Free Space Optical Using Different Modulation Techniques – A Review

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Abstract — *Free space optics is now a day's replacing radio frequency communication because of its high speed, large bandwidth, maximum performance, minimum error and efficient communication. All these can be achieved by using free space optical communication system. Because FSO system is license free and cost effective, therefore, it has become need of the hour. Turbulence manifests in increased Bit Error Rate (BER) leading to degradation in the link performance. This paper focuses on detailed survey of FSO system, modulation techniques used and environmental effects on link performance, while using different modulation techniques and turbulence models. In paper, we observed that MPPM gives best performance under turbulence conditions.*

Keywords — *FSO (Free Space Optics), Bit Error Rate (BER), IM, OOK, PPM, DPSK, SIM, DWDM.*

I. INTRODUCTION

FSO was originally developed by US military and NASA, and being used for more than three decades in various forms to provide fast communication links. The latest fourth-generation FSO lasers are 100 per cent class 1m eye-safe technology. These systems offer excellent automatic power-level control, and eliminate short-distance optical saturation [1].Free Space Optics (FSO) is a communication technology that uses light as carrier and free space as medium to transfer information between transmitter and receiver separated by certain distance. FSO link is a wireless link between a transmitter and a receiver in optical communication system.The data which has to be transmitted is modulated on the intensity, phase and frequency of the carrier signal. In FSO system different modulation techniques are used to modulate information signal at source. Each FSO system uses a high-power optical transmitter for transmit source signal towards destination and receiving side high sensitivity receiver used. But the atmospheric attenuation is major challenge for faced by FSO systems which affect the performance of the link. The other factors which can affect the FSO are humidity, water vapour, signals absorption, smoke, beam scintillation, spreading and wandering are some of the factors.FSO systems operate in the infrared (IR) range of spectrum. It desires an unobstructed line-of-sight between the transmitter and receiver for proper operation of an FSO system. FSO systems operates around 850 and 1550 nm wavelengths and the frequencies corresponding to this range of wavelengths is around 200 THz.1550nm wavelength is preferred because of more eye safety and reduced solar background radiation[2].It has a capability to transmit the information signal with very high data rate ,with very high speed up to 2.5Gbps through the free space with secure transmission of voice and image signals over distances up to several kilometres as compared to other technologies[2].With the help of tracking mechanism, DWDM kind of technologies, fourth-generation FSO systems with speeds up to 10Gbps are available in the market. It has various advantages over conventional fibre optical system such that the capital investment for the installation of FSO system is less than a fifth as compared to ground based fibre optic technology.FSO channels are immune to electromagnetic interference (EMI).This system do not require any license fees. So, it is easily affordable. Moreover, they can be installed much more quickly. Some common applications are metro network extensions, Wireless Video surveillance and monitoring, last-mile access, disaster recovery, Security, enterprise connectivity, fibre backup, backhaul, service acceleration and broadcasting applications etc.[3],[4].

This paper presents a comprehensive survey of FSO communication with primary focus to study different conditions of atmosphere so as to minimize the different losses taking place when light signal passes through free space and study different techniques to improve the FSO link performance under different weather and turbulence conditions. In this paper we have studied the performance of different modulation schemes in FSO system. Rest of the paper organized as follows: Section II discussed the literature survey of FSO system, its factors modulation techniques and turbulence models and demonstrates Performance enhancement techniques viz., aperture averaging, receiver diversity and analysis of different modulation schemes for performance enhancement of FSO under turbulence conditions. Section III discussed the work done by researchers. Future scope and conclusions are given in Section IV&V.

II. LITERATURE SURVEY

In this survey, we have discussed on free space optical communication system, its modulation techniques, factor affecting the FSO link and atmospheric turbulence models.

