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Review of Channel Modelling for Optical Wireless Links

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ABSTRACT

Atmospheric adversities impacts on the performance of free space optical (FSO) links, with turbulence-induced fading being the most prominent among them. Since FSO links involve transmission of optically modulated signal through atmosphere, it is crucial to have well defined mathematical model to understand and map association of atmospheric turbulence with channel link characteristics. To model a reliable optical wireless communication link, it is important to have an accurate probability density function (PDF) of received intensity, as it allows us to understand the atmospheric factors and magnitude of their impact that may lead to impairment of the link. It was observed that the variation in turbulence has a direct impact on channel behaviour and in turn affects the PDF of received intensity. This paper also analyses the performance of different channel models by contrasting their PDF for varying degrees of turbulence.

Keywords: Atmospheric turbulence, channel fading, channel modelling, Cumulative Distribution Function (CDF), Irradiance Probability Density Function (PDF), variance

INTRODUCTION

An exponential rise in demand for higher bandwidth has led to a scenario where we have to look for something beyond Radio Frequency (RF) links which have reached saturation levels in delivering higher data rates to serve the bandwidth-starved smart device era. The Free space optical (FSO) communication is technology which has been experimentally tested to provide data rates as high as 10 Gbps (Willebrand, Ghuman, 2001) which can serve as reliable solution. It transmits optically modulated data using visible or IR part of frequencies which is essentially non-licensed. The FSO transmission being line of sight offers unprecedented security and privacy. Being optically modulated using very narrow

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wavelengths, FSO links are not only immune to co-channel interference and but also immune to RF interferences (Leitgeb, Awan, Brandl, Plank, Capsoni, Nebuloni, Loschnigg; 2009; Hogan, 2013).

However, the link can be a major dampener, namely degrading the performance of free space optical communication links. This is because the atmospheric and metrological conditions such as wind, rain, fog, temperature variations may impair the link owing to scatter and absorption of light. In comparison to atmospheric conditions, the turbulence effect of atmosphere can cause serious damages to the link over time. The atmosphere is composed of absorption, turbulence induced fading and scattering (Kedar & Arnon, 2004). Due to absorption and scattering, light is unable to reach its destination with full intensity because it gets scattered by water molecules. As mentioned above, the most dominating effect which weakens the link is turbulence-induced fading (Andrews & Phillips, 2005) which occurs in clear atmosphere due to temperature variations whereby the air's refractive index changes. The turbulence effect causes fluctuations in modulated signal phase and amplitude which may make it either difficult or impossible for the receiver to extract information, and this effect is known as fading. The Kolmogorov theory explains the concept of turbulence-induced fading as discussed by Tatarskii, Zavorotnyi, (1985) using parameters which characterise the turbulence: the inner and outer scale turbulence l_0 and L_0, respectively and index of refraction C^2_n. It is worth mentioning that for the given link atmospheric, turbulence is never constant i.e. its strength may vary from weak to strong, depending upon dynamic link and atmospheric conditions. To describe the extent of turbulence, the factor scintillation index (SI) is used as standard, which is defined in equation 1 and explained by Khalighi and Uysal (2014):

