrum has congested. Therefore a change from RF carrier to optical carrier is needed. Unlike RF carrier, optical carrier has large bandwidth and does not require licensing, making it a very attractive area to explore and work upon. Wireless optical communication (WOC) is the technology that transfers information through an unguided channel like free space or air using optical carrier. It is the next frontier for high speed communication. Free Space Optical communication is a WOC that transmits information by using light present in the free space for telecommunication and computer networking [1] [2].

A. Free Space Optics System

The FSO system consists of the transmitter, receiver and separate optical aperture as a tracking telescope. FSO system can exhibit characteristics of reflective, refractive, diffusional or combinational circuit [3]. It can exhibit another configuration of a simple optic performing a combined function thus saving cost, weight and size.

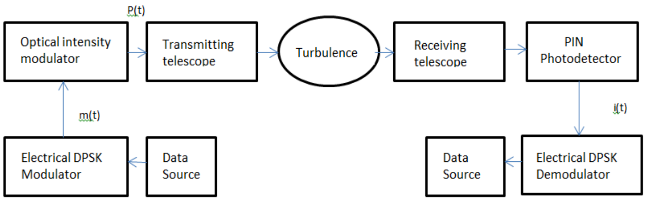

Fig 1: Free Space Optical Subsystem

The transmit telescope comprises lens assembly usually Plano convex lenses. The aspects of optical system which are considered on the transmitter section are size and quality of the system. Quality is determined by the minimum divergence. Whereas at the receiver section there is noise interference, signal distortion and background radiation. Amidst these conditions, the signal is optically collected and detected depending upon the f-number and aperture size [4].

F-number tells about the detectors' field of view and the amount of light collected on the receiver is determined by aperture size.

B. *Advantages of FSO Communication*

To begin with, RF technology had been developing since 1900s whereas FSO technology has gained momentum in the past 10 years. Hertz and Marcon started developing models for propagation of light through RF waves and since then many models have been developed under the RF technology. At first experiments and measurements were recorded, the first LASER was developed in 1960 and then analysis and observations were done. This shows that we are behind 70 years in FSO technology. It is because of this reason that fewer models of FSO have been developed which can be used.

In 1960 people had got an idea of transmission of information through atmosphere after the discovery of LASER. However due to the degradation in performance due to non-predictable weather conditions major focus was done on the development of fibre optics.[5]-[7] In FSO, we have the high usable bandwidth due to high carrier frequency that is a big advantage compared to RF. Despite of this, RF technology was more favoured due the degradation in performance in the presence of fog and clouds. High frequency also means short wavelength (some µm), and that means the same size like the small particles within the fog and clouds. It is the same relation like in RF between RF wavelengths and the size of rain particles. In both the cases Mie scattering is the main attenuator, due to rain particles in RF and fog and clouds in FSO. [8] Now, we have models for the attenuation (from fog, clouds, rain etc.) and we have additional models for atmospheric turbulences in the FSO field. The different models are necessary, because the atmospheric turbulences (the so called scintillations) have completely different influences on the transmitted light, they are disturbing the wave-front and they also cause beam-wandering or beam-spreading.

The advantages FSO communication offers over RF communication are:

(i) Potential increase in information transfer rate: The information transfer rate increases with the increase in bandwidth of the modulated carrier. Bandwidth of the modulated carrier is generally limited to a fixed fraction of the carrier frequency itself. A usable bandwidth at an optical frequency of ~200 THz will increase the transfer rate by about 10^5 times as compared to a carrier in the RF range.

(ii) Narrow beam divergence: the beam divergence is roughly proportional to λ/D, where λ is the carrier wavelength and D is the aperture diameter, and varies inversely with antenna gain. Thus, a longer wavelength necessitates a proportionately larger antenna to achieve the same gain. Therefore it leads to station compactness.[9]

(iii) Unlicensed spectrum: In RF system, Spectrum congestion happens because of interference from adjacent carrier. This leads to the need for spectrum licensing. On the other hand, FSO is license free till now.

(iv) High Security: FSO is more secure as compared to RF technology as FSO cannot be detected by spectrum analysers or RF meters.

C. *Applications of FSO*

FSO system operates in the IR wavelength range between 750-1600nm. There are several atmospheric transmission windows within this range that have an attenuation of <0.2 dB/km and so are nearly transparent. The majority of free-space lasercom systems are designed to operate in the windows of 780–850 and 1520–1600 nm.[10]

1. Transmitting window 780-850 nm.

These wavelengths are chosen according to the requirement
of the system. At 780 nm, inexpensive CD lasers are available, but the average lifespan of those lasers is an issue.
Around 850nm, reliable, inexpensive, high performance transmitter and detector components are there like Silicon
avalanche Photo Diode (APD).