A. *Free Space Optics System*

The FSO system can be reflective, refractive, diffractive or combination of these. Fig.1 illustrates the transmitter, receiver and tracking telescope as separate optical apertures [4]. Another configuration can be a single optic which performs all three functions, thus saving cost, weight and size. The transmit telescope consist of lens assembly usually Plano convex lenses. The important aspects of optical system on transmitter side are size and quality of the system. Quality determines the minimum divergence by the system. At the receiver the signal is optically collected and detected in the presence of noise interference, signal distortion and background radiation, depends upon the f-number and aperture size. Detector's field of view is determined by f-number and amount of light collected on the receiver is determined by aperture size. To acquire and maintain link integrity, wide view of tracking system field is taken.

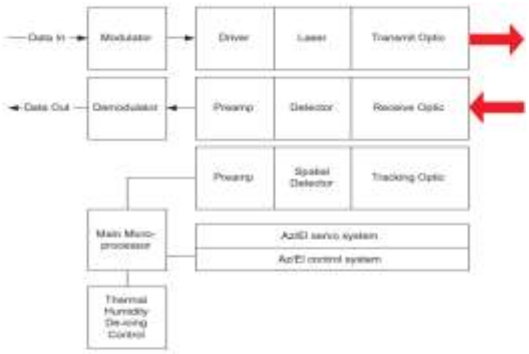

Fig.1: Free Space Optics Subsystem [4]

Diode lasers are driven with a DC bias current to put the devices above threshold and then are modulated using on-off keying (OOK). The receiver detector is coupled to the receiver aperture through either free space or fiber. Detectors used in this are generally avalanche photodiode (APD). APD must be capable of meeting the system bandwidth requirements. Trans-impedance amplifiers that provide highest gain at fastest rate are used after the detector. Devices such as CMOS or quad cells, which are having large area, are used as tracking detectors .The tracking bandwidth should be low in case building mounted FSO systems as the building motion is uneven thermal effect. But if the FSO system mounted on the tall poles or towers then it should be large to remove the vibrations in the signal caused by wind [5],[6].

B. *Factors Affecting FSO Link*

The performance of FSO systems can be highly affected by atmospheric turbulence. In practical applications of FSO, the medium is always the free space atmosphere which includes many ingredients which affects the light signal while it travels through it. These include fog, rain, snow, smoke, humidity and many more. Other factors that affect FSO performance include turbulence, strong wind, building sway and background radiations [7].All these ingredients have different index of refraction, which affect the speed of light travelling through them. Hence, these ingredients cause absorption and scattering losses of the light signal which causes the signal degradation. These adverse effects can be caused by scattering or refraction of light as it passes through the turbulent medium. The turbulence in medium is caused due to eddies or cells formed from different refractive indexes in the atmosphere.

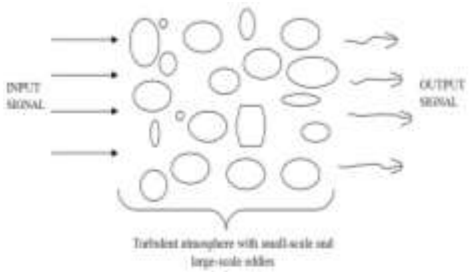

Fig. 2: FSO communication system with turbulent atmosphere as medium [8]

However, in order to achieve high performance under the control of such effects, suitable transmission power and spatial diversity techniques can be used to maintain required link availability [9].To study the effect of these adversaries, a number of models have been proposed and developed by various researchers which provides the idea of behavior of the communication system as the signal passes through the turbulent medium. Among those models, three models have emerged to be the most popular 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 $f(I)$ [10].

$$f(I) = \frac{1}{\sqrt{2\pi\sigma_k^2 I}} \exp\left[-\frac{(\ln(I) - m_k)^2}{2\sigma_k^2}\right], I \geq 0 \qquad (1)$$

Where m_k is mean and σ_k^2 is log-irradiance variance.

Log-irradiance variance is given by $\sigma_k^2 = \ln(\sigma_{SI}^2 + 1)$ 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 in homogeneity increases which in turn affects the accuracy of performance analysis.