$$\sigma^2_I = E\{I^2\}/E\{I\}^2 - 1 \tag{1}$$

where I is intensity of optical wave and $E\{.\}$ defines the expected value of I. To define the quantum of loss of signal intensity due these channel fluctuations, various models have been proposed over the years. The main focus of this paper is to analyse effective channel modelling technique that allows transmission of optically modulated data through the turbulent conditions with minimum fading effects. In the recent past, channel modelling techniques such as Log Normal distribution, Rayleigh distribution, Rician distribution, Negative exponential distribution have been proposed but these models consider turbulence effects either as weak or strong general models which only define the turbulence effect either as weak or strong (Al-Habash, Andrews, Phillips, 2001). Additionally, other models such as Gamma-Gamma and Weibull are based on doubly stochastic theory discussed (Chatzidiamantis, Sandalidis, Karagiannidis, Kotsopoulos, Matthaiou, 2010; Kashani, Uysal and Kavehrad, 2013). These models are capable of describing fading effects of turbulence in all regimes ranging from weak to strong turbulences as cited by Navas, Balsells, Paris and Notario, (2011). The performance of these channel models has been studied and contrasted by determining the probability density function (PDF) of received irradiance in different turbulence regimes. As a rule of thumb, channel turbulence has a direct impact on PDF of received intensity. To model a reliable and interference free optical wireless communication it is very important to build an accurate PDF of received intensity using a channel model that ensures that minimum fading effects are induced on channel. In this paper, the Cumulative Distribution Function of received intensity has also been taken into consideration when developing these channel models. *Section I* of this paper explains the introductory concepts related to free space optical links and channel modelling. Mathematical models to define these channels have been described in *Section II* while qualitative analysis, calculation and interpretation of effect of turbulence on channel fading is described in *Section III. Section IV* contains discussion and conclusive remarks.

A simplified schema of a free space optical communication link along with its basic subsystems is illustrated in Figure 1. The information source is suitably modulated onto optical modulator using laser diode. This signal, known as optically modulated signal, is then transmitted over atmospheric channel to remote destinations using line of sight communication.

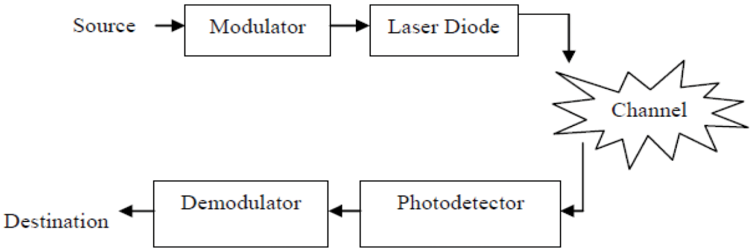

Figure 1. Basic block diagram of free space optical communication system

On the receiver side, the signal is optically collected using photo detectors which convert the optical signals back to electrical information. The free space optical communication provides large bandwidth to support more users than radio frequency (RF) communication.

METHODS

Lognormal Distribution

This model is used to define the fading effect in FSO channel and is best suited to simulate weak atmospheres turbulence (Zhu & Kahn, 2002; Ghassemlooy, Popoola, & Leitgeb, 2007). The turbulence is characterised using Rytov variance denoted by σ^2_I and the turbulence is essentially considered having values of $\sigma^2_I < 1.2$ (Popoola & Ghassemlooy, 2009) also the Rytov variance is defined as

$$\sigma^2_I = 1.23\, C^2_n\, K^{7/6} L^{11/6}$$

where L is link distance, k is wave number and $C^2_{n.}$ is refractive index parameter. The Probability density function (PDF) of Lognormal is given in equation. 2 cited from works of Ghassemlooy et al., (2007), Popoola, Ghassemlooy, Allen, Leitgeb, and Gao, (2008), and Yang and Cheng, (2016);

$$p(I) = \frac{1}{\left(\sqrt{2\pi\sigma^2_I}\right)I} \exp\left\{-\frac{(\ln\left(\frac{I}{Io}\right)+\frac{\sigma^2_I}{2})^2}{2\sigma^{2^I}_I}\right\}, I>0 \tag{2}$$

Where *I* is irradiance *Io* is irradiance without scintillation. The cumulative distribution function (CDF) of Lognormal is given in equation 3.

$$\mathrm{P(I)}= (1/2)\mathrm{erfc}\left\{-\frac{\ln\left(\frac{I}{Io}\right)+\sigma_I^2/2}{\sqrt{2\sigma}}\right\} \tag{3}$$

Rayleigh Distribution

The Rayleigh distribution can be effectively used to model fading effects of moderate to strong values of turbulence. As the value of variance fluctuates between high and low, link performance degrades as PDF of received intensity decreases. This distribution is used to express channel gain. For convenience, the scintillation index for this model was assumed as unity. The probability density function (PDF) for Rayleigh distribution is given in equation 4.

$$\mathrm{p}(I)= \frac{I}{2\sigma^2}\exp\left\{-\frac{I}{2\sigma^2}\right\}, \mathrm{I}>0 \tag{4}$$

