Comparison of channel models based on Atmospheric turbulences of FSO system- A Review

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Abstract- With the worldwide demand of larger bandwidth and higher data rates, there is rapid advancement in wireless communication technologies. Today the term wireless is used almost for 'radio-frequency' technologies as a result of large scale utilization of RF devices. But RF spectrum is limited in capacity and costly as the band is licensed. These shortcomings can be overcome by Free space optics (FSO) with data rates of 2.5 Gbps over distances upto 4km. FSO provides numerous advantages such as high security, license free spectrum, 'last-mile connectivity' etc. Even though it gives various benefits but there are some factors that limit the system performance such as scattering, absorption, fog, rain, haze, snow. Among all these factors atmospheric turbulence is the major impairment. Based on the various levels of turbulences, different atmospheric channel models and the comparison based on their performance have been discussed.

Keywords- *Atmospheric turbulences, Scintillation, Rytov, Channel Models*

I. INTRODUCTION

Free space optics is the advanced communication technology which uses air as a medium to transmit the data. The technology is more feasible where the physical connections are failed and where high data rate transmission is required. FSO is the simple line of sight (LOS) communication which requires clear line of sight (LOS) between transmitter and remote receiver. Besides providing various benefits such as full duplex transmission, high bandwidth, license free spectrum, 'last-mile' connectivity, high security, ease of installation and license free spectrum, there are several limitations imposed on system performance. The major impairment in the FSO system performance is atmospheric turbulence [1]. The other factors which can affect the FSO are humidity, water vapours, signal absorption, smoke, beam scintillation, spreading and beam wandering. When the laser beam travels along a horizontal path in free space it results in irradiance fluctuations called as scintillation. These irradiance fluctuations result in signal fading at the receiver and deterioration in the quality of the received signal. To make the system reliable, various mitigation techniques are employed which are aperture averaging, diversity techniques, Hybrid RF/FSO, Adaptive coding and modulation, OFDM-FSO [2] etc. As the system suffers from different losses, various statistical channel models have been developed based on these losses such as for geometric and misalignment losses there are Rayleigh and Rician distribution models, for atmospheric losses there is Monte –Carlo simulations, for background radiation there is Poisson distribution based model [2] and for atmospheric turbulence induced fading there are Kolmogorov spectrum, Gamma-Gamma distribution, Lognormal, I-K, K- distribution, Negative exponential distribution based models [3]. The channel models developed for atmospheric turbulence is classified based upon the various turbulence regimes i.e. from weak to strong turbulent conditions.

The basic block diagram of FSO system is shown in Fig.1.

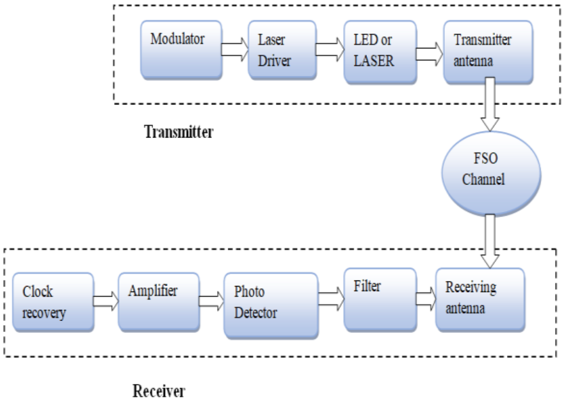

Fig.1.Basic block diagram of FSO

II. SCINTILLATION

When laser beam propagates through the atmosphere, there are random fluctuations in the parameters of the wave. These fluctuations are because of sun radiations which lead to increase in temperature near earth's surface results in inhomogenities in index of refraction [17]. Also the wind speed and pressure gradient in earth's atmosphere causes these inhomogenities. As a result, there are irradiance fluctuations known as Scintillation [4], [5]. The random fluctuations in the index of refraction result in the optical beam deflection and power fluctuations at the receiver [5]. $'C_n^2'$ is the parameter that describes the refractive index fluctuations. In [5], the largest values of $'C_n^2'$ have been observed near noon and the lowest values have been seen at night. Thus it can be observed that temperature and time of day affects the parameter $'C_n^2'$. Thus, FSO link performance depends upon the temperature variations. The strength of irradiance fluctuations (i.e. optical turbulence) is measured by scintillation index (S.I) given [4] by eq.1:

$$\sigma_I = \frac{<I^2>}{<I^2>} - 1 \qquad (1)$$

where, *'I'* denotes the irradiance fluctuations of the optical wave and '<>' defines the ensemble average or long time average.

