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Comparative BER Analysis of Free Space Optical System Using Wavelength Diversity over Exponentiated Weibull Channel

Dhaval Shah, Hardik Joshi, and Dilipkumar Kothari

***Abstract*—Atmospheric turbulence is considered as major threat to Free Space Optical (FSO) communication as it causes irradiance and phase fluctuations of the transmitted signal which degrade the performance of FSO system. Wavelength diversity is one of the techniques to mitigate these effects. In this paper, the wavelength diversity technique is applied to FSO system to improve the performance under different turbulence conditions which are modeled using Exponentiated Weibull (EW) channel. In this technique, the data was communicated through 1.55 μm, 1.31 μm, and 0.85 μm carrier wavelengths. Optimal Combining (OC) scheme has been considered to receive the signals at receiver. Mathematical equation for average BER is derived for wavelength diversity based FSO system. Results are obtained for the different link length under different turbulence conditions. The obtained average BER results for different turbulence conditions characterized by EW channel is compared with the published result of average BER for different turbulence which is presented by classical channel model. A comparative BER analysis shows that maximum advantage of wavelength diversity technique is obtained when different turbulence conditions are modeled by EW channel.**

***Keywords*—Bit error rate, Exponentiated Weibull distribution, FSO, Wavelingth Diversity, Optimal combining**

I. INTRODUCTION

FSO communication is a rapidly growing technology in wireless communication field. Higher bandwidth, high security, free spectrum, ease of placement and less power intake compared to Radio Frequency (RF) transmission makes FSO more suitable for the high-speed broadband networks [1]. Further, it does not require any digging or permission for the use of transmission medium, unlike Fiber Optical Communication (FOC) system. This reduces the setup time and installation cost too. Despite the tremendous potential to compete with existing communication technologies, the growth of FSO technology hampered by various parameters like building motion, atmospheric losses because of weather and atmospheric turbulence [2]. The solution for the effect of building motion and worst weather conditions are reported [3]–[5]. However, performance degradation due to atmospheric turbulence is still a challenging problem. It creates random fluctuation in the phase and intensity of the signal. It happens due to pressure and temperature variations in the free space. These variations cause fluctuation in the refractive index of the propagating signal [6] and measured in the terms of scintillation index. It helps to categorize the turbulence strength as either weak, moderate or strong [7]. Refractive index structure constant (C_n^2) is used to measure the turbulence strength [7]. FSO channel under different turbulence conditions is categorized using well defined statistical channel models. Lognormal channel and Gamma-Gamma channel models are found suitable for turbulence range (weak and moderate to strong) [8], [9]. Whereas, strong turbulence condition is modelled by Negative Exponential (NE) and K channels [10], [11]. In the [12], authors have reported that Exponentiated Weibull (EW) channel model has a potential to describe all turbulence scenario. In this paper, we have opted this model to represent the different turbulence scenario.

Different turbulence mitigation techniques have been proposed in the literature. Aperture averaging mitigates turbulence effect by increasing receiver aperture size. This method demands very large size of receiver aperture for strong turbulence condition and fails to improve the performance of FSO under weak turbulence condition [13]. Adaptive optics technique corrects the distorted wavefront of the received signal in real time, but distorted wave-front measurement sensor performance is very poor under strong turbulence [14]. On other hand, use of error-correcting codes improve the performance of FSO under all turbulence conditions but it demands large memory to store long data stream and also adds latencies to the output [15]–[17]. Diversity technique is also capable to improve the performance of FSO system under different turbulence conditions. In this technique, multiple copies of the signal are transmitted either at a different time, wavelength or using multiple transmitter/receiver or both which is known as time diversity, wavelength diversity and spatial diversity, respectively. Use of time diversity to improve the performance of FSO under different turbulence condition drastically reduces the data rate [18]. Whereas, spatial diversity technique requires more than 5 pairs of transceivers to improve performance under strong turbulence condition [19]. Wavelength diversity technique is also a promising technique to mitigate atmospheric turbulence effect. In this technique, multiple copies of information are sent on different wavelengths at the same time. The performance of FSO system under moderate to strong turbulence with wavelength diversity is investigated in the Ref.19. Similarly, the performance improvement with

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wavelength diversity under strong turbulence using K channel model is reported in our previous work [20]. The performance of FSO with wavelength diversity under all turbulence conditions using single channel model is yet to be investigated as per best of our knowledge.