Where, *I* is the irradiance, σ^2 is the variance. The cumulative distribution function of Rayleigh is given in equation 5.

$$\mathrm{P(I)}=1-\exp\left\{\frac{-I^2}{\sigma^2}\right\}, \mathrm{I}>0 \tag{5}$$

Negative Exponential Distribution

The negative exponential model, describes turbulence under strong regime of fading effects only; this is because negative exponential model gives optimum values at negative region only (Al-Habash et al., 2001). The probability density function (PDF) of negative exponential is given in equation 6 and is cited from Al-Habash et al. (2001) and Nistazakis, Stassinakis, Muhammad, Tombras, (2014).

$$\mathrm{p}(I)= \frac{1}{Io}\exp\left[\frac{-I}{Io}\right], I > 0 \tag{6}$$

where *Io* is the average value of irradiance, *E[I]=Io*. The cumulative distribution function of negative exponential distribution is given in equation 7.

$$\mathrm{P(I)}=1-\exp\left[\frac{-I}{Io}\right] \tag{7}$$

Rician Distribution

The Rician distribution is used to model the effects of strong turbulence. It is principally based on realization that along with direct path between sources to destination there exists multipath component as well. The probability density function (PDF) of Rician distribution as described by Papoulis (1991) is given in equation 8:

$$\mathrm{p}(I)= \frac{1}{\sigma^2}\exp\left\{-\frac{I^2+k_d^2}{2\sigma^2}\right\}Io\left(\frac{Ik_d}{\sigma^2}\right), \mathrm{I}>0 \tag{8}$$

where I is irradiance, σ^2_I=1.23 C^2n $K^{7/6}$ $L^{11/6}$ and Rician factor=K (dB) =$10\log_{10}(k_d^2/2\sigma^2)$. The cumulative distribution function of Rician distribution is given in equation 9 where k_d is the strength of direct component

$$P(I)=1\text{-}Q(\frac{kd}{\sigma},\frac{I}{\sigma}) \tag{9}$$

where Q is Marcum function.

Gamma-Gamma Distribution

The Gamma-Gamma distribution models turbulent atmosphere, in which the light fluctuations consists of both small scale effects which are basically scattered and large effects of refraction. This distribution is based on doubly stochastic theory. The received irradiance I is the function of two random processes $\boldsymbol{I_x}$ **and** $\boldsymbol{I_y}$. Where I_x and I_y irradiance arises from small and large turbulence eddies. The probability density function (PDF) of Gamma-Gamma distribution is given in equation 10 as explained recently by Anees and Bhatnagar, (2015), and Bhatnagar and Ghassemlooy (2015, 2016).

$$p(I)=\frac{2(\alpha\beta)^{\frac{(\alpha+\beta)}{2}}}{\Gamma(\alpha)\,\Gamma(\beta)}I^{((\alpha+\beta)/2)-1}K_{\alpha-\beta}(2\sqrt{\alpha\beta I}),\ I>0 \tag{10}$$

$$\alpha=\frac{1}{exp\left[\frac{0.49\sigma^2}{(1+1.11\sigma^{12/5})^{7/6}}\right]-1} \tag{11}$$

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

Where I is irradiance Γ (.) is gamma function $K\ (\alpha,\ \beta)$ is Bessel function of second order.

RESULTS AND DISCUSSION

The probability density function and cumulative distribution function for various channel models have been studied for their variation in PDF and CDF. The scintillation index is considered as 1. The analytical results were obtained using MATLAB. The plot of PDF versus irradiance is shown in Figure 2 as analysed previously in equation 2 for log normal link model. It was shown that for various values of variance, the link delivers higher values of PDF for weak turbulence condition only. Figure 3 illustrates behaviour of channel modelled using Rayleigh link conditions. This link gives low irradiance PDF values at different values of variance, hence it can be concluded such links are heavily affected in strong turbulence conditions. The PDF for negative exponential distribution is shown Figure 4. The slope of this graph is negative which means that the negative exponential distribution has its optimum values in negative region and this model, like Rayleigh, performs miserably in conditions of strong turbulence.