The Scintillation index characterises the laser beam propagation through random media.

III. FREE SPACE CHANNEL MODELS

According to the temperature and pressure gradients, there are irradiance fluctuations in the received signal which results in distortion and beam broadening of received spectrum [6]. As per the different levels of turbulent conditions such as weak (where S.I <1), moderate (where S.I=1), strong (where (S.I>1), various statistical channel models for transmission in free space are developed which are Kolmogorov spectrum model, Gamma-Gamma channel model, lognormal model, K–channel distribution, I-K channel model, Negative exponential model etc. [7]. The effect of scintillation on FSO is considered by these channel models according to the various regimes. For the FSO using Intensity modulation/direct detection (IM/DD) system, the laser beam propagates in the free space in a horizontal path with white additive Gaussian noise. The basic channel statistics used for all the models assume the channel to be memory less, stationary and should have slow fading statistics [8]. The basic channel statistics assumed for all the channel models is given by eq.(2):

$$y = S_m + n = \eta I_m + n \tag{2}$$

where, 'y' is the signal at the receiver, S□ = ηI□ is the instantaneous intensity gain, η is the effective photo-current conversion ratio of the receiver, I is the normalized irradiance signal (and takes values "0" or "1"), and n is the AWGN with zero mean and variance $N_o/2$.

A. Kolmogorov Spectrum Model:

Kolmogorov power spectrum model is used for weak fluctuations because for strong strength of turbulence or increasing path length the effect of multiple self-interference causes the optical wave to become less coherent [4]. Kolmogorov theory assumes that the turbulent cells range in size from macro scale (L_0) to micro scale (l_0) [5].

Each turbulent cell is homogeneous but has different refractive index. The range between macro scale to micro scale is called inertial range. For inertial range, power spectrum [5] is defined by Kolmogorov in eq. (3):

$$\varphi_n(\mathrm{k})=0.33C_n^2 k^{-11/3} \qquad 1/L_0 \ll k \ll 1/l_0 \tag{3}$$

where, L_0 and l_0 are large and small cell or turbulence size, $\emptyset$□(k) is the measure of atmospheric turbulence, C_n^2 is the refractive index structure parameter.

For a plane wave model along a horizontal path, the scintillation index in Kolmogorov model is defined by Rytov variance [4] given in eq. (4).

$$\sigma_r = 1.23 C_n^2 k^{7/6} L^{11/6} \tag{4}$$

where, the index-of-refraction parameter C_n^2 is a measure of refractive index fluctuations, k denotes the optical wave number, and L is the propagation path.

B. Log-normal Model:

Several experiments in [4], [5] showed that Kolmogorov model is sometimes incomplete to describe the atmospheric turbulences as they are no longer homogeneous in three dimensions. Also this theory is valid only for the inertial range of turbulent conditions. So, log-normal model in [9] is developed which is employed in case of weak turbulent conditions or fluctuations. Log normal model is widely accepted because of its simplicity in terms of mathematical calculations [10].

