Optical Wireless Communication: Atmospheric turbulence and pointing error models

[1]NITIN GARG, [2]ANWAR AHMAD
[1]Student, [2]Professor
[1]Electronics and Communication Department,
[1]Jamia Millia Islamia, Delhi, India

Abstract: Optical wireless communication (OWC) has many advantages over RF communication like High Bandwidth and transmission rate, License free spectrum, Easy to employ and deploy, Cost effective, low Interference and power and Security. Due to this OWC gained significance importance. OWC is line of sight communication and weather dependent technology. Any changes in the atmosphere affect the OWC channel and lead to atmospheric turbulence. Also misalignment between the OWC transceiver due to various factors like thermal expansion, wind loads, earthquakes lead to pointing losses. This paper presents the comprehensive survey on the different atmospheric turbulence models. This paper also focuses on various pointing error models and effect on the atmospheric channel. In this paper we compare the performance of different atmospheric turbulence models and also discuss most generalized turbulence channels modeled by M´alaga (*M*) distribution. This paper also discusses the advantage and application of OWC system.

***IndexTerms* – Atmospheric turbulence, pointing errors, Optical wireless communication (OWC), Log-normal, Gamma-Gamma distribution, M´alaga (*M*) distribution**

I. INTRODUCTION

Optical wireless communication is the emerging technology used for next generation indoor and outdoor broadband wireless applications. OWC is used to handle high data rate and it has very large information handling capacity and introduced a huge potential to the future of the global telecommunication industry. Optical communication systems are classified according to their transmission medium: guided medium such as fiber communication and unguided medium like optical wireless communication (OWC) or free space optical communication (FSOC) [1]-[2]. Fig. 1 represents the different type of optical wireless communication system.

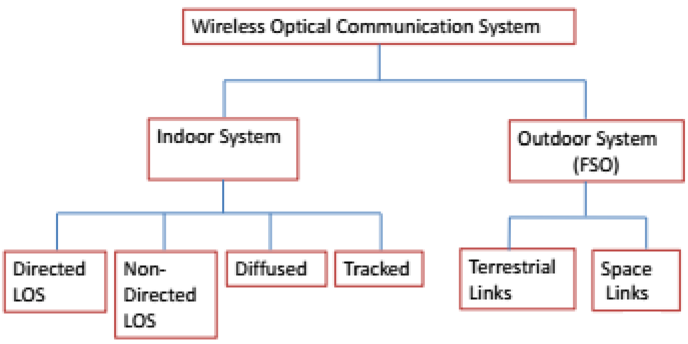

Figure 1 Optical wireless communication system Classification

Optical wireless communication systems also provide as alternative solution to the fiber optics technology. Optical wireless communication has proven their usefulness through a wide range of communication applications. As optical wireless communication provide a very high data rate can replace the radio frequency (RF) communication which is limited to low data rate up to a several Mbps[3]-[4]. Even RF communication has some more limitation such as traffic congestion, interference and most importantly license spectrum. Optical wireless communication carrier signal is licensing free spectrum and therefore, it become an attractive solution for high data rate and capacity applications. OWC is also providing the solution of bottleneck connectivity problem in RF network. A bottleneck problem in network results in slow speeds in communication and limits user performance on a network [5]. Optical wireless communication is the technology which uses optical as carrier signal for the transmission and reception purpose through the atmosphere channel. OWC provide a huge bandwidth and high data speed broadband connection. OWC provide unlicensed spectrum allocation and it is cost effective technique. OWC is easy to employ and deploy and it reduced the power consumption. Optical wireless communication is line of sight technology (LOS) which propagates the light in free space means vacuum, air space, or like a wireless communication [6]. Optical wireless communication is dependent on weather conditions and geographical location. The main challenge face by the optical wireless communication is the atmospheric channel. The attenuation in air mainly caused by absorption of signal due to water drops; scattering of signal due haze particles; fluctuation of signal due smog, snow particles etc. and scintillation of optical signal due to eddies produces in air. Higher attenuation due to thick fog results in limit the range at which OWC is deployed. As the smog increase error performance of the OWC link is affected [7]. It also affects the outage and visibility range of an optical wireless communication link; result in fluctuation of received optical signal which degrade the performance of OWC link. To cater the losses occur in OWC link due to aerosols and gasses in the atmosphere more optical power is needed to transmit the optical signal for a long distance. Now the OWC link with greater than a range of 1.2 km is viable. A hybrid of RF and OWC link provide a better performance. Integration of Milli-Meter wavelength (MMW) RF link over OWC link is known as hybrid RF/OWC link [8]-[10]. Practically fog has no effect on the RF link and OWC link performance is degraded by only small scale fading; led to long distance communication system. So a combined scheme of RF/OWC system improves the reliability of a communication system; prevent RF interference; provide high data rate and conserve RF power. Some challenges are occur when there is switch over from OWC to RF and from RF to OWC link. During switch over loss of data occurrence chances are increased.