2) *Negative Exponential Model:*

This model is used for low turbulence conditions where link length spans several kilometres, number of independent scatter become large. In that case, signal amplitude obeys a Rayleigh distribution which in turn leads to the negative exponential statistics for irradiance, which is given by [9].

$$p(I) = \frac{1}{I_0}\exp\left(-\frac{I}{I_0}\right) \ , I_0 > 0 \qquad (2)$$

Where I_0 is the mean received radiance.

3) *Gamma-Gamma Model:*

This model was given by Andrews et al. [11]. It states that as the signal in form of light traverses through a turbulent medium (i.e. atmosphere), it faces scattering and refraction effects, also known as small scale and large scale effects, respectively. These small scale effects are caused by cells or eddy smaller in size than Fresnel zone whereas, large-scale effects are caused due to eddies larger than Fresnel zone. The power of electromagnetic radiation per unit area incident on a receiver surface (i.e. irradiance) is a function of independent irradiances of small-scale and large-scale eddies and is given by: $I = I_x I_y$ where, I_x and I_y are caused by large-scale and small scale turbulent eddies, respectively. Both these irradiances follows the gamma distribution giving the probability density functions as follows [9].

$$p(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\left(\frac{\alpha+\beta}{2}\right)-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) , I > 0 \qquad (3)$$

Where, α and β are the number of large-scale and small scale eddies respectively; $K_{\alpha-\beta}(.)$ is modified Bessel function of second kind; Γ(.) is gamma function. These parameters are directly related to atmospheric conditions according to [11].

$$\alpha = \left[\exp\left(\frac{0.49\sigma_l^2}{\left(1+1.11\sigma_l^{12/5}\right)^{7/6}}\right)-1\right]^{-1} \qquad (4)$$

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

Where σ_l^2 represents log irradiance variance.

C. Modulation Schemes Used in FSO

The optical transmission system involves modulation of optical signal, its transmission, detection and demodulation. In FSO communication systems, the intensity of an optical source is modulated to transmit signals over channel. The optical signal can be modulated in its amplitude, frequency, phase, and polarization. There are different types of modulation schemes suitable for FSO systems which has compared in terms of the average received optical power required to achieve desired BER at given data rate. A power-efficient modulation scheme is desirable in order to maximize the ratio of peak to average power. The simplest and most commonly used modulation scheme in free space optics is intensity modulation with direct detection. The modulation scheme should be chosen based upon power efficiency, bandwidth efficiency, simple design requirement, low cost implementation and immune to interference background radiations .[4]

Among the various IM schemes, OOK is very simple in implementation and bandwidth efficient. This modulation scheme requires adaptive threshold in turbulent atmospheric conditions for best results [8]. Using this scheme, the light source is turned on to transmit a logic "one" and turned off to transmit logic "zero". It is also known as non-return to zero (NRZ) modulation. Besides NRZ, return to zero (RZ) coding can also be used in which the logic "one" returns to zero in the middle of the sample. RZ shows higher sensitivity than NRZ [6]. OOK is affected by amplitude distortion i.e. fading and propagation of signal through different roots. These issues are least effective when sky is clear. 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 [12], [13]. Under all the turbulence conditions, the BER performance of subcarrier BPSK is always better than that of OOK.The coherent receivers are one to two times more sensitive than OOK systems but instead of that the complexity of coherent system is also more. OOK are more robust than coherent systems. As a result, OOK systems have been preferred for optical links inside the atmosphere. Pulse position modulation (PPM) scheme is an orthogonal modulation technique. PPM requires both slot and symbol synchronization. Pulse position modulation (PPM), where information is encoded into the position of the optical pulse rather than amplitude, offers higher resilience to turbulence due to the availability of soft demodulation algorithms. The technique can improve on the power efficiency of OOK, but at the expense of an increased bandwidth requirement and greater complexity. It does not require dynamic thresholding for optimal detection. Subcarrier intensity modulation (SIM) schemes modulate the frequency and phase of the RF carrier. The phase fluctuation is less pronounced in turbulent atmosphere and thus SIM offers better performance over OOK [14].An improved version of PPM with increased throughput or bandwidth efficiency is the differential pulse position modulation (DPPM) scheme. The empty slots following a pulse in a PPM symbol are removed, which improves the spectral efficiency of the system. In DPIM, the information is represented by the number of empty slots between pulses, potentially allowing higher data rates and improvements in power efficiency compared to OOK and PPM. Dual-header pulse interval modulation (DH-PIM), which is a variation on PIM reduces the number of 'empty' slots, and therefore symbol length, by introducing a second pulse at the start of the information symbol. DAPPM is a combination of PAM and DPPM, multiple pulse amplitude and position modulation is used to improve the data throughput, bandwidth capacity and peak-to-average power ratio. In DAPPM, the symbol length and pulse amplitude are modulated according to the input data bit stream [8],[15]. A summary of the literature related to Features Comparison of different modulation schemes is presented in table I and schematic waveform comparison for modulation schemes is shown in fig.3.