The lognormal pdf describes the scintillation and fading statistics of weak turbulence. Considering the log normal model, the probability density function of received optical signal is given by [7]:

$$f_{I_m}(I_m) = \frac{1}{I_m\, \sigma_m \sqrt[2]{\pi}} \exp\left(\frac{(\ln I_m + \frac{\sigma_m^2)}{2}}{2\,\sigma_m^2}\right) \tag{5}$$

where, 'I□' is the normalized irradiance arrived at each receiver, 'σ□$'$ represents the log irradiance variance which depends on the channel characteristics as given in eq. (6):

$$\sigma_m^2 = \exp\left[\frac{0.49\sigma_r^2}{(1+0.18d^2+0.56\sigma_r^{12/5})^{7/6}} \frac{0.51\sigma_r^2}{(1+0.9d^2+0.62d^2\sigma_r^{12/5})^{5/6}}\right] -1 \tag{6}$$

Log-normal channel model is suitable only for short distance ranges to 100 meters because as distance increases it encounters with elements in the atmosphere causing fading and scattering. It is only valid for weak turbulence conditions (i.e. S.I <1) because as the strength of turbulence increases, scattering effects are also taken into consideration due to which detection and fading probabilities are not accurately analysed. Hence system accuracy [7], [10] is affected.

C. Gamma-Gamma Distribution Model:

As log-normal model is restricted only for the weak fluctuations, there is another model given by modified Rytov theory [10] known as Gamma- Gamma channel model in which the irradiance fluctuations are developed as a multiplicative of two random processes i.e. weak and strong turbulent eddies given by the eq. (7):

$$I=XY \tag{7}$$

X-fluctuations from small range

Y-fluctuations from long range

These turbulent eddies follow gamma distribution and the pdf given by this distribution is gamma-gamma pdf [12] defined as:

$$f(I)= \frac{2(\alpha\beta)^{\alpha+\beta/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{\frac{(\alpha+\beta)-2}{2}} k_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \tag{8}$$

where, I is the signal intensity, Γ(.) is the gamma function, K- is the modified Bessel function of the second kind order, α and β are the effective number of small- scale and large scale eddies of the scattering environment. These parameters can be related directly with atmospheric turbulence as given in [7], [12]:

$$\alpha = \frac{1}{\exp\left[\frac{0.49\sigma_R^2}{\left((1+1.11\sigma_R^{12/5})^{\frac{7}{6}}\right)}\right]-1} \quad (9)$$

$$\beta = \frac{1}{\exp\left[\frac{0.51\sigma_R^2}{\left((1+0.69\sigma_R^{12/5})^{\frac{5}{6}}\right)}\right]-1} \quad (10)$$

where $'\sigma_R'$ is the Rytov Variance given by eq. (4). Here C_n^2 varies from $10^{-13}m^{-2/3}$ for strong turbulence to $10^{-17}m^{-2/3}$ for weak turbulence.

The scintillation index S.I can be expressed in terms of α and β as follows:

$$S.I = \frac{1}{\alpha} + \frac{1}{\beta} + \frac{1}{\alpha\beta} \quad (11)$$

Gamma-Gamma channel model is straightly related to the atmospheric conditions and work under weak to strong turbulences (i.e. S. I>1). In [7], with the increase in the turbulence strength, there is smaller decrease in BER but increase in the power level. Thus it effects the power of received signal. The main advantage of this model is that it works under sub channel correlation effect where other channels fail to perform better [13].

D. K-Channel model:

For strong turbulent regimes where S.I is nearly 1, K-distribution is suitable [2]. It gives experimentally and practically good results in the system [14]. K-channel model can be considered as a product of two independent models exponential distribution and gamma distributions [7], [10], [15]. Thus it can provide benefits of both the models.

The conditional probability density function of irradiance, 'I' is derived by the negative exponential distribution given as:

$$f_{\frac{1}{\mu}} = \frac{1}{\mu}\exp(-1/\mu) \quad (12)$$

Here, μ is mean irradiance and it follows the gamma distribution.

$$f_\mu(\mu) = \frac{\alpha^\alpha \mu^{\alpha-1}}{\Gamma(\alpha)} \exp(-\alpha\mu) \quad (13)$$

The unconditional distribution for irradiance for K- distribution is given in [7]:

$$P_I(I) = \int_0^\infty f_{\frac{1}{\mu}}\left(\frac{1}{\mu}\right) * f_\mu(\mu)\ dI \quad (14)$$

where, $'\mu'$ is the irradiance

$$P_I(I) = 2\frac{\alpha^{\frac{\alpha+1}{2}}}{\Gamma(\alpha)}\frac{I^{\frac{\alpha+1}{2}}}{\xi^{\frac{\alpha+1}{4}}}K_{\alpha-1}\left(2\sqrt{\alpha I}\right) \quad (15)$$

where, $'\alpha'$ is the channel factor related to number of discrete scatters, '$'\xi'$ is the average electrical SNR, $'\Gamma'$ is the gamma function and 'I' is the intensity.