The other parameter that affects the OWC channel is atmospheric scintillation. When there is variation in the refractive index, n of free space; result in to the random fluctuation in temperature and atmospheric pressure in the path of propagation. It will make the small size and large size turbulent cells of different refractive index. These cells are called as turbulent eddies. These eddies work like a lens and the optical beam propagating through the channel feels the constructive and destructive interference. This interference lead to random fluctuation in to the intensity and phase of received optical signal and redistribute the signal energy. This fluctuation in the received signal is known to be scintillation. The scintillation degrades the optical wireless communication system error performance [11]-[12].

In Optical wireless communication information or signals/data between the two points is carried by using an optical carrier. Modulation of data can be take place by varying intensity, frequency or phase of the optical radiations as optical carrier signal. Optical wireless communication is line of sight technology (LOS) so that the transmission take place between the source and destination is successful. An OWC system comprises of three main subsystems: Transmitter, Channel and Receiver. Figure 2 show block diagram of an OWC systems through atmospheric channel.

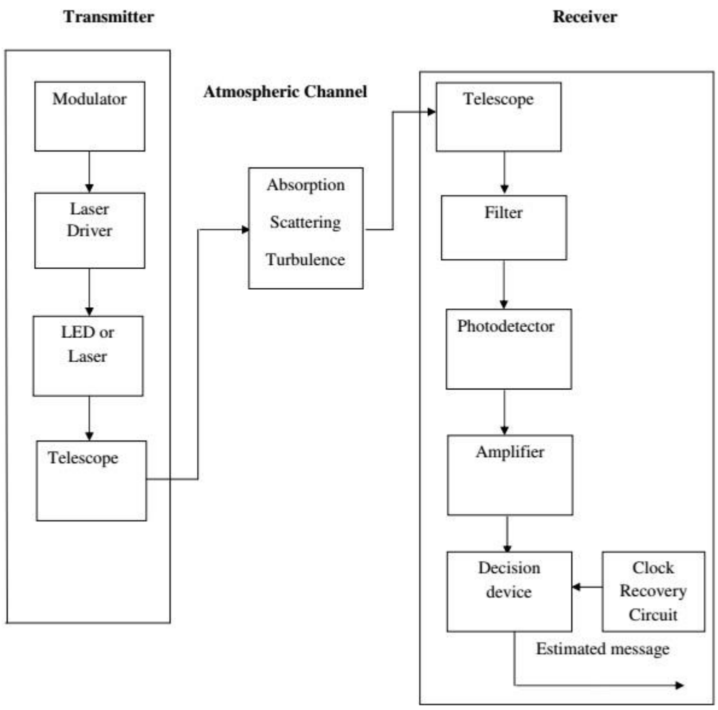

Figure 2 Block diagram of OWC systems through atmospheric channel

2. Atmospheric Channel

In the atmospheric channel attenuation due to weather change is main challenge. Any changes in the weather like foggy, rain, smog, and snowfall affect he optical wireless communication link. It will result in degrade the performance of OWC system. The performance of a communication system affected by atmosphere is categorized as: attenuation of received power and fading in the received optical power because of turbulence regimes [12].

2.1 **Atmospheric Attenuation**

The transmitted laser power is attenuated as the weather is changed. The Beer-lambert law describes the equation for transmittance of optical signal through atmosphere as [13]-[14]

$$\tau(\lambda, L) = \frac{P_R}{P_T} = exp(-\gamma_T(\lambda)L)$$

Where $\tau(\lambda, L)$ = the transmittance at wavelength λ
$\gamma_T(\lambda)$= extension coefficient (m^{-1})
P_T = optical signal power at the transmitter
P_R = optical signal power received at distance L (in km)

The scattering of the signal basically dependent upon the wavelength and the size of particle present in the atmosphere. Size of particle corresponding to spectrum window of different wavelength like 780nm, 850nm, 1550 nm decide the different type of scattering i.e. Rayleigh scattering or Mie scattering.