The plot in Figure 5 shows PDF versus irradiance of Rician distribution based on equation. 8 and under strong turbulence regions low PDF values were obtained. Figure 5 illustrates variation in PDF with respect to irradiance for different values of Rician factor K_d.

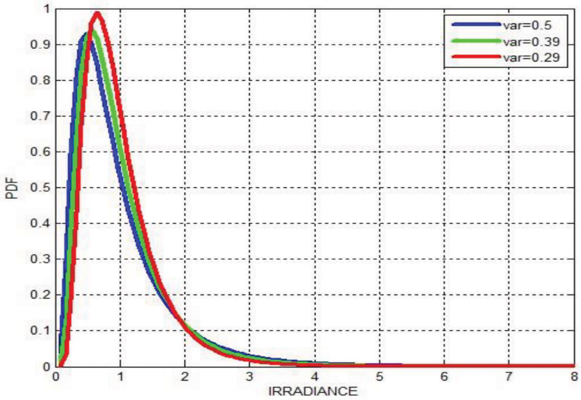

Figure 2. Probability Density Functions (PDF) vs. irradiance for lognormal model

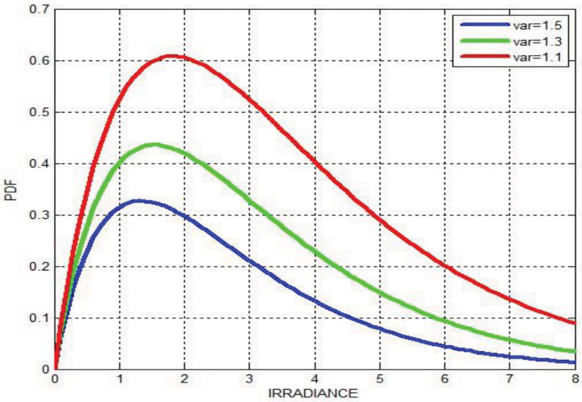

Figure 3. Probability Density Functions (PDF) vs. irradiance for Rayleigh model

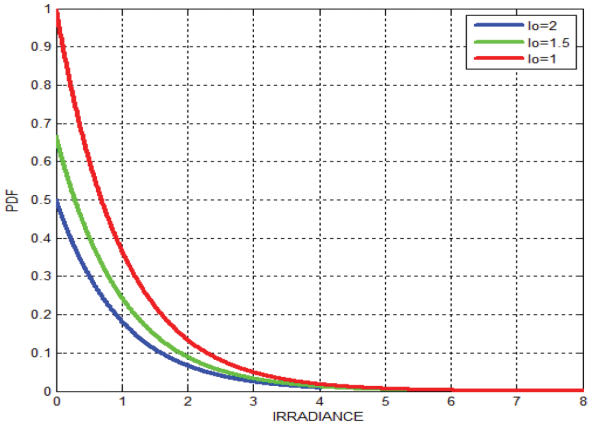

Figure 4. Probability Density Functions (PDF) vs. irradiance for Negative exponential model

