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Free Space Optics: A Last Mile Technology (Review)

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Abstract

Communications using optical signals over fibers have revolutionized the flow of information. Free space optics has emerged as new technology in recent two decades. License free spectrum, ease of installation, high data rate made FSO a convenient option for future use as a last mile technology. In this paper review of the development taken place in the field of FSO is presented.

Index Terms - On off Keying(OOK),On Off Keying Non Return To Zero (OOK NRZ), On Off Keying Return To Zero (OOK RZ), Phase shift keying (PSK), Binary phase shift keying (BPSK), Quadrature phase shift keying (QPSK), Free Space Optics (FSO),4th generation cellular network (4G), Spatial diversity reception technique (SDRT).

1. Introduction

Due to increased demand of internet and many other application which need huge bandwidth, we are getting short of radio spectrum and this diverts our attention toward some other mode of communication like optical communication that is communication through light. The concept of optical communication came into existence in 1880, Graham Bell Patented the photo phone which modulated the light with a voice signal and transmitted that across free space to solid state detector [16]. Later, optical fibers were used as a medium to carry optical signals. Optical fibers offers high speed data transmission but in many cases deploying optical fibers cannot be possible so to overcome this problems a new technique have emerged from last two decades which is wireless optical communication also known as free space optics which uses infrared light for transmission of signal.

FSO uses 750 nm or 1550 nm wavelength, THZ frequency spectrum and line of sight path. In terrestrial link its range is limited to a few kilometers. FSO is a cheap alternative with high data rate, excellent security to wired communication system. One of its major advantage is that it is protocol independent therefore can support multiple platform and interfaces [3]. The security of FSO is due to narrow beam of light and due to line of sight path and infrared rays do not interfere with relatively nearby signal of same nature as well as with radio signal facilitating system design and therefore resulting in a significant cost reduction also infrared signals are more immune to fading compared to radio signals [15]. FSO links are very robust, in [30], five year observation of link is done and the availability of the link is found very high. FSO link works in emergency situations also, when other means of communication are not working or destroyed. On March 11, 2011 a massive earthquake hit Japan when main shock reached the site of FSO set up, the error signal increased significantly but even then, the ROFSO system was not shut down. After that, three aftershocks of magnitude 7 came but high tracking error was recorded only once, even when the aftershock intensity was less than 5 the FSO system is not affected at all [7]. It can be used for point to point link and point to multipoint links but most of the workdone until now is concentrated on point to point link and BER is taken as the performance measure.

The block diagram of FSO link is as

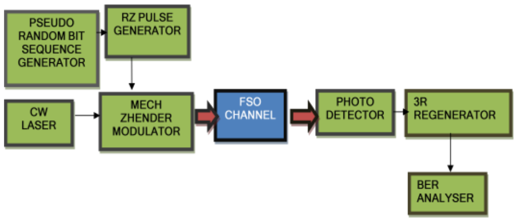

Figure1. Block diagram of single channel FSO

The Pseudo random bit sequence generator generates randomly any input bit sequence which is then converted into line code by RZ pulse generator. CW laser generates optical signal for modulation. The random input and laser are modulated by Mech Zhender modulator. The modulated signal is then passed through a FSO channel. On the receiver side the signal is detected by photo detector which takes the optical signal and gives output in electrical form. This signal is then passed through 3R regenerator which performs Reamplification, Reshaping and Retiming of the signal. To analyze the signal any visualizer tool can be used as BER analyzer or eye diagram. The performance of a free space optical link is deteriorated by parameters like rain, fog, snow, clouds. Out of all these factors fog affects FSO link the most, other affecting factors are pointing loss, geometric loss, transmitter loss and receiver loss. The atmospheric attenuation is caused by absorption and scattering, water particles and carbon dioxide mainly causes the absorption of optical signal whereas fog, rain, snow and clouds causes the scattering of optical signal transmitted in free space.

Fog highly deteriorates the FSO signal, the reason is that the size of the fog particles is comparable to the transmission wavelength of optical waves [22].

The optical signal passing through air has to go through turbulence due to varying refractive index. Refractive index variation occurs because of factors like atmospheric pressure, humidity and temperature .Out of all above factors temperature fluctuation dominates. Distribution of temperature in the air can be determined by random microstructure created by large scale variation in temperature, but due to wind and convection these large structures are broken up into smaller eddies each with a different refractive index.

PSD (power spectral density) of turbulence $\propto C_n^{\ 2}$

Here $C_n^{\ 2}$ = Refractive index structure parameter or it is a measure of strength of fluctuation in the refractive index [18].

Atmospheric attenuation can be calculated by Beer's law [2].

$$\tau\alpha = e^{-(\beta_{abs}+\beta_{scat})}R \quad \ldots\ldots(1)$$

Where β_{abs} and β_{scat} = The absorption and scattering coefficients.