2.2 **Atmospheric Turbulence**

Because of change in temperature eddies or air pockets are produce in the air causes the fluctuation in the optical signal. Due to scintillation refractive index of air is change and performance of link is degraded [15]. Atmospheric turbulence also affects the link in many ways:

- Beam is missed from its line of sight due to deviation in angle (Beam steering)
- Change in power density due to fluctuation into the random signal and introduced the interference in the optical beam. It is also called as beam scintillation.
- Atmospheric turbulence affects the polarization of received optical signal.
- Received power is decreased due scattering of the signal also called as beam spreading.
- Phases of the received signal are also varied because of atmospheric turbulence and this loss in phase coherence is known as phase coherence degradation.

3. **Atmospheric turbulence Models**

There are various models defined for atmospheric turbulence in all turbulence regimes (weak, medium, strong). Most commonly used atmospheric channel models are:

- Log-Normal Model
- Gamma-Gamma distribution
- Negative exponential
- K-distribution
- Mala'ga distibution

3.1 ***Log-Normal (LN)model***

LN distribution is the continuous distribution of any random variable X, whose logarithm value $ln(X)$ is normally distributed. In the LN distribution the random variable has only positive values. Let a random variable X is log-normally distributed; the parameters μ and σ are mean and standard deviation of the variable X. So the random variable X can be written as:

$$X = e^{\mu + \sigma Z}$$

where Z is standard variable. The pdf of X is defined as:

$$p = \frac{1}{\sqrt{2\Pi\sigma_x^2}} exp\left\{-\frac{(X - E[X])^2}{2\sigma_x^2}\right\}$$

where $E[X]$ is expectation of random variable X and σ_x^2 is variance of X. If I is the irradiance in the turbulent channel and I_O is the irradiance when there is no turbulence then:

$$I = I_O \exp(l)$$

In optical wireless communication the pdf of optical beam with the intensity I is defined as [16]-[17]:

$$p = \frac{1}{\sqrt{2\Pi\sigma_l^2}} \frac{1}{l} \exp\left\{-\frac{(\ln(I/I_O) - E[l])^2}{2\sigma_l^2}\right\}$$

where l is log-intensity of I.Here the variance $\sigma_l^2 = 4\sigma_x^2$ and the expectation E[l] = 2$E[X]$. This type of model is for weak turbulence and the pdf plot of log-normal distributed for different value of irradiance is shown in figure 3.

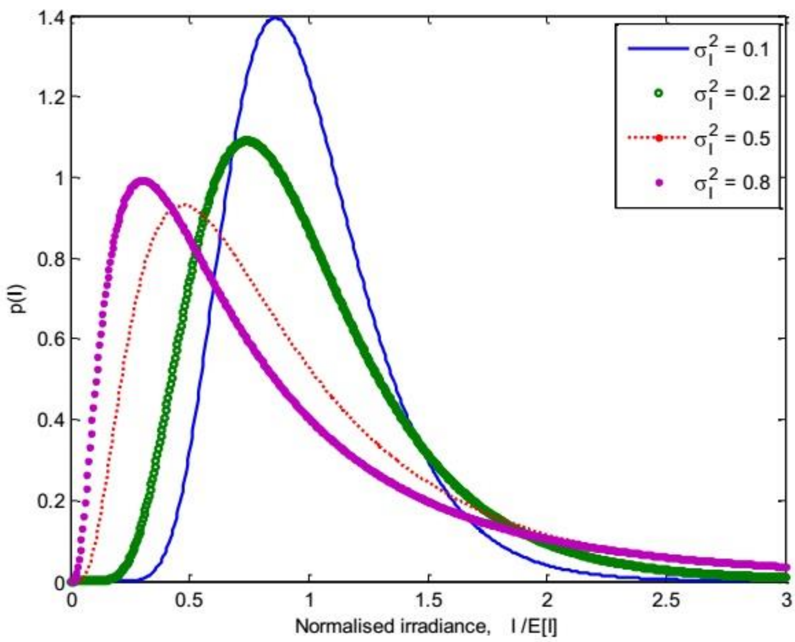

Figure 3: Probability density function of log-normal model in atmospheric channel

The above equations represent the log-normal model in turbulence medium but there are some limitations of log-normal model. As the optical beam travel through a communication channel it degrades with the distance and atmospheric turbulence in the channel. Based on the experimental results, log-normal model is applicable to the low value of c_n^2 and with increase in the value of c_n^2 the air pockets result in scattering of the signal [17]. This was also result in increasing scintillation index and causes multiple scattering. So the log-normal model is limited to weak turbulence regimes and in strong turbulence log-normal model performance is degraded.