2. Wavelength range 1520-1600 nm

This wavelength range is more efficient due to the high quality of transmitter and detector components. We use wavelength division multiplexing in this range to get more data rates even in conditions like fog, snow etc.[11] This wavelength range also focuses on retina. Although interference increases in this range but as much power can be
transmitted at this frequency that can be transmitted at 780-
850nm for the same eye safety.

For low cost applications, 780-850 nm window is used and for achieving quality performance, 1520-1600 nm window I preferred.

Application	Wavelength	Mission
Inter satellite Communication	830 nm	Semi-conductor Inter-satellite Link Experiment (SILEX) [12]
Ground to Satellite link	Uplink: 514.5 nm Downlink: 830 nm	Ground/Orbiter Lasercomm Demonstration (GOLD) [13]
Deep space missions	1064 nm	RF Optical System for Aurora (ROSA) [14]
Spectroscopy	880 nm	Mars Polar Lander [15]

Table 1: Applications of FSO

II. Challenges in FSO communication

In practical applications of FSO, it is highly affected by atmospheric turbulence. The free space atmosphere includes many ingredients like fog, rain, snow, humidity, smoke etc. which affects the light signal travelling through it. Turbulence is caused by eddies or cells formed from different refractive indexes [16]. The prime factors which characterize communication channel is firstly attenuation due to atmosphere which results from scattering and absorption and secondly scintillation.

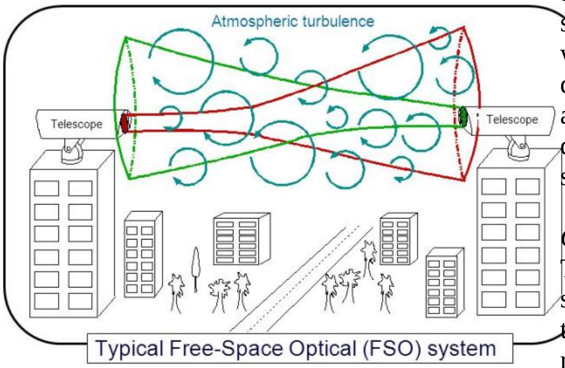

Fig 2: FSO communication in turbulent atmosphere [17]

Absorption of light by gas molecules and Rayleigh or Mie
scattering by gas molecules or aerosol particles suspended in the air cause reduction in the optical wave power leading to attenuation. Vibrational-rotational absorption lines of water vapour, CO_2, CH_4, and other gases of minor constituents in the atmosphere cause individual absorption lines. Scattering from aerosols and particulates such as in fog, clouds, smoke, and dust also contribute to the total attenuation of the optical beam.

Fluctuations in the signal detected at receiver end as a result of random variations in the refractive index of the turbulent atmosphere is called scintillation. It is maximum around midday and changes during the course of the day. The turbulence strength of the atmosphere is usually expressed in terms of a scintillation index [18].

In FSO we use an open medium that is atmosphere outside to transfer signals. The disturbing effect on signal is caused due to various elements present in the atmosphere. FSO is also a line-of-sight technology .It means interconnecting points must be free from physical obstruction and able to "see" each other. The list of atmospheric disturbances is given below.

A. Fog

Fog is the major challenge which FSO communication faces.

Fog is formed by vapour formed from water droplets, which may be very tiny, but it can completely hinder the passage of light through a combination of absorption, scattering and reflection factor. Fog substantially attenuates visible radiation. Optical beam of light is absorbed, scattered, and reflected by the hindrance caused by fog. Scattering caused by fog, also known as Mie scattering, is largely a matter of boosting the transmitted power [19].

B.Rain

The rain is another factor that restrains the FSO link between the transmitter and the receiver. Rain attenuation exists due to rainfall. It is a nonselective scattering process. Attenuation due to rain is wavelength independent. The visibility of FSO system depends upon the quantity of the rain. Rain has the ability to produce the fluctuation effects in laser delivery. In case of heavy rain, water droplets have solid composed [20].

C. Snow

The snow is divided into two types-wet snow and dry snow. Wet snow gives higher attenuation as compared to dry snow. The dry snow effects on the low snow rate, whereas wet snow effects at high snow rate. The amount of attenuation decreases as the visibility increases during the snowfall [21].