In this work, we have considered EW channel to represent all turbulence conditions varying from weak to strong. Wavelength diversity has been applied to enhance the BER of FSO system under different turbulence conditions. The mathematical expression of average BER is derived considering OC method at receiver. The obtained BER results using EW channel for different turbulence scenario are compared with the results published in the literature for different turbulence conditions using different channel models.

The rest of the paper is ordered as follows: Section 2 presents the wavelength diversity based FSO system model. The mathematical expression of average BER using OC method is derived in section 3. The obtained results of average BER under different turbulence conditions with wavelength diversity are discussed in section 4. A comparative BER performance analysis is reported in section 5. The conclusion is presented in section 6.

II. SYSTEM MODEL

FSO system model with wavelength diversity is modeled considering system that uses the composite transmitter which transmits same information signal on different wavelengths towards different detectors on the receiver side. Each of the receiver is capable of receiving signal of a particular wavelength only. This can be understand as considering FSO system with different transceivers in which signal is sent by W transmitter at W different wavelengths. In this case, each wth copies of signal, w = 1,2,..W, will be received by wth receiver considering that it identify only wth wavelength. This is possible as optical receivers operate correctly in a narrow region around their nominal operational wavelength so, w$_{\text{th}}$ signal in receiver will be originated from the wth transmitter which works at the wth wavelength. The possibility of information signal transmission on a different wavelength from the single terminal is examined and reported [20]. Further, it is also investigated that as few centimeter spacing between receivers gives independent fading to each received signal [21], [22]. This validates the use of composite transmitter which is transmitting along W wavelength branches to W receivers. In our case, there is one composite transmitter and multiple receivers which resembles as Single Input Multiple Output (SIMO) diversity case.

Considering this, the wavelength diversity based FSO system model, the output signal (y_w) at each receiver can be expressed as

$$y_w = h_w x + n = \xi_w x I_w + n, \quad w = 1, \ldots\ldots, W \tag{1}$$

where, (y_w) is the output signal of each of W receivers, $h_w = \zeta_w I_w$ is the instantaneous intensity gain, ζ_w is the photo current conversion ratio of each receiver, x is the binary modulated signal that takes the value ‘0’ or ‘1’ (as On-Off Keying (OOK) modulation is considered), n represents the AWGN with zero mean and variance $N_0/2$ and I_w is the normalized irradiance arrived in each receiver passing through turbulence. Different turbulence conditions (weak to strong) are modeled using an EW distribution. The probability density function (PDF) of the EW distribution after applying the wavelength diversity over the EW distribution is given as [12]

$$\begin{aligned} f_{I_w}\left(I_w\right) = \frac{\alpha_w \beta_w}{\eta_w}\left(\frac{I_w}{\eta_w}\right)^{(\beta_w - 1)} e^{\left[-\left(\frac{I_w}{\eta_w}\right)^{\beta_w}\right]} \times \\ \left\{1 - e^{\left[-\left(\frac{I_w}{\eta_w}\right)^{\beta_w}\right]}\right\}^{\alpha_w - 1}, I_w \geq 0 \end{aligned} \tag{2}$$

where, α_w, $\beta_w > 0$ are two shape parameters related to the scintillation index, and $\eta_w > 0$ is a scale parameter related to the mean value of I_w for w$_{\text{th}}$ wavelength channel. α_w provides more flexibility to the shape of the tails [23]. When the data is envisioned on a logarithmic scale, α_w regulates the lower-tail steepness for the constant values of β_w and the η_w . This is an significant property of the EW distribution, because the lower tails represents the fading probability and error rate [24].