R = link distance.

When the wavefront passes from the atmosphere than due to the turbulence present in the atmosphere focusing and defocusing of the beam occurs causes fluctuation of the signal .Such fluctuation of the signal is known as scintillation [9] and the scintillation index is a measure of turbulence induced in optical transmitted signal and is defined as [18]

$$\sigma_I^{\ 2} = \langle I^2 \rangle \big/ \langle I^2 \rangle - 1 \quad \ldots\ldots(2)$$

Here I = received intensity of the optical field after passing through the turbulent medium Due to scintillation effects in atmosphere power is lost and can be calculated by power scintillation index [6];

$$\sigma_P^2 = \frac{\langle [P - \langle P \rangle]^2 \rangle}{\langle P \rangle^2} \quad \ldots\ldots(3)$$

σ_P^2 =Power scintillation index.

P = received optical power.

<.> = Ensemble average.

In inter satellite communication FSO link can go up to thousands of kilometers due to absence of atmospheric turbulence. In [4], for 20dB transmitted power the distance travelled is 5300 with quality factor 5.81 and minimum BER is 2.96×10^{-9} .On the basis of wavelengths used FSO systems are categorized into conventional FSO and next generation FSO link [14].Conventional FSO uses 850nm wavelength and in this electrical to optical and optical to electrical conversion is required but due to power and band width limitation of optical devices in this wavelength band, it is not possible to operate above 2.5Gbps [14].In next generation FSO 1550nm wavelength is used. In this system, the need of conversion from optical to electrical and vice versa is not required. In this, signal can directly be emitted from optical fiber to free space just need to put a transmitting antenna on the end of optical fiber cable. Next generation FSO system is affected by atmosphere more but overall it gives acceptable performance [14].

The paper is organized as follows

In section 1 introduction of the free space optical system is given after that in section 2 turbulence models are described for different atmospheric conditions. From section 3 to Section 5 techniques that helps to reduce scintillation are discussed. In Section 3 modulation schemes are described. In section 4 and 5 Aperture averaging technique and spatial diversity technique are described respectively. In section 6 application of FSO are mentioned.

2. Models Of Atmospheric Turbulence

Many models have been purposed to describe atmospheric turbulence condition but it is not specified yet that which model represent atmospheric turbulence in a best way [19].

Most commonly used model for describing weak atmospheric turbulence is log normal model and is given by

$$y(I) = \frac{1}{I\sigma\sqrt{2\pi}} \exp\left[\frac{\left(\ln \frac{I}{I_0} + \frac{\sigma^2}{2} \right)^2}{2\sigma^2} \right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where y(I) = Power density function.

I_0 = Average optical irradiance without turbulence.

I= Average optical irradiance with turbulence.

σ^2 = Log irradiance variance and it is considered as a Rytov parameter. For weak turbulence case [11]

$\sigma^2 < 0.3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$ (5)

Lognormal distribution is very effective when used with aperture averaging to receive irradiance fluctuation for many weak to strong channels [20].

For strong atmospheric turbulence the model used is K distribution. K distribution is considered as the product of exponential and Gamma distribution and its PDF is given by [17]

$$\frac{2\alpha_{mn}^{\frac{(\alpha_{mn}+1)}{2}}}{(\alpha_{mn})} I_{mn}^{\frac{(\alpha_{mn}-1)}{2}} K_{\alpha mn_{-1}}(2\sqrt{\alpha_{mn} I_{mn}}), I_{mn} > 0 \ldots\ldots (6)$$

Here α_{mn} = channel parameter related to the effective number of discrete scatterers.

$\Gamma(\cdot)$ = Gamma function.

In K distribution scintillation index (SI) is

$$\text{SI} = \frac{\alpha_{mn} + 2}{\alpha_{mn}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

From above expression it is clear that for lower value of α_{mn} SI is high [17].

Gamma Gamma distribution is most widely deployed model as it describes both small scale and large scale atmospheric fluctuation and factorizes the irradiance as the product of two independent random processes each having a gamma PDF defined as

$$P_X(X) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} X^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta X}), \quad X>0 \ldots\ldots (8)$$

where $\Gamma(.)$ = Gamma function.

$K_n(.)$ = Modified Bessel function of the second kind of order.

α, β = Effective numbers of small scale and large scale eddies of the scattering environment.

The scattering in case of fog can be predicted by Mie scattering process but it involves complex computation and detailed information of fog parameters therefore another method of calculation is used based on visibility range information. On the basis of visibility range information three models are used Kruse, Kim and Al-Naboulsi models

The attenuation coefficient for both Kim and Kruse models

$$\alpha_{fog} = \frac{10 \log V\%}{V(km)} \left(\frac{\lambda}{\lambda_0}\right)^{-q} \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Here V (km) = visibility range,

V% = transmission of air drops to percentage of clear sky.