3.2 Gamma-Gamma (GG) model

GG distribution is mostly used model which is based on the theory of double stochastic. The gamma-gamma distribution is proposed by Andrews et al. [18]. In gamma-gamma model the atmospheric channel consist of small scale and large scale eddies. In this atmospheric channel receive optical irraradiance I is the product of independent random process I_X and I_Y.

$$I = I_X I_Y$$

where I_X= Irradiance received from large scale eddies

I_Y = Irradiance received from small scale eddies

I_X and I_Y both follow the gamma distribution and this is called as gamma-gamma distribution. There pdf are given as(61):

$$p(I_X) = \frac{\alpha(\alpha I_X)^{\alpha-1}}{\Gamma(\alpha)} \exp(-\alpha I_X); \qquad \alpha > 0; I_X > 0$$

$$p(I_Y) = \frac{\beta(\beta I_Y)^{\beta-1}}{\Gamma(\beta)} \exp(-\beta I_Y); \qquad \beta > 0; I_Y > 0$$

By using the above equation the pdf of I is defined as:

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

where I is the received optical signal intensity, α and β are defined as the number of large and small scale air pockets in the atmospheric channel. $K_{(\alpha-\beta)}$ is Bessel function of $(\alpha - \beta)$ order. α and β are important parameters in gamma-gamma distribution model, because these parameters describe the atmospheric turbulence and these parameters are defined as [19]-[20]:

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

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

Figure 4 show the plot of pdf of gamma-gamma distribution.

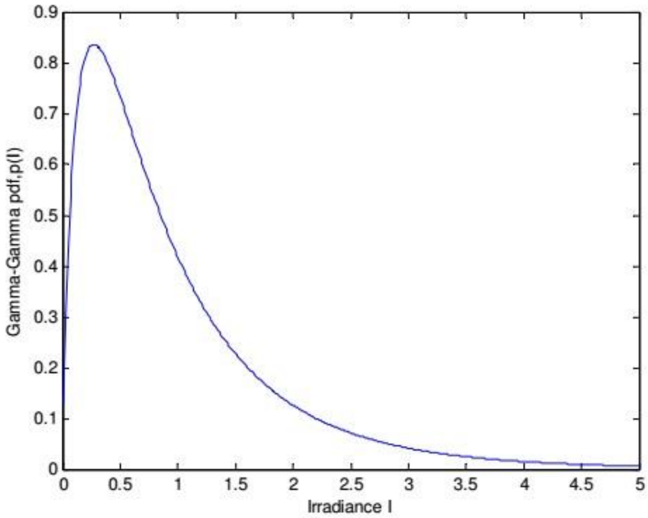

Figure 4: Probability density function of gamma-gamma model in atmospheric channel

3.3 Negative Exponential Model

Negative exponential distribution is the distribution process in which continuous events occur at constant average rate. Negative exponential is important case of gamma distribution in strong turbulence regime. Negative exponential model is used where number of scattering components is large and the distance between transmitter and receiver is long.

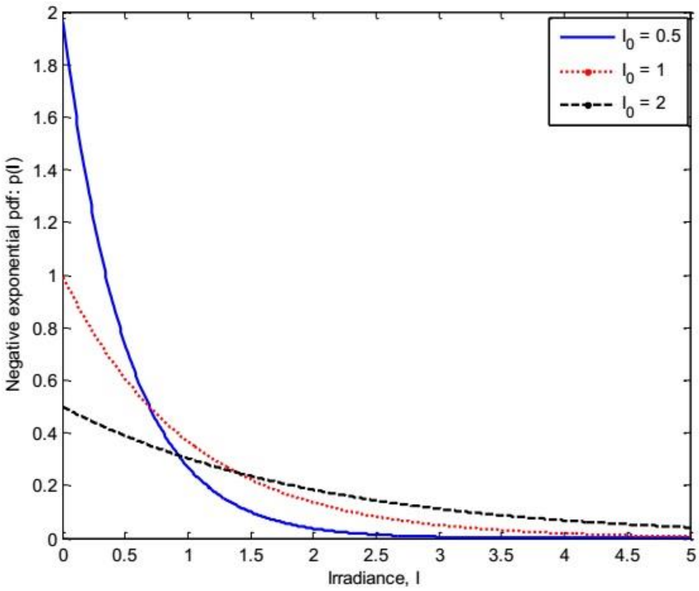

Figure 5: Probability density function of negative exponential model in atmospheric channel