The cumulative distribution function (CDF) of I_w can be easily derived by

$$F_{I_w}\left(I_w\right) = \int_0^\infty f_{I_w}\left(I_w\right) dI_w \tag{3}$$

OR

$$F_{I_w}\left(I_w\right) = \left\{1 - exp.\left[-\left(\frac{I_w}{\eta_w}\right)^{\beta_w}\right]\right\}^{\alpha_w}, I_w \geq 0 \tag{4}$$

Where, α_w, β_w and η_w are the shape and scale parameter respectively for the w$_{\text{th}}$ wavelength. The value of these parameters with wavelength diversity is obtained from [12] and [18]. The expression for the shape parameter α_w for the w$_{\text{th}}$ wavelength is calculated as

$$\alpha_w \approx 3.931\left(\frac{D}{\rho_{0,w}}\right)^{-0.519} \tag{5}$$

where, D is the receiving aperture diameter and $\rho_{0,w}$ is the atmospheric coherence radius with w$_{\text{th}}$ wavelength which is calculates as [12].

$$\rho_{0,w} = \left(1.46 C_n^2 {k_w}^2 L\right)^{-3/5} \tag{6}$$

Here, $k_w(wavenumber) = 2\pi/\lambda_w$, λ_w is the operational wavelength of each of the W channels and L is the link length. C_n^2 signifies the refractive index structure parameter which rely on the atmospheric conditions altitude [25].

The shape parameter β_w related to the scintillation index σ_I^2 is calculated by

$$\beta_w \approx \left(\alpha_w \sigma_I^2\right)^{-6/11} \tag{7}$$

and the scale parameter η_w is given by

$$\eta_w = \frac{1}{\alpha_m \Gamma\left(1 + 1/\beta_w\right) g\left(\alpha_w, \beta_w\right)} \tag{8}$$

where, $g(\alpha_w, \beta_w)$ with w$_{\text{th}}$ wavelength can be obtained as

$$g\left(\alpha_w, \beta_w\right) = \sum_{i=0}^{\infty} \frac{(-1)^i (i+1)^{-(1+\beta_w)/\beta_w} \Gamma\left(\alpha_w\right)}{i! \Gamma\left(\alpha_w - i\right)} \tag{9}$$

where, $\Gamma(.)$ represents the gamma function.

The instantaneous electrical SNR for the $\mathrm{W_{th}}$ wavelength can be defined as $\gamma_w = \frac{(\zeta_w I_w)^2}{N_0}$ and the average electrical SNR is calculated as $\mu_w = \frac{(\zeta_w E[I_w])^2}{N_0}$. Here, $E[I_w] = 1$ since I_w is normalized [23]. After a power transformation of the random variable I_w, the PDF of the instantaneous electrical SNR γ_w with $\mathrm{W_{th}}$ wavelength is derived as

$$f_{\gamma_w}(\gamma_w) = \frac{\alpha_w \beta_w}{\eta_w} \left(\frac{1}{\eta_w} \sqrt{\frac{\gamma_m}{\mu_m}} \right)^{(\beta_w - 1)} e^{\left[-\left(\frac{1}{\eta_w} \sqrt{\frac{\gamma_w}{\mu_w}} \right)^{\beta_w} \right]} \times \left\{ 1 - e^{\left[-\left(\frac{1}{\eta_w} \sqrt{\frac{\gamma_w}{\mu_w}} \right)^{\beta_w} \right]} \right\}^{\alpha_w - 1}, \gamma_w > 0 \tag{10}$$

and the respective CDF of the γ_w is given by

$$F_{\gamma_w}(\gamma_w) = \left\{ 1 - e^{\left[-\left(\frac{1}{\eta_w} \sqrt{\frac{\gamma_w}{\mu_w}} \right)^{\beta_w} \right]} \right\}^{\alpha_w}, \gamma_w > 0 \tag{11}$$