λ = wavelength (in nanometers).

λ_o = visibility range reference (550 nm).

q = size distribution coefficient of scattering. According to Kruse model q parameter is

$$q = \begin{cases} 1.6 & \text{if} \quad V > 50km \\ 1.3 & \text{if} \quad 6km < V < 50km \\ 0.585V^{\frac{1}{3}} & \text{if} \quad V < 0.5km \end{cases} \quad \ldots\ldots.(10)$$

According to Kim the value of the q parameter is

$$q = \begin{cases} 1.6 & \text{if} \quad v > 50km \\ 1.3 & \text{if} \quad 6km < V < 50km \\ 0.16V + 1.34 & \text{if} \quad 1km < V < 6km \\ V - 0.5 & \text{if} \quad 0.5km < V < 1km \\ 0 & \text{if} \quad v < 0.5km \end{cases} \quad \ldots\ldots\ldots (11)$$

From Kruse model there will be less attenuation for higher wavelengths but Kim rejects this fact.

Al-Naboulsi characterizes advection and radiation fog separately and proposed two different models for advection and radiation fog. The advection fog is formed by the movements of wet and warm air masses above the colder maritime surfaces while Radiation fog is related to the ground cooling by radiations over continental surfaces. According to Al-Naboulsi the advection fog model is

$$\alpha_{adv}(\lambda) = \frac{0.11478 + 3.8367}{V} \quad \ldots\ldots\ldots\ldots\ldots\ldots(12)$$

For radiation fog model is

$$\alpha_{RAD}(\lambda) = \frac{0.18126\lambda^2 + 0.13709\lambda + 3.7502}{V} \quad \ldots.(13)$$

Attenuation for both types of fog can simply be Calculated as [22]

$$A_{fog}(db/km) = \frac{10}{\ln(10)}(\alpha(\lambda)) \quad \ldots\ldots\ldots\ldots\ldots\ldots..(14)$$

3. Modulation

The choice of modulation technique for optical signal transmission plays an important role in reduction of turbulence. The selection of the modulation scheme should be such that it adapts to the weather conditions. Optical carrier can be frequency modulated, phase modulated or amplitude modulated. OOK RZ and OOK NRZ are mostly deployed techniques but other techniques can also be implemented [8].

In [9], considering lognormal distribution comparison of OOK and DPSK is done and it was analyzed that DPSK has higher sensitivity than OOK under same bandwidth and same channel conditions and up to a certain extent can reduce scintillation and perform better than OOK and PSK in atmospheric turbulence and fog conditions. The BER of DPSK remains less than 0.1 for scintillation index 0.1 to 0.7 with parameters used 650 nm wavelength visibility v=10 and data rate =40Gbps.

For weak turbulence condition a comparison of OOK NRZ, OOK RZ and BPSK is done and found that OOK-RZ outperforms OOK-NRZ. When OOK and BPSK are compared, BPSK performance is found superior to OOK, the reason behind this is turbulence affects more on the intensity of signal than the phase [11].

In [13], QPSK and BPSK modulation techniques are studied the channel considered are AWGN and Rayleigh channel. QPSK is a form of phase shift keying technique which doubles the data rate to that of BPSK with same bandwidth.

The BER equation of BPSK is [13]

BER= $\frac{1}{2}\, erfc\sqrt{SNR}$ …………………………(15)

And for QPSK BER equation is [13]

BER= $erfc\sqrt{SNR}$ …………………………..(16)

QPSK modulation provides better performance than BPSK in terms of data rate.

In[27], OOK, DPSK, DQPSK modulation techniques comparison is done with SDRT and without SDRT. With spatial diversity number of receiver used are two. Variance of light intensity is taken as 0.16, 1.2, and 4 to represent weak, moderate and strong atmospheric turbulence conditions. In strong atmospheric turbulence condition OOK SDRT gain is 19.5db and DPSK SDRT gain is 20.3dB which is 0.8db more than OOK. In strong atmospheric turbulence the modulation gain of DPSK over OOK is 2.4dB more without SDRT and with SDRT it is 3.2dB more. For moderate turbulence channel, OOK SDRT gain is 12.1dB and DPSK is 12.7dB and modulation gain of DPSK over OOK is 3.1dB without SDRT and 3.7 with SDRT. Clearly, DPSK performs better than OOK in strong and moderate turbulent channel with or without the use of SDRT. In weak turbulent channel DPSK without SDRT performs same as OOK with SDRT at

BER=10^{-3} also the modulation gain of DPSK decreases as the channel changes from weak to strong turbulence without SDRT.

DPSK and DQPSK performs almost same in strong and moderate turbulence conditions but DQPSK is capable of sending two bits simultaneously, therefore it is more beneficial.