Table 1. Literature on features comparison of different modulation techniques

Modulation Techniques	Literature References	Features
OOK-NRZ	[6][16]	Moderate SNR, Low Cost, requires adaptive threshold
OOK-RZ	[6][16]	High sensitivity
PPM	[4][8]	Superior power efficiency than any other baseband modulation
MPPM	[16][17]	High bandwidth efficiency, spectral efficiency than PPM
DPPM	[8][15][16]	Improved power efficiency, bandwidth efficiency, throughput than MPPM
DPIM	[15][16]	High bandwidth efficiency, spectral efficiency than PPM
OPPM	[15]	High bandwidth efficiency than PPM
SIM	[26]	Low cost, poor power efficiency, high capacity, improved throughput

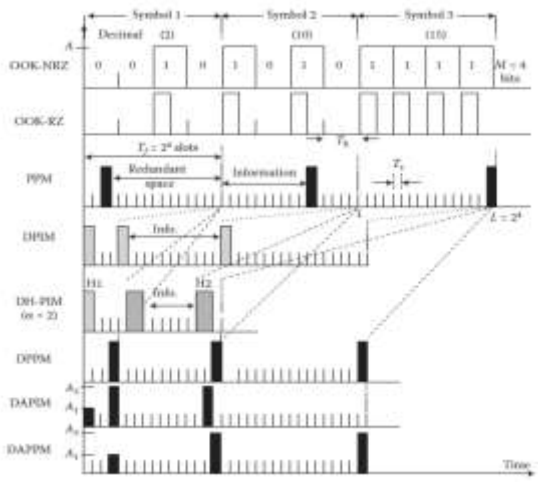

Fig.3 Waveforms for OOK, PPM, DPI, DH-PIM, DPPM, DAPIM and DAPPM signals [9]

D. Performance Enhancement Techniques

Performance of FSO communication system depends upon number of parameters. These parameters can be divided into two categories such as (i) internal parameters (ii) external parameters. Internal parameters are concerned with design of FSO system and include wavelength, optical power, transmission bandwidth, divergence angle and optical loss on the transmitter and bit error rate (BER), receiver lens diameter, and receive field of view (FOV) on the receiver. External parameters are linked with environment such as visibility, atmospheric attenuation, scintillation etc. which come under the effects of atmospheric conditions[18].There are a number of techniques to take the edge off these channel effects such as selection of an efficient modulation scheme, aperture averaging, receiver diversity, diversity (in space, time or frequency), coding, adaptive optics etc. Spatial coherence radius determines the effectiveness of aperture averaging and receiver diversity. This coherence radius defines the distance at which the modulus of the complex degree of coherence drops to 1 / e. The spatial coherence radius for FSO downlink is given by:

$$\rho_{0,d} = \left(1.45k^2 \sec\xi \int_{h_0}^{H} C_n^2\,(z)dz\right)^{-3/5} \qquad (6)$$