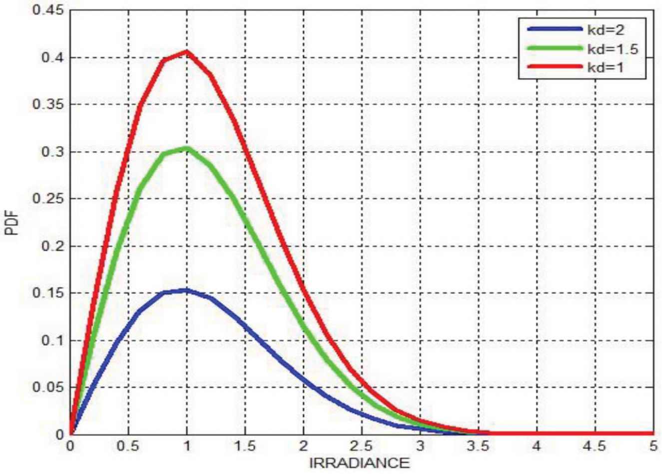

Figure 5. Probability Density Functions (PDF) vs. Irradiance for Rician model

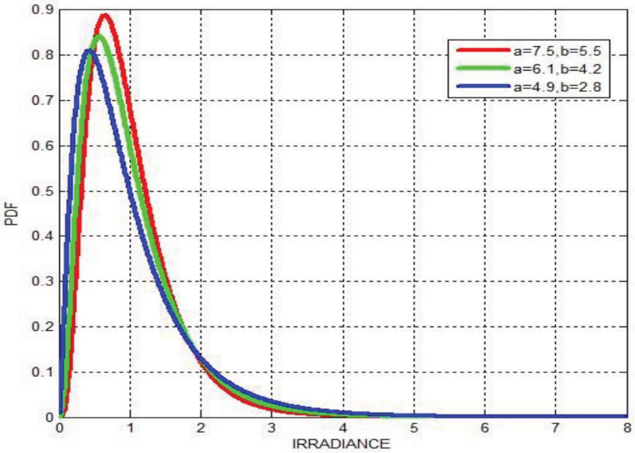

Figure 6. Probability Density Functions (PDF) vs. irradiance for Gamma-Gamma model

The plot in Figure 6 is based on equation 10 and illustrates the PDF variation for Gamma-Gamma link model. In this analysis, the effect of both small and large scale eddy are considered. It can be seen that appreciable PDF of irradiance can be obtained in weak-to-strong turbulence conditions. Figure 7 gives compares performance of different channels models under turbulent atmospheric conditions. It was an obvious observation that channel model is the most appropriate model for describe fading effects and determination of irradiance PDF, irrespective of turbulence regimes. Table 1 defines the PDF values of different channel models, assuming irradiance to be unity. As shown in Table 1, the negative exponential and Rician distribution have lower value (0.38) of PDF in strong turbulence conditions indicating such links would fail to perform in strong turbulence, whereas lognormal and Rayleigh can be used to define weak turbulence and strong turbulence. The Gamma-Gamma analysis gave best results at irradiance equal to unity. It delivered PDF of 0.99 which is higher compared with other channel models.

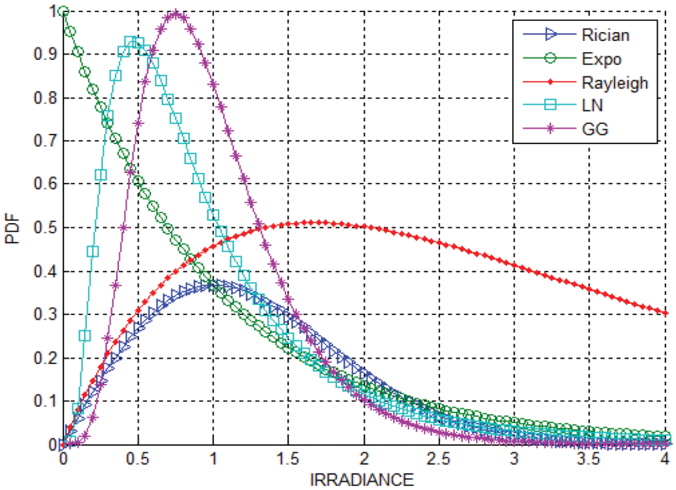

Figure 7. Probability Density Functions (PDF) vs. irradiance of different channel models

Table 1

PDF based comparison of different models

Channel model	Key factor	PDF(at intensity=1)
Lognormal	Variance(σ^2)	0.52
Rayleigh	Variance(σ^2) σ^2)	0.47
Negative exponential	Average irradiance(*Io*)	0.38
Rician	k_d	0.38
Gamma-Gamma	Alpha (α or a), beta (β or b)	0.99