4. Aperture Averaging

Aperture averaging is to increase the telescope collecting area, which decreases the scintillation effect. The problem of aperture averaging starts in advanced FSO system, earlier it was not present in conventional FSO system as large diameter aperture receivers were used then [6].

The size of the receiver should be kept optimum neither too large nor too small as the reduction in scintillation depends nonlinearly with increase in the diameter, as we increase the diameter of the receiver up to a certain limit scintillation effects are reduced but after that it becomes ineffective [29]. Aperture averaging helps to reduce scintillation in strong turbulence conditions as well. Fading reduction by aperture averaging is defined by aperture averaging factor which is defined as

$$A = \frac{\sigma_I^2(D)}{\sigma_I^2(0)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

Where $\sigma_I^2(D)$ =Scintillation index for a receiver lens of diameter D.

$\sigma_I^2(0)$ =Scintillation index for a receiver lens of diameter 0 [12].

Low bit error rate (BER) values can be achieved for smaller SNR by using larger receiver aperture due to averaging of irradiance fluctuations [10].

Aperture averaging effects are studied with OOK and BPSK and aperture averaging is found effective in both of the cases, it helps to reduce the turbulence induced fading [12].

5. Spatial Diversity

Spatial diversity scheme is used to improve the performance of FSO system especially in strong atmospheric turbulence. In this many receivers are used to receive the signal and these receivers are kept apart so that the fading distribution of each receiver can be assumed to be independent.

In [17], spatial diversity technique is employed and channel is modelled as K distribution then it is analyzed that with spatial diversity performance is improved and link distance is also increased in heavy weather conditions and it also reduces the chances of temporal blockage of laser beam by obstruction.

In [27], comparison of DPSK and OOK techniques is done with space diversity reception technique and without space diversity reception. Number of receiving antenna with diversity are taken as N=2. Modulation gain of DPSK format over OOK was 2.4dB without SDRT and it is 3.2 dB with SDRT, also it is analyzed that SDRT gain of both DPSK and OOK formats increases as the variance of light grows this means that SDRT is very effective when turbulence is strong.

6. Applications Of Free Space Optics

The range of FSO is limited to a few kilometers because of atmospheric turbulence therefore this technology is considered as a last mile technology but there are many other applications where FSO can be employed like as a Rf/Fso wireless network or as a 4G backbone.

6.1. Rf/Fso Wireless Network:

In [23], performance of RF only link and RF/FSO link is studied .From base station to primary nodes FSO links are employed and from primary node to secondary node RF link is used and it is found that RF/FSO link lasts twice as with RF only link so RF/FSO link can be used as a good alternative to RF only link on the basis of its longer life time.

From performance perspective in [1], performance analysis of asymmetric dual hop RF/FSO link is done with RF channel as Rayleigh and FSO link as Gamma Gamma distribution and found that RF/FSO link gives less performance upto a SNR value of 40dB, after this value the performance goes almost equal but less performance of FSO link can be compensated with its features like high data rate, which is not present in RF links.

6.2. Backbone for 4g network:

FSO network can be used as a backbone network for 4th generation cellular network. In [3], comparison between RF and FSO is done and found that RF link shows a low linear decay of signal to noise ratio through all the distance while FSO show a low linear slope until 10 meters then it starts to decay linearly but with a fast slope till the end. This proves FSO superiority over short haul and medium haul communication therefore we can say that it can be a good choice as a backbone network for 4G as it gives enhanced data rate.

7. Conclusion

The atmospheric turbulence is described by various models. The models are based on the level of turbulence but there is no certainty about which model presents the atmospheric turbulence in an appropriate manner. Generally, Gamma-Gamma distribution is preferably used out of all the models presented because this is the only model which represents all the turbulence conditions.

In modulation techniques OOK is the most widely deployed technique due to is simplicity reason, but various phase shift keying techniques are studied and compared with OOK technique and found that PSK techniques gives good performance with respect of various performance parameters. Then techniques like aperture averaging and spatial diversity help to improve the performance of FSO communication link and very good results are obtained by the use of these techniques. The reduction factor of BER is very high in very strong atmospheric turbulence conditions, which is not possible without the use of these techniques. The problem associated with spatial diversity technique is that the hardware requirement is increased as multiple transmitter and receivers have to be employed. With aperture averaging complexity of FSO system goes high due to large aperture size.

A few applications other than last mile technology are presented. FSO technique can be applicable in cellular networks and also as a backbone for 4G network.

FSO can be a very good alternative to the existing wireless system with very high data rate, but with a constraint that is atmospheric turbulence which restrict the link distance upto a few kilometers.

To make FSO work in an efficient manner and for a longer distance techniques to mitigate the effect of turbulence have to be implemented like aperture averaging, spatial diversity. Optical amplifiers, Multihop relaying, error correction and detection techniques can further help to improve the quality of free space optical communication.

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