Where $k=2\pi/\lambda$, λ is wavelength. For example at $\xi = 0^o$ and wind velocity 21 ms^{-1}, the typical values of $\rho_{0,d}$ for $C_n^2(0) = 1x10^{-2}, 5x10^{-13}, 1x10^{-12}m^{-2/3}$ Are 3.62, 1.43 and 0.92 cm, respectively. These values entail the feasibility of using aperture averaging and receiver diversity techniques for performance enhancement. By using above mentioned values authors improved the link performance by increasing receiver diameter and array of finite sized receivers using averaging and receiver diversity. Then compared for OOK, M-PPM, M-DPPM modulation schemes. Among the three modulation schemes, link with M-PPM scheme gives the best performance in terms of BER followed by M-DPPM and OOK schemes with or without diversity techniques in presence of turbulence and different weather conditions in [19].authors compared the three modulation techniques i.e. OOK, M-DPPM and M-PPM to evaluate the BER with rise in temperature by using aperture averaging and finally concluded that M-PPM perform better than the other two schemes with lower BER. Thus MPPM scheme should be preferred in FSO link design as compared to other two modulation schemes in [20]. S.Rajbhandari et al. has experimentally investigated the performance such as *Q*-factors as well as the slot error rates for different modulation schemes under the atmospheric turbulence conditions for FSO links. The results has been shown that PPM offers the best performance followed by PPM-BPSK for the scintillation index (σ_I^2) <0.5 under weak turbulence conditions. It was observed that PPM offers marginally superior error performance in comparison to BPSK even at higher values of scintillation index σ_I^2 in [14].

III. WORK DONE BY RESEARCHERS

There is a large number of current works as well as efforts that are on the go, to overcome atmospheric turbulence and to enhance the FSO link performance. They have worked on numerous fields of FSO regarding modulation schemes, errors, turbulences and many more.

In [21], Sharif *et al*. Analysed the attenuation in an FSO link due to fog, rain and humidity by using NRZ-OOK modulation technique at three different wavelengths. Furthermore it investigated that both Kim and Kruse models could work better under longer distances than AL Nabulus model. The receiver signal power, link margin, data rate and BER are investigated by using suitable wavelength to evaluate the performance of the system. The results showed that the 1550 nm is better than other wavelengths. The results also showed that transmission distance increases to more than 1 km by increasing the receiver diameter from 5 cm to 15 cm, the transmission distance of the link margin and data rate is enhanced by 61 % and 63%. Simulation results also showed that BER of 10^{-10} and 10^{-6} can achieve at distance 0.95 and 1 km, respectively, for receiver diameter of 15 cm at 1550 nm.

In [2] authors demonstrated the performance of FSO link. Moreover the attenuation and scattering due to haze for 1000nm, 1550nm and 80 nm wavelengths has been studied and observed that less attenuation higher wavelengths. Finally bit error rate performance has been investigated using DPSK modulation and observed that it is better for higher wavelengths as compared to lower wavelengths.

In [7] authors presented the BER of SIM using DPSK for FSO system under weak atmospheric turbulence besides this they analysed the performance by selection combining (SelC) spatial diversity in order to prevent the effects of scintillation. Results also showed that link margin reduced up to 7 dB by using SelC spatial diversity as compared when no spatial diversity is used in very weak turbulence. Moreover, SelC start to pay off, resulting in ~9 dB link margin with two photo detectors with increase in turbulence. But due to random varying characteristic of turbulence, the spatial diversity will not be suggested instead temporal diversity, error control coding and adaptive optics can be used to mitigate scintillation when using DPSK based SIM.