However, research has been done to overcome these problems. With the help of suitable special diversity techniques and transmission power high performance can be achieved.

III. Channel Models

To maintain the required link performance, a number of models have been proposed. These models are called channel models. These models study the effect of adversaries on the FSO link under turbulent atmosphere. Among these models, the most popular models have been listed viz. gamma-gamma, log normal and negative exponential models.

1) Lognormal Model:
This model is used for low turbulence conditions and for propagation distances less than 100 m. Considering this model, the pdf of the received optical field **I** is given as *f* (*I*)[22]

$$f(I)= \frac{1}{2\pi I\sigma^2} \exp\left[\frac{-(\ln(I)-m_i)^2}{2\sigma_i^2}\right] \quad (1)$$

Where m$_k$ is mean and $\sigma_i$is log-irradiance variance.

Log-irradiance variance is given by$\sigma_{SI}^2 = e^{\sigma_i^2} - 1$ and can be computed for given scintillation index. For weak turbulence, scintillation index falls in the range of [0, 0.75]. As the turbulence strength increases, The distribution becomes more tilted with longer tails in the infinity direction This indicate the degree of fluctuation of the irradiance as the channel inhomogeneity increases which in turn affects the accuracy of performance analysis.

2) *Gamma-Gamma model*
Andrews introduced the modified rytov theory and proposed gamma-gamma pdf as a useful mathematical model for atmospheric turbulence. This modified rytov theory defines the optical field as a function of perturbations which are due to large scale and small scale atmospheric effects. The normalized irradiance is given as I= Ix*Iy where Ix and Iy arise from large scale and small scale turbulent eddies and each of them follows gamma distribution. This gives the gamma-gamma pdf as[23]

$$f(I)= \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}\left(\sqrt{2\alpha\beta I}\right), I > 0 \quad (2)$$

Where $K_a(.)$ is the modified Bessel function of second kind of order a. α and β are the effective number of small scale and large scale eddies of the scattering environment.

3) Negative Exponential Model:
In case of strong irradiance fluctuations where link length spans several kilometres, number of independent scatter become large. In that case, signal amplitude follows a Rayleigh distribution which in turn leads to a negative exponential statistics for the signal intensity (square of field amplitude).[23] This is given by

$$P(I)=\frac{1}{I_o}\exp\left(\frac{-I}{I_0}\right), I \geq 0 \quad (3)$$

where I_o is the mean radiance (average photon count per slot). Here σ_{SI}^2=1.[24]

IV. Modulation Techniques

The optical transmission system follows a series of steps. It includes modulation of optical signal, its transmission in the medium, its detection and then followed in the last by demodulation. Modulation in FSO communication Systems means varying the intensity of an optical source to transmit signals over channel. The various parameters in optical signal can be modulated is amplitude, frequency, phase, and polarization. There are various modulation schemes suitable for FSO systems which can be compared on different parameters viz. BER, optical power, SNR etc.[24] Till now the modulation scheme that has been majorly used is intensity modulation with direct detection. The criteria on which the modulation schemes are chosen are power efficiency, bandwidth efficiency, simple design requirement, low cost implementation and immune to interference background radiations.

On-Off Keying (OOK) is the most simple and efficient Intensity Modulation (IM) scheme. In a binary OOK system, the transmitter sends a pulse of light into a channel to represent a “1” and does not send any light for a “0”. When signal plus noise is present at the receiver input, there are two ways in which errors can occur. The receiver decides a “0” was sent when in fact a “1” was transmitted. Also, the receiver may decide a “1” was transmitted when a “0” was actually sent. It can use both NRZ (Non Return to Zero) and RZ (Return to Zero) coding techniques. RZ shows higher sensitivity than NRZ [25].
Apart from the above mentioned schemes, coherent modulation schemes such as Binary Phase Shift Keying (BPSK) and Differential Phase Shift Keying (DPSK) can also be used [26].Under all the turbulence conditions, the BER performance of subcarrier BPSK is always better than that of OOK. Pulse position modulation (PPM) scheme is an orthogonal modulation technique. PPM requires both slot and symbol synchronization, where information is encoded into the position of the optical pulse rather than amplitude, offers higher resilience to turbulence due the availability of soft demodulation algorithms[27][28].