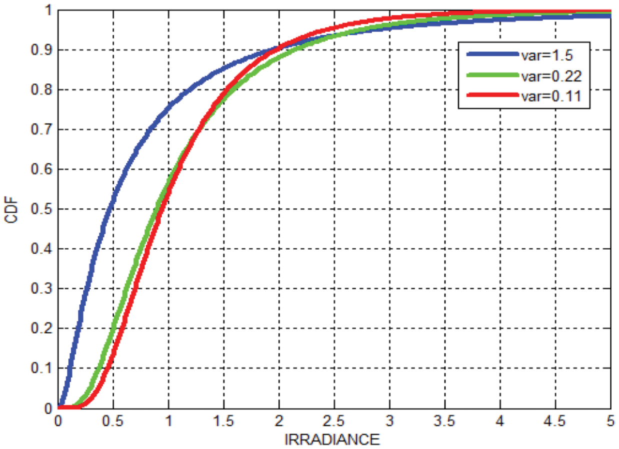

Figure 8. Cumulative Distribution Functions (CDF) vs. irradiance for Log normal model

The plot in Figure 8 is based on equation 3 and it gives CDF values at different variance. As variance decreases, the CDF increases. The CDF determination is also one of the tools to understand the fading effects in channel model for a range of turbulence. In Figure 8 and 9, CDF for Lognormal (LN) and Rayleigh channel model is determined for different values of variance. Clearly, increase in variance decreases the CDF associated with received irradiance.

The plot in Figure 10 is based on 7 and it provides CDF values at different values of I_o. Figure 11 is CDF of Rician distribution and it is an analysis of equation 9. Figure 12 compares the performance of different channel models on the basis on CDF for received irradiance and it has been noted that Lognormal channel model has higher CDF value of 0.80 at intensity =1 indicating that these models explain only weak turbulence condition whereas Negative exponential and Rician have lower values of CDF corresponding to a strong turbulence regime. Table 2 shows the CDF values of different channel models at irradiance=1. The Table 2 represent comparative picture of analysed results.

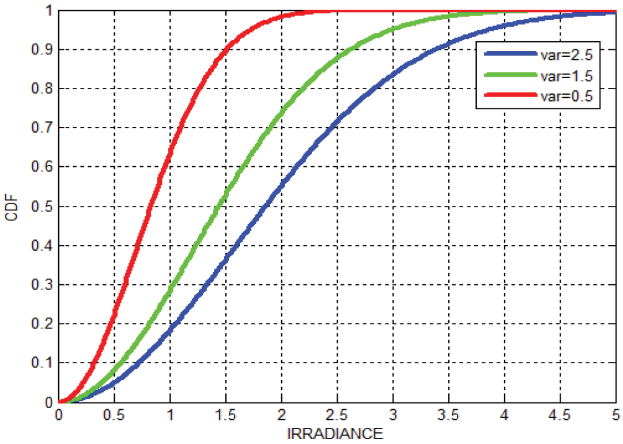

Figure 9. Cumulative Distribution Functions (CDF) vs. irradiance for Rayleigh model

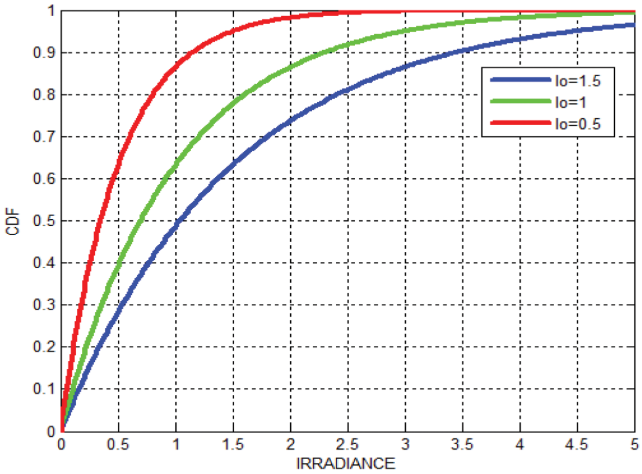

*Figure 10. C*umulative Distribution Function (CDF) vs. irradiance for Negative-exponential model

The lognormal modelled channel experiences highest CDF of 0.80 at the receiver which essentially means it can be used to quantify weak turbulence conditions. Table 3 shows the turbulence condition for all channel models and the key factors on which the performance of channel models depends.