In [22] authors described modulation of transmitted signal by using Digital Phase Shift Keying (DPSK) modulation technique at 33% of modulation signal. Based on the analysis, it is recommended to develop an FSO system of 40 Gbps with 1550 nm wavelength, 10mW power and link range up to 700 km .The implementation of this system requires a new design of OCDMA technique to avoid the problem of multiple access interference (MAI) in order to achieve an Optical Code Division Multiplexer (OCDMA) system asynchronous transmission, secure communication and high degree of scalability.

In [23] authors investigated the Performance of FSO system such as Calculation of attenuation due to fog by using KIM and KRUZE Model and other parameters like received power, BER and Q factor in different weather conditions. It has been observed that As the visibility decreases, the attenuation increases and the received power decreases. This paper has achieved quality factor of 13.1 in fog conditions and 20.0 for normal condition and 7.11 for rainy condition. Also it has been calculated OSNR, Noise figure, Gain, Optical power. This analysis described that the different attenuation conditions leads to different weather conditions like clear weather, rain, snow, light fog, heavy fog. Hence based upon this analysis the multiple transceiver FSO system can be well operated under different weather conditions.

In [24] authors analysed Four fog models for optical beam propagation horizontally at different wavelengths using NRZ-OOK and 16-PPM modulation techniques. They studied the characteristics of BER for 16-PPM and NRZ -OOK modulation techniques. They studied the effect of fog on a receiver signal power, SNR, and BER. When a distance increases, receiving signal power goes on decreasing. The results showed that 1550nm is more suitable than the other wavelength. Moreover, the theoretical results showed that the performance of 16 - PPM is far better than the NRZ-OOK.

In [25]author has analyzed the performance of WDM-FSO communications system for parameters such as the received signal power, signal to noise ratio, Q. factor, and BER using NRZ modulation technique over different weather conditions. Finally he concluded that the WDM over FSO communication system is very suitable and effective in providing high data rate transmission with very low bit error rate (BER).

In [26] author analyzed the performance of FSO link in various atmospheric turbulence for different bit rate using NRZ and RZ technique. He investigated the effect of turbulence on the link performance by varying bit rate, turbulence strength and modulation format. Finally results shown that RZ format is best for strong turbulence. Whereas NRZ technique is used for low and medium turbulence conditions.

IV. FUTURE SCOPE

There is a large number of current works as well as efforts that are on the go, to overcome atmospheric turbulence and to enhance the FSO link performance and provide gigabit capacity low cost.It has been reported in [27], that the mobile backhaul in United States will be increase 9.7 times by 2016 due to rapid growth of data demands. This technology is very admired due to easy availability of components, simple installation, high data rate and no licensing fee required. Terrestrial FSO links with transmission rates of 10 Gbps are already available in the market. In [28], 80 Gbps FSO link is experimentally verified using OAM and MIMO-based spatial multiplexing. In[29]with the help of advanced modulation schemes, the wireless backhaul capacity can further be increased beyond 100 Gbps which will fulfil the requirement for future 5G cellular networks. Latest reports in [30] have established 2.56 Tbps data rate transmission with spectral efficiency of 95.7 bps/Hz using four light beams with 32 OAM modes employing 16 QAM. In [31], 100.8 Tbps data transmission has been reported by using 42 wavelengths with 24 modes. One more upcoming technology that ropes fifth generation mobile network is the use of steered laser transceiver (SALT) on a nano satellite (picosatellite) whose weight is assumed to be less than 20 lb (or less than 3 lb). Due to their small size and low launch cost, it is predictable to launch about 1000 small satellites into LEO orbit for the purpose of Earth exploration, data imaging, weather sensing, Tracking using FSO technology [32]. The power consumption is assumed to be 0.5 to 5 W depending upon the data rates. SALT or Advanced SALT (ASALT) system would be used for optical communication between aircraft and ground station or inter-satellite communication up to several 1000 kms.

V. CONCLUSION

In this paper, we present a comprehensive survey 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. Finally we have concluded that MPPM gives best performance under turbulence conditions.

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