III. AVERAGE BER OF THE SYSTEM

The BER P_e of the FSO system with IM/DD and OOK in the presence of AWGN can be found through the expression [11]

$$P_e = P(1)\, P(e|1) + P(0)\, P(e|0) \tag{12}$$

Here, $P(1)$ and $P(0)$ are the probabilities of sending 1 and 0 bits respectively, while $P(e|1)$ and $P(e|0)$ represent the conditional bit error probabilities when the transmitted bit is 1 and 0. Assuming that the condition is symmetric, i.e. $P(0) = P(1) = 0.5$, and $P(e|1) = P(e|0)$, the BER for Single Input Single Output (SISO) link (Assuming the case W = 1), as a function of I, is given as

$$\begin{aligned} P_e(I) &= P(e|1, I) + P(e|0, I) \\ &= P\left(v > \frac{\xi I}{2} \right) = P\left(v > \frac{-\xi I}{2} \right) \\ &= Q\left(\frac{\xi I}{\sqrt{2N_0}} \right) = Q\left(\sqrt{\frac{\gamma}{2}} \right) \end{aligned} \tag{13}$$

where, Q(.) is the Gaussian Q-function defined as $Q(x) = \left(\frac{1}{\sqrt{2N_0}} \right) \int\limits_x^{\infty} exp\left(\frac{t^2}{2} \right) dt$ and it is also related to the complimentary error function erfc(.) by erfc(x)=2Q($\sqrt{2}$x). The average BER of the EW channel for SISO link of the FSO system, P_{av} is obtained by averaging (13) over the fading coefficient I, i.e.

$$P_{av} = \int\limits_0^{+\infty} P_e(I) f_I(I)\, dI = \int\limits_0^{+\infty} Q\left(\frac{\xi I}{\sqrt{2\pi}} \right) f_I(I)\, dI \tag{14}$$

In this scenario, we will compute the average BER from the CDF $F_I(I)$ as follows

$$P_{av} = -\int\limits_0^{+\infty} P_e^{'}(I) F_I(I)\, dI \tag{15}$$

where, $P_e^{'}(I)$ is the first order derivative of the conditional BER $P_e(I)$ and it is derived as

$$P_e^{'}(I) = -\frac{1}{\sqrt{\pi}} exp.\left(\frac{-\xi^2 I^2}{4N_0} \right) = -\frac{1}{\sqrt{\pi}} exp.\left(\frac{-\gamma}{4} \right) \tag{16}$$

Substituting (4) and (16) into (15), we get

$$P_{av} = \frac{1}{\sqrt{\pi}} \int\limits_0^{+\infty} exp.\left(\frac{-\xi^2 I^2}{4N_0} \right) \left\{ 1 - exp.\left[-\left(\frac{I}{\eta} \right)^{\beta} \right] \right\}^{\alpha} dI \tag{17}$$

The closed-form solution for the integral (17) is not available. On the other hand, it can be approximated by using the Gauss–Hermite quadrature rule. After applying Gauss–Hermite quadrature approximation [26] on (17), the final equation for the average BER can be written as

$$P_{av} \approx \frac{2\sqrt{N_0}}{\xi\sqrt{\pi}} \sum_{i=1}^{n} m_i \left\{ 1 - exp.\left[-\left(\frac{2\sqrt{N_0}}{\xi\eta} x_i \right)^{\beta} \right] \right\}^{\alpha} \tag{18}$$

In terms of the average electrical SNR of the SISO system μ, (18) can be written as

$$P_{av} \approx \frac{2}{\sqrt{\pi\mu}} \sum_{i=1}^{n} m_i \left\{ 1 - exp.\left[-\left(\frac{2}{\eta\sqrt{\mu}} x_i \right)^{\beta} \right] \right\}^{\alpha} \tag{19}$$

If the wavelength diversity is to be used, its average BER will be derived by considering the channel model presented in Section 2, i.e. one transmitter and W receivers. This case can be compared to a single input multiple output (SIMO). Considering the above case, the optimum decision metric for OOK will be given by [19].

$$P(\vec{y}|off, I_w) \underset{on}{\overset{off}{\lessgtr}} P(\vec{y}|on, I_w) \tag{20}$$

where, vector signal $\vec{y} = (y_1,\ y_2,\ \ldots,\ y_w)$ is received at different receiver. In this respect, the expressions for the average BER for wavelength diversity FSO system with W different channels at receiver has been derived. The average BER of the FSO system with the W different wavelength channels considering OC method can be achieved as follows [19]

$$P_{W,\,OC} = \int\limits_{\vec{I}} f_{\vec{I}}\left(\vec{I} \right) Q\left(\frac{1}{\sqrt{2WN_0}} \sqrt{\sum\nolimits_{w=1}^{W} {\xi_w}^2 {I_w}^2} \right) d\vec{I} \tag{21}$$