As gamma-gamma distribution, K-channel could not easily relate the channel parameters with atmospheric turbulences. Therefore, it has limited utilization and applications [10]. K distribution channel model is suitable to achieve distance of 1km with SNR ranges from 20-27 dB as given in [15].

E. I-K Channel model:

The unconditional *I-K* distribution for the intensity fluctuations is a generalized form of the K distribution that is applicable to all conditions of atmospheric turbulence, including weak turbulence for which the K distribution is not theoretically applicable [16]. So it is suitable for both weak as well as strong turbulence regimes. The PDF of normalized signal irradiance is given in [17] as:

$$P_I(I) = \begin{cases} 2\alpha(1+\rho)\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha-1}{2}} \times K_{\alpha-1}(2\sqrt{\alpha\rho}) \times \\ I_{\alpha-1}\left(2\sqrt{\alpha(1+\rho)I}\right);\ for\ I < \frac{\rho}{1+\rho} \\ 2\alpha(1+\rho)\left(\frac{1+\rho}{\rho}\right)^{\frac{\alpha-1}{2}} \times I_{\alpha-1}(2\sqrt{\alpha\rho}) \times \\ K_{\alpha-1}\left(2\sqrt{\alpha(1+\rho)I}\right);\ for\ I > \frac{\rho}{1+\rho} \end{cases} \quad (16)$$

where, α and ρ are distribution parameters and represent effective no. of scatters. The parameter ρ is a measure of the power ratio of mean intensities of the coherent and random components of the field. For extremely weak scattering, ρ is relatively large since the field is dominated by the coherent component. The power ratio decreases monotonically as the strength of turbulence increases and, in fact, must eventually be zero in the regime of super saturation [10].

The major advantage of I- K distribution model is its tractability i.e. the parameters can be easily controlled [16]. Also it becomes useful where K-distribution is not quite fit experimentally.

F. Negative Exponential Distribution:

For the cases of strong atmospheric fluctuations where link length reaches several kilometres, number of scatter becomes large results in fading which is assumed to be a random process [18]. In that case signal amplitude follows a Negative-exponential distribution for the signal intensity given in [18] as:

$$f(I) = {}^{I}/_{I_o}\ \exp(-{}^{I}/_{I_o}),\ I > 0 \quad (17)$$

where, E[I] = $I_o$is the mean received irradiance. During the saturation regime, the value of the scintillation index, S. I→1.

III. LATEST RESEARCH WORK IN CHANNEL MODELS

The channel models are designed to work under every kind of atmospheric conditions. There are many techniques which can be used to overcome these conditions. These techniques can be employed with the given channel models to improve the system performance. Certain researches in the channel models with these techniques have been discussed in table 1.