It is used where the turbulence is strong and beyond the saturation regime. In this case signal amplitude fluctuations of an optical wave propagating through atmospheric turbulence is following the negative exponential statistics for the optical signal intensity [21]. The signals follow the Rayleigh distribution and given as:

$$p(I) = \frac{1}{I_O} exp\left(-\frac{I}{I_O}\right) \quad , \qquad I \geq 0$$

In case of negative exponential distribution the value of scintillation index is 1 if the turbulence is beyond the saturation regime. Figure 5 show the pdf of negative exponential model.

3.4 K-distribution

K-distribution is the most important distribution in the atmospheric channel for strong turbulence regime. This type of distribution is deriving from gamma-gamma distribution and use the parameter of gamma distribution. It is mostly used when the radiation wavelength is smaller than the cell size and number of scattering cells are N. In negative exponential the cells N are scattering in such a way that it fluctuates from one cell to another cell. If the scattering is coherent radiated then it is known as k-distribution [22]. It has best performance in the highly scatter parameters and experimentally proven for strong turbulent media [23]. The pdf of the received optical signal is given as:

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

Where α is the effective number of scatters and K(.) is Bessel function. K- distribution is converted to negative exponential distribution if $\alpha \to \infty$. And the pdf of K-distribution is shown in figure 6.

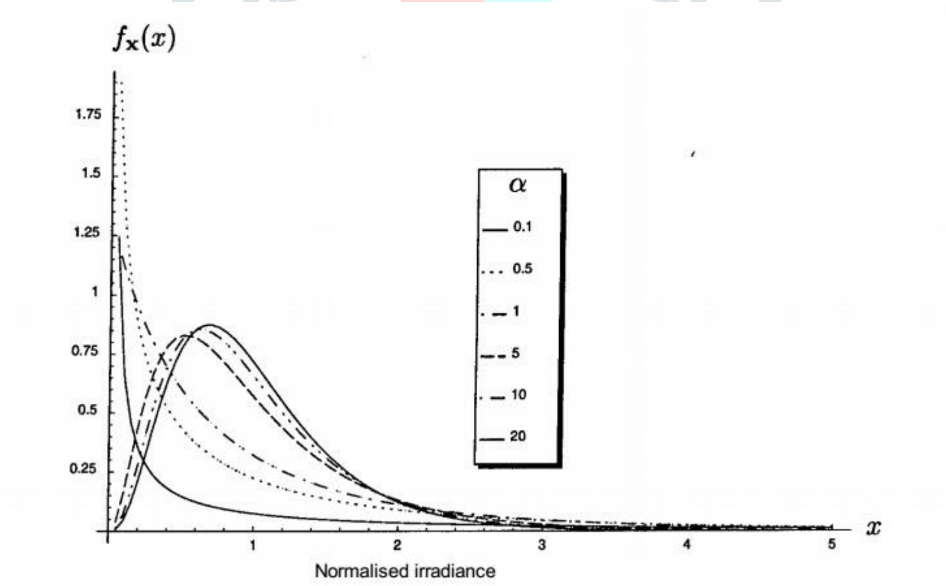

Figure 6: pdf of K-distribution in atmospheric channel

3.5 M Atmospheric turbulence model

In Malaga atmospheric turbulence channel the induced signal intensity I is shown as a product of two random variables. The signal intensity $I = XY$ where X is large fading and Y is small fading characteristics of channel. The received signal at the receiver consists of mainly three different components. The received signal is consist of a line-of-sight (LOS) field component U_L. Other two components are caused by small scale fluctuation. First component is scattered by the eddies on the axis, which is coupled to the LOS contribution U_{SC} [24]. Another component, U_{GS} is the scatter optical signal. And this component is associated to the energy scattered due to off-axis eddies, which is statistically independent. This turbulence channel is modeled by the Ma'laga distribution in different turbulence conditions, whose PDF is given by

$$f_{I_a}(I_a) = A \sum_{m=1}^{\beta} b_m \ (I_a)^{\frac{\alpha+m}{2}-1} K_{\alpha-m}\left(2\sqrt{\frac{\alpha\beta I_a}{g\beta+\Omega'}}\right)$$