The comparison of various techniques is given in the table given below:[20][30]

Modulation Techniques	Features
OOK-NRZ	Moderate SNR, Low Cost, requires adaptive threshold
OOK-RZ	High sensitivity
BPSK	Hybrid channel (Non-uniform and rate-compatible LDPC codes) & Adaptive Codes used and MI detection used
PPM	Superior power efficiency than any other baseband modulation

Table 2: Comparison of modulation techniques

V. Relationship between SNR and BER

The performance of the FSO system can be determined by the BER of the system. BER of a system depends on the modulation format, and the signal-to-noise ratio (SNR). Dark current noise, signal shot noise, thermal/Johnson noise in the photo detector, and the background noise, all contribute to the noises interfering in a system. Assuming a Gaussian distribution of noise, the SNR at the output of the photo detector in the absence of turbulence is given by

$$SNR_0 = \frac{P_S}{\sqrt{\left(\frac{2h\nu B}{\eta}\right)(P_S+P_B)+\left(\frac{h\nu}{\eta e}\right)^2\left(\frac{4kT_{NB}}{R}\right)}}$$

(4)

where P_S is the signal power of the optical transmitter and P_B is the background noise, both in watts, η is the detector quantum efficiency, e is the electronic charge in coulombs, h is the Planck's constant, v is the optical frequency in hertz, k is the Boltzmann constant, B is the bandwidth of the (detector) filter, T_N is the effective noise temperature and R is the effective input resistance to the amplifier of the detector.

In presence of turbulence, the SNR is a fluctuating term (i.e., an instantaneous value) and the average (mean) value is to be taken. The mean SNR can be expressed

$$\langle SNR \rangle = \frac{SNR_0}{\sqrt{\frac{P_{S0}}{\langle P_S \rangle}+\sigma_1^2(D)SNR_0^2}}$$

(5)

where SNR_0 is the signal-to-noise-ratio in absence of turbulence defined earlier, PS_0 is the signal power in the absence of atmospheric effects, the mean input signal power $\langle PS \rangle$ (i.e., the mean of the instantaneous input signal power P_S), and $\sigma^2 I$ (D) is the aperture-averaged scintillation index.

The signal entering the decision circuit fluctuates due to the various noise mechanisms. Therefore the SNR_0 varies making <SNR> a variable quantity. [2][29]

Reason for increase in BER

For any type of detector, we can assume that the bit error probability (i.e., the relative frequency of errors) is functionally related to the signal strength (denoted by s) which can be defined as the number of signal photons per bit incident on the detector. The bit error probability can be written as E(s) for a signal pulse of strength s. If the signal strength fluctuates randomly due to atmospheric turbulence, s becomes a random variable with a probability distribution P(s). Therefore the bit error probability will also become a random variable. Most of the statistical information about E is contained in the first two moments of the distribution (the mean and the variance), which can be expressed as

$$\langle E \rangle = \int_0^\infty E(s)P(s)\,ds$$

(6)

$$\mathrm{Var}\quad (E) \quad = \int_0^\infty (E - \langle E \rangle)^2$$

(7)

where <E> denotes ensemble average and "var" indicates the variance. If we express E(s) as a finite Taylor formula about <s>, with a second degree error term, we can write

$$\langle E \rangle = E(\langle s \rangle) = 1/2 \int_0^\infty E^{(2)}(\langle s \rangle + \theta(s)(s - \langle s \rangle)(s - \langle s \rangle)^2 P(s)\,ds$$

(8)

where $E^{(2)}$ is the second derivative of E(s), and θ(s)is between 0 and 1 for each value of s, but is otherwise completely unknown. It is evident from the above equation that <E> is always greater than E(<s>) if the second derivative of E(s) is positive for all s. Therefore a sufficient condition for atmospheric turbulence to cause an increase in the bit error rate is that the second derivative of the bit error probability function, E(s) be everywhere positive.[2][30]

VI. Conclusion

In this paper, we present a review of FSO communication system with main focus on the study of different turbulent conditions of atmosphere. Moreover, work done by different researchers in the field of FSO system using different modulation techniques in various turbulence models is discussed. Also methods for performance enhancement of FSO link are described in the work. We have also studied different modulation schemes and their applications in different situations. Finally we have concluded that PPM gives best performance under turbulence conditions. Also a comprehensive analysis of the parameters BER and SNR of FSO system is done in the atmospheric channel.

Acknowledgment

We wish to acknowledge contributors for developing and maintaining the IJETT style files which have been used in the preparation of this document.

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