In terms of CDF $F_{(I_w)}(I_w)$, the average BER for $\mathrm{w_{th}}$ wavelength is given as

$$P_{W,\,OC} = \prod_{w=1}^{W} \frac{1}{\sqrt{\pi}} \int\limits_0^{+\infty} e^{\left(\frac{-{\xi_w}^2 {I_w}^2}{4N_0} \right)} \left\{ 1 - e^{\left[-\left(\frac{I_w}{\eta_w} \right)^{\beta_w} \right]} \right\}^{\alpha_w} dI_w \tag{22}$$

where,$\vec{I} = (I_1,\ I_2,\ \ldots,\ I_w)$ is the vector of the normalized irradiances for each of the W receivers. After following the calculation procedure of the SISO link, the average BER expression with wavelength diversity is expressed as

$$P_{W,\,OC} \approx \prod_{w=1}^{W} \frac{2\sqrt{N_0}}{\xi_w\sqrt{\pi}} \sum_{i=1}^{n} m_i \left\{ 1 - exp\left[-\left(\frac{2\sqrt{N_0}}{\xi_w \eta_w} x_i \right)^{\beta_w} \right] \right\}^{\alpha_w} \tag{23}$$

In the form of the average electrical SNR μ_w, the final average BER expression for the OC method is written as

$$P_{W,\,OC} \approx \prod_{w=1}^{W} \frac{2\sqrt{N_0}}{\xi_w\sqrt{\pi}} \sum_{i=1}^{n} m_i \left\{ 1 - exp\left[-\left(\frac{2\sqrt{N_0}}{\xi_w \eta_w} x_i \right)^{\beta_w} \right] \right\}^{\alpha_u} \tag{24}$$

where, μ_w defines the average electrical SNR for the $\mathrm{W_{th}}$ wavelength channel.

IV. RESULTS AND DISCUSSION

This section presents the numerical results of average BER obtained using (24). Results are obtained for the different turbulence conditions at different link distances. The value of refractive structure parameter (C_n^2) is kept as $1\times10^{-17}m^{-2/3}$, $6\times10^{-14}m^{-2/3})$ and $2\times0^{-13}m^{-2/3}$ for weak, moderate and strong turbulence scenario, respectively. The aperture diameter of the receiver D is considered as 10 mm. To make the receiver diversity effective, few centimeter spacing between the receivers is sufficient [21], [22]. Based on that independent channel fading for all the receivers is considered. Three different wavelengths chosen for the diversity are: $\lambda_1 = 1.55\ \mu m$, $\lambda_2 = 1.31\ \mu m$, and $\lambda_3 = 0.85\ \mu m$ as the commercial FSO equipment uses these carrier wavelengths for data transmission. The values of α_w, β_w and η_w parameters of EW model for the different diversity scenario is calculated from Eq. 5,7 and 8, respectively. For the wavelength diversity scheme, we have considered same average electrical SNR for all the W receivers. The BER performance of the FSO communication system with wavelength diversity are compared to that of without diversity scenario. In the present case, W =1 represented diversity less scenario, W =2 and W =3 represented the wavelength diversity of the order of 2 and 3, respectively. For the diversity less scenario, the signal is transmitted using 1.55 μm wavelength. The signal is transmitted at 1.55 μm and 1.31 μm in the case of W =2. For the diversity order of 3, the signal is transmitted on 1.55 μm, 1.31 μm and 0.85 μm.

Fig. 1 shows the BER performance of FSO system with wavelength diversity under weak turbulence conditions. It is evident that increase in the diversity order reduces the average BER of the system. An improvement of about 7 dB in the average BER is observed with the diversity order of 2 compared to no diversity case at SNR of 10 dB. An additional improvement of 2 dB is observed with increase in the diversity order to 3. Similar results are observed at distance of 1.5 km. The detailed results are given in table I.

Table I presents the average BER results at the distance of 1 and 1.5 km with wavelength diversity. It is clear that increase in the diversity order improves the average BER of the system at both the distances. Moreover, weak turbulence characterizes by EW channel achieves the BER in the range of 10^{-7} without deploying any diversity at both the distance. It is more than sufficient to cater to the need of modern wireless communication system with data rates in the range of 100 Mbps [26].