Where

$$A = \frac{2\alpha^{\alpha/2}}{g^{(1+\alpha/2)}\Gamma(\alpha)}\left(\frac{g\beta}{g\beta+\Omega'}\right)^{\beta+\alpha/2}$$

$$b_m = \binom{\beta-1}{m-1}\frac{(g\beta+\Omega')^{1-m/2}}{\Gamma(m)}\left(\frac{\Omega'}{g}\right)^{m-1}\left(\frac{\alpha}{\beta}\right)^{m/2}$$

α is the effective number of large scale cell while β represents the amount of scatter and called the fading parameter. The optical power associated with LOS component is $\Omega = E[|U_L|^2]$ whereas the average of the total scatter component power is denoted by $\xi = 2b_o = E[\ U_{SC}{}^2 + U_{SG}{}^2]$.The parameter ρ, represents the scattering power coupled to the LOS component and $\xi_g = \rho\xi$ and $\xi_g = 2b_o(1-\rho)$ denote the average optical power of the classic scattering components, where $\rho \in [0, 1]$ is a scale factor and ξ is the average scatter power. $K_v(.)$ is Bessel function of v_{th} order. $\Gamma(.)$ 95 is a typical gamma function and the average power of the coherent contributions can be defined as $\Omega_o = \Omega + 2b_o\rho + 2\sqrt{2b_o\rho\Omega}cos(\varphi_x - \varphi_y)$. The pdf of

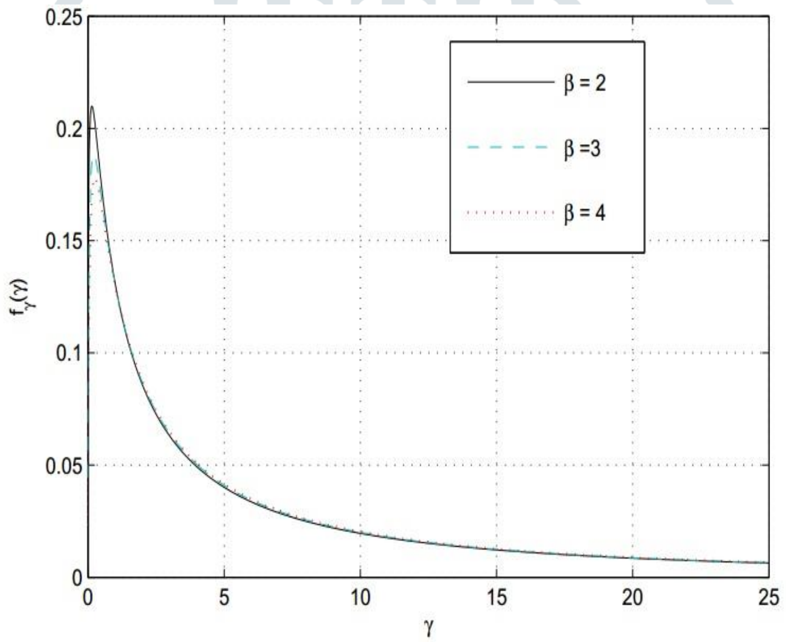

Fig. 7: PDF of the received SNR of M-distribution

3.6 **Comparison of all turbulence models**

Atmospheric Channel Model	Turbulence type
Log-Normal	Weak
Negative Exponential	Beyond saturation regime
Gamma- Gamma	Weak to strong
K-distribution	Very strong
I-K distribution	Weak
M-distribution	All type