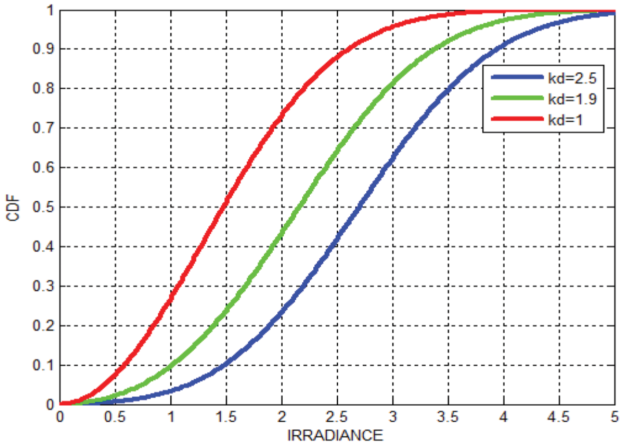

Figure 11. Cumulative Distribution Function (CDF) vs. irradiance for Rician model

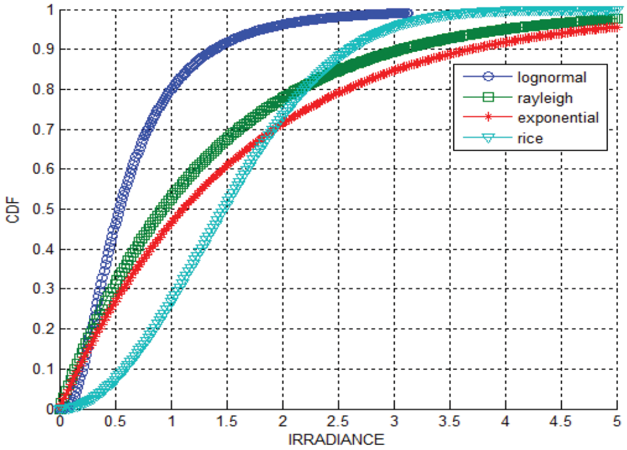

Figure 12. Plot of cumulative distribution functions vs. irradiance of different channel models

Table 2
CDF based comparison of different models

Channel model	Key factor	CDF (at intensity=1)
Lognormal	Variance (σ^2)	0.80
Rayleigh	Variance (σ^2)	0.53
Negative exponential	Average irradiance (*Io*)	0.47
Rician	k_d	0.28

CONCLUSION

This paper analysed the performance of different channel models used in free space optical communication. The scintillation index was unity while PDF associated with irradiance and atmospheric turbulence was used as a benchmark to determine performance for various categories of link modelling. It can be concluded that Lognormal, Rayleigh and Rician channel models are suitable to model channel conditions for weak or strong turbulence conditions only.

Table 3

Turbulence condition of different channel models on basis of PDF and CDF

Channel model	Key factor	Turbulence condition
Lognormal	σ^2	Weak
Rayleigh	σ^2	Strong
Negative exponential	Io	Very strong
Rician	k_d	Strong
Gamma-gamma	α, β	Weak to strong

However, the negative exponential and Gamma-Gamma model are valid for mapping weak to strong turbulence regime with optimum values for the former in the negative region. The paper thus concludes that the Gamma-Gamma model is an appropriate choice as it takes into account effect both large and small turbulence eddies. Effective link modelling allows reducing drastically, if not rule out, the effect of atmospheric turbulences on FSO links.

REFERENCES

Al-Habash, M. A., Andrews, L. C., & Phillips, R. L. (2001). Mathematical model for the irradiance probability density function of a laser beam propagating through turbulent media. *Optical Engineering, 40*(8), 1554-1562.

Andrews, L. C., & Phillips, R. L. (2005). *Laser beam propagation through random media* (Vol. 1). Bellingham, WA: SPIE press.

Anees, S., & Bhatnagar, M. R. (2015). Performance evaluation of decode-and-forward dual-hop asymmetric radio frequency-free space optical communication system. *IET Optoelectronics, 9*(5), 232-240

Bhatnagar, M. R., & Ghassemlooy, Z. (2015, June). Performance evaluation of FSO MIMO links in Gamma-Gamma fading with pointing errors. In *International Conference on Communications (ICC), 2015 IEEE* (pp. 5084-5090). IEEE.