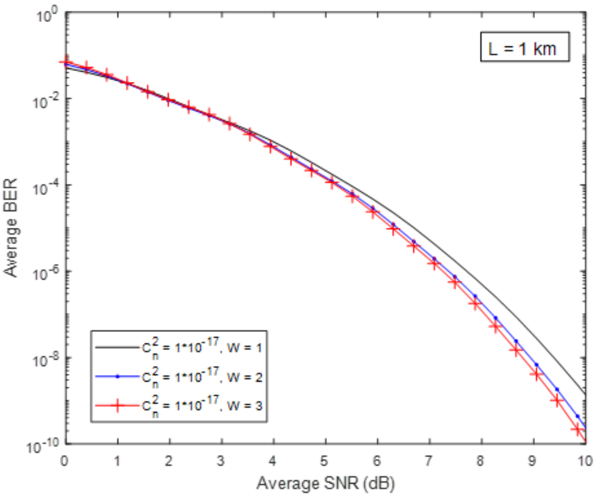

Fig. 1. Average BER under weak turbulence condition with wavelength diversity

TABLE I
AVERAGE BER OF THE SYSTEM UNDER THE WEAK TURBULENCE CONDITION

Diversity order	D = 10 mm , SNR = 10 dB , $C_n^2 = 1\times10^{-17}$	
	L = 1 km	L = 1.5 km
W=1	2.31×10^{-9}	6.14×10^{-10}
W=2	4.37×10^{-10}	9.15×10^{-11}
W=3	2.17×10^{-10}	4.11×10^{-11}

The BER performance improvement of wavelength diversity based FSO system under moderate $(C_n^2 = 6\times10^{-14}m^{-2/3})$ and strong $(C_n^2 = 2\times10^{-13}m^{-2/3})$ turbulence conditions at 1.5 km is shown in fig. 2. The obtained BER is in the range of 10^{-7} and 10^{-6} under moderate and strong turbulence, respectively for diversity less scenario at 20 dB SNR. Applying wavelength diversity significantly improves the average BER under both turbulence conditions.

The observed improvement of 30 dB and 20 dB in BER is obtained with a diversity order of 3 compared to no wavelength diversity under the moderate and strong turbulence regime, respectively at the same SNR. The results are also analyzed for the link distance of 2.5 km. It also shows the similar improvement with wavelength diversity under both turbulence scenario. A consistent 10 dB improvement in BER is observed as the diversity order increases at the distance of 2.5 km under both turbulence scenario at the SNR of 20 dB. The detailed result of average BER at the distance of 1.5 and 2.5 km is shown in table II.

V. COMPARATIVE BER PERFORMANCE ANALYSIS

In this section, BER results achieved using EW channel for different turbulence conditions is compared with the published results in the literatures for different turbulence conditions using different channel models. For the fair comparison,

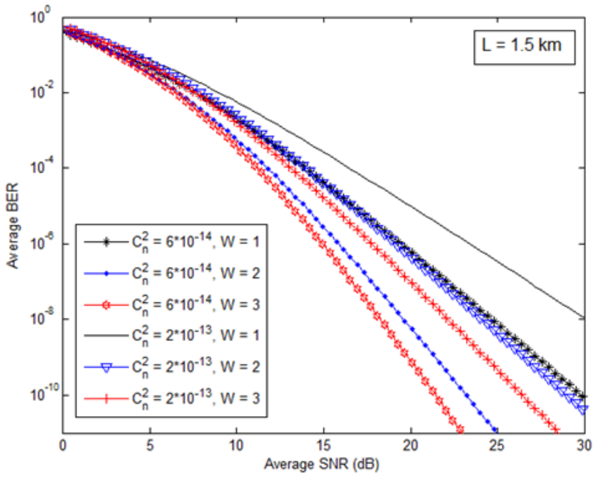

Fig. 2. Average BER under moderate and strong turbulence conditions with wavelength diversity