Table 1. Comparison of FSO channel models

REFERENCE	MODEL	PARAMETERS	ATMOSPHERIC TURBULENCE	FINDINGS
(Rahman et al. 2014)	Kolmogrov spectrum model	▪ Wavelength-1550 nm ▪ Distance-2km ▪ Power transmitted 0dBm ▪ Radius of curvature-infinite ▪ Spot Beam at transmitter-0.25m	Weak($\sigma_i^2 \le 0.3$)	▪ For a fixed distance of 2km, the dual diffuser modulation shows better performance than OOK modulation. ▪ The improvement using DDM technique is 96.8%. ▪ At 622Mbps data bit rate the DDM technique can detect more weak signal approximately -15dBm
(Jaiswal et al. 2016)	Log-normal model	▪ Link length-100m ▪ Bit rate-1Gbps ▪ Diffraction angle-2mrad ▪ Receiver diameter-0.1m ▪ Temperature- 300K ▪ Attenuation coefficient -0.1 db/km	Weak($\sigma_i^2 \le 0.3$)	▪ For variable data rate average transmitted power improved from 3 to 232.18 Mbps. ▪ For modulation schemes like OOK, PPM spectral efficiency increases from 0.093 to 0.375 Mbps. ▪ c) For varying code rate spectral efficiency improved from 0.6 to 0.823
(Nistazakis et al. 2017)	Log-normal channel model	▪ Transmitted Power- 400mW (26 dBm) ▪ Wavelength -1550 nm ▪ Transmitted Aperture Diameter- 2 mm ▪ Beam Divergence- 1 mrad ▪ Bandwidth - 0.5 GHz ▪ Receiver Aperture Diameter - 180 mm ▪ Receiver Sensitivity -30 or -40 dBm.	Weak($\sigma_i^2 = 0.297$)	▪ Under weak turbulence condition, maximum effective link value is 3.45 km. ▪ Availability above 99.9%, i.e., Pout $=6.5\times 10^{-4}$. ▪ Maximum efficiency of 18.63 (b/s/Hz) for weak turbulence conditions at 5 km. ▪ SNR for weak turbulence level at -30 dB receiver threshold is 54.52 dB.
(Wang et al. 2015)	Gamma-Gamma channel distribution	▪ Number of subcarriers-256 ▪ Electrical Bandwidth -10GHZ ▪ System temperature in atmospheric turbulence-300K	Moderate to strong($0.3 < \sigma_i^2 < 5$)	▪ Effect of phase noise on SER is higher in weak turbulence than strong turbulence. ▪ Under strong turbulence, effect of phase noise on system sensitivity is smaller than under weak turbulence. ▪ Outage probability for N=128 rises to 0.040, and rises to 0.060 and 0.135 for N=256 and N=1024.
(Tourki et al. 2017)	Gamma-Gamma channel distribution	▪ Amplifier gain-10Gb ▪ Link length-3Km ▪ $k_b = 1$	Moderate to strong($0.25 < \sigma_i^2 < 0.75$)	▪ With the increase in transmitted power, SER decreases for weak as well as strong turbulence. ▪ For BPPM, transmitted power is 17 dB but for 8PPM it is 11 dB. At BER 10^{-1}.
(Mishra et. al 2016)	K- distribution model	▪ Wavelengths-1550,1310,850 nm ▪ Link distance-2.5 km, 3 km ▪ Channels -3 ▪ $C_n^2 = 2 \times 10^{-13} m^{-2/3}$	Strong($\sigma_i^2 \gg 1$)	▪ Outage probability becomes smaller as the number of elements of different wavelength increases. ▪ System becomes complex and costly.
(Singh et. al 2013)	Negative exponential channel model	▪ Bandwidth -1.93×10^{13}Hz ▪ Transmitted power-50mW ▪ Optical frequency-2.5×10^{11} Hz ▪ Number of subcarriers-52 ▪ Temperature-300K ▪ Photodetector responsivity-0.8 A/W	Strong Saturation regimes where S.I=1	▪ For OFDM QPSK-FSO modulation system, BER of 3×10^{-2} is achieved at SNR of 7dB for Log-normal distribution. ▪ For negative exponential at same SNR value i.e.7dB , BER is 6×10^{-3} ▪ Negative exponential model gives better results in terms of BER improvement.

IV. CONCLUSION

In this paper, it is observed that besides providing various advantages FSO suffers from a lot of impairments out of which atmospheric turbulence is the major one. There are many techniques used to enhance the system performance. Depending on the turbulence conditions researchers developed various channel models such as log-normal model is used for weak to moderate turbulence conditions, gamma–gamma is used for moderate to strong fluctuations, K distribution is used only for strong atmospheric turbulences. Gamma–Gamma model is best suitable as it works under all kinds of atmospheric conditions.

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