Table 1: All turbulence channel

4. Pointing error model

In line of sight OWC communication link, pointing error play an important role to find out the link performance and reliability. Transceivers are place at the top most of buildings to provide the line of sight communication. Due to the thermal expansion, earthquake or wind loads buildings are sway from their positions. This building sways result in misaligned the transmitter and receiver. This is known as pointing errors. Let us take the receiver aperture is positioned at center (0,0) [25]. Due to the pointing error overall random movement of the beam eight center at (x_d, y_d). As shown in figure 3.9, the solid cycle represents the receiver aperture with center at (0, 0) and the dash cycle represents the average beam spot of the received random beams with beam center at (x_d, y_d). These pointing errors mainly lead by the two components: boresight and jitter. The boresight is due to thermal expansion and it is fix amount of displacement between the transmitter and receiver. Jitter is offset of laser beam along the horizontal and vertical axes of construction. The jitter is mainly caused by sway of buildings, dynamic wind pressure, and earthquakes. Depending upon the radial displacement pointing error follows Rayleigh, Rician or Hoyt distribution. Hoyt distribution has Zero boresight and jitter as non-identical component, Rician model represent Non-zero boresight and jitter as identical component and Rayleigh distribution has Zero boresight and jitter as identical component. Instead of this Beckmann gives a versatile model that includes many distributions as special cases.

4.1 Beckmann distribution

In optical wireless communication system, pointing error plays an important role by the determining the link performance. For deriving a generalized pointing error model we consider the effect of misalignment fading.
The pointing errors can be approximated as

$$I_p = B_o\, exp\left(\frac{-2r^2}{2w_{z_{eq}}^2}\right) \quad , \qquad r \geq 0$$

And $w_{z_{eq}}^2 = \frac{w_z^2\sqrt{\pi}\,\mathrm{erf}(v)}{2\delta\,\exp(-\delta^2)}$, $\delta = \frac{\sqrt{\pi}a}{\sqrt{2}w_z}$ where $w_{z_{eq}}$ is equivalent beam width, B_o=[erf(δ)]^2 with erf(.) being the error function. In this we will consider well known Beckmann distribution whose integral PDF is given as follows.

$$f_r(r) = \frac{r}{2\pi\sigma_x\sigma_y}\int_0^{2\pi} exp\left(-\frac{(r\cos\theta-\mu_x)^2}{2\sigma_x^2} - \frac{\left(r\sin\theta-\mu_y\right)^2}{2\sigma_y^2}\right)d\theta \qquad r \geq 0$$

Where r is the radial displacement. A circular detection aperture at the receiver is shown in Fig. 8, where the beam footprint with misalignment on the detector plane is illustrated.

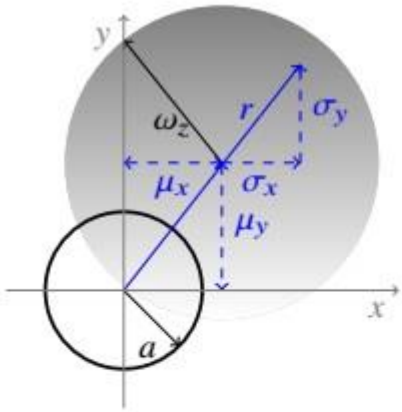

Figure 22: Beam footprint on the receiver aperture plane.

A novel expression of above equation is presented in [26]. The Beckmann distribution can be approximated as follows

$$f_r(r) = \frac{r}{\sigma_{mod}^2}\exp\left(-\frac{r^2}{2\sigma_{mod}^2}\right) \quad , \qquad r \geq 0$$

The PDF of I_p is calculated by combining above equation (5) and (6), and

$$f_{I_P}(I_P) = \frac{\xi^2}{{B_o}^{\xi^2}} {I_P}^{(\xi^2-1)}\; 0 \leq I_P \leq B_o$$

Where

$$\xi = \frac{w_{z_{eq}}}{2\sigma_s}$$

5. Future scope

The OWC has accomplished a fast growth in recent years because of its low expenditure and many advantages.

The OWC technology provide a better solution in 4G mobile communication by using large bandwidth and data rate to providing a backhaul connectivity between the mobile towers. This technology also used in remote places where 3G and 4G are difficult to access. It can be used in secure transmission on the battlefield. It can provide high resolution images in RADAR communication. And also It will provide high data rates which is 5 to 100 times faster than any other communication systems. OWC system will be used to deliver high resolution images or videos in a communication system.

6. Conclusion

Due to increasing demand of data rate it is necessary to shift from RF communication to OWC communication. But due to atmospheric turbulence some losses are occur in the received signal. To fulfill the demands of user optical wireless communication has to overcome various challenge in atmospheric channel. This paper present the survey on atmospheric turbulence models in different turbulence regimes. The probability density functions for the combined statistic of different models are represented with respect to their signal to noise ratio. Also the effect of pointing error is considered. In this paper, we compare the different atmospheric turbulence model. In OWC systems had so much advancement that in near future it has very high growth and bring a revolution in communication.

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