Bhatnagar, M. R., & Ghassemlooy, Z. (2016). Performance analysis of Gamma–Gamma fading FSO MIMO links with pointing errors. *Journal of Lightwave Technology, 34*(9), 2158-2169.

Chatzidiamantis, N. D., Sandalidis, H. G., Karagiannidis, G. K., Kotsopoulos, S. A., & Matthaiou, M. (2010, April). New results on turbulence modeling for free-space optical systems. In *17th International Conference on Telecommunications (ICT), 2010 IEEE* (pp. 487-492). IEEE.

Ghassemlooy, Z., Popoola, W. O., & Leitgeb, E. (2007, July). Free-space optical communication using subearrier modulation in gamma-gamma atmospheric turbulence. In *9th International Conference on Transparent Optical Networks, ICTON'07, 2007* (Vol. 3, pp. 156-160). IEEE.

Hogan, H. (2013). Data Demands: Drive Free-Space Optics. *Photonics Spectra, 47*(2), 38-41.

Kashani, M., Uysal, M., & Kavehrad, M. (2013). A novel statistical model of turbulence-induced fading for free space optical systems. *15th International Conference on Transparent Optical Networks (ICTON)* (pp. 1-5). IEEE.

Kedar, D., & Arnon, S. (2004). Urban optical wireless communication networks: the main challenges and possible solutions. *IEEE Communications Magazine, 42*(5), S2-S7.

Khalighi, M. A., & Uysal, M. (2014). Survey on free space optical communication: A communication theory perspective. *IEEE Communications Surveys and Tutorials, 16*(4), 2231-2258.

Leitgeb, E., Awan, M. S., Brandl, P., Plank, T., Capsoni, C., Nebuloni, R., ... & Loschnigg, M. (2009, June). Current optical technologies for wireless access. In *10th International Conference on Telecommunications, ConTEL 2009* (pp. 7-17). IEEE.

Navas, A. J., Balsells, J. M. G., Paris, J. F., & Notario, A. P. (2011). A unifying statistical model for atmospheric optical scintillation. In J. Awrejcewicz (Ed.), *Numerical Simulations of Physical and Engineering Processes* (pp. 181-206). Rijeka, Croatia: InTech.

Nistazakis, H. E., Stassinakis, A. N., Muhammad, S. S., & Tombras, G. S. (2014). BER estimation for multi-hop RoFSO QAM or PSK OFDM communication systems over gamma gamma or exponentially modeled turbulence channels. *Optics and Laser Technology*, *64*, 106-112.

Papoulis, A., & Pillai, S. U. (2002). *Probability, random variables, and stochastic processes*. United Kingdom, UK: McGraw-Hill Education.

Popoola, W. O., & Ghassemlooy, Z. (2009). BPSK subcarrier intensity modulated free-space optical communications in atmospheric turbulence. *Journal of Lightwave Technology, 27*(8), 967 -973.

Popoola, W. O., Ghassemlooy, Z., Allen, J. I. H., Leitgeb, E., & Gao, S. (2008). Free-space optical communication employing subcarrier modulation and spatial diversity in atmospheric turbulence channel. *IET optoelectronics*, *2*(1), 16-23.

Tatarskii, V. I., & Zavorotnyi, V. U. (1985). Wave propagation in random media with fluctuating turbulent parameters. *JOSA A*, *2*(12), 2069-2076.

Willebrand, H. A., & Ghuman, B. S. (2001). Fiber optics without fiber. *IEEE spectrum*, *38*(8), 40-45.

Yang, F., & Cheng, J. (2016, February). Recent results on correlated lognormal atmospheric turbulence channels. In *International Conference on Computing, Networking and Communications (ICNC), 2016* (pp. 1-6). IEEE.

Zhu, X., & Kahn, J. M. (2002). Free-space optical communication through atmospheric turbulence channels. *IEEE Transactions on communications*, *50*(8), 1293-1300.