TABLE II
AVERAGE BER UNDER MODERATE AND STRONG TURBULENCE CONDITIONS

Diversity order	Turbulence condition	D = 10 mm, SNR = 20dB	
		L = 1.5 km	L = 2.5 km
W = 1	Moderate	3.21×10^{-7}	1.10×10^{-6}
	Strong	9.30×10^{-6}	2.40×10^{-5}
W = 2	Moderate	5.52×10^{-9}	2.68×10^{-8}
	Strong	4.25×10^{-7}	1.10×10^{-6}
W = 3	Moderate	7.29×10^{-10}	4.20×10^{-9}
	strong	9.04×10^{-8}	3.58×10^{-7}

all the required parameters (such as receiver aperture size, refractive index structure parameter, wavelength and distance) are considered same as mentioned in the published articles.

A. Comparison under Weak Turbulence Condition

The performance improvement of FSO system with wavelength diversity under weak turbulence condition using Log-normal (LN) channel is already reported [27]. In this article, BER results are presented for two different C_n^2 values at the distance of 1 and 1.5 km. fig. 3 and 4 shows the comparison of BER results obtained with EW and LN channel model at the distance of 1 km with the refractive index structure parameter $C_n^2 = 1 \times 10^{-14} m^{-2/3}$ and $C_n^2 = 5 \times 10^{-14} m^{-2/3}$, respectively. The results with LN channel model is plotted using (Eq. (20) of [27]). It is clearly evident that increase in the wavelength diversity order improves the performance of FSO system under the turbulence conditions characterized by both the channel models at the distance of 1 km. However, the BER achieved is much lower when turbulence condition is characterized by EW channel. It is almost 20 dB lesser than the obtained with LN channel model with the $C_n^2 = 1 \times 10^{-14} m^{-2/3}$ at the diversity of the order of 3. The same was of about similar trend is observed with the $C_n^2 = 5 \times 10^{-14} m^{-2/3}$. The similar trend is observed at the distance of 1.5 km. The detailed results are shown in the table III.

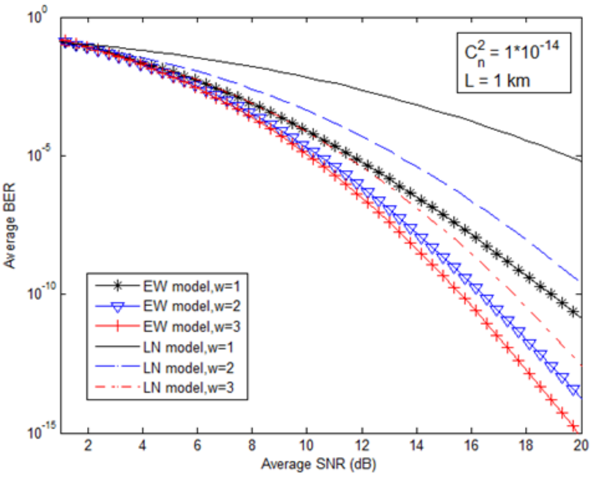

Fig. 3. BER Performance comparison of LN and EW with $C_n^2 = 1 \times 10^{-}14m^{-2/3}$

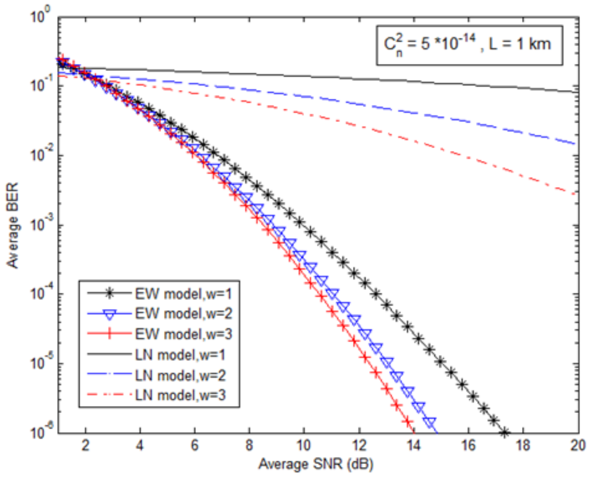

Fig. 4. BER Performance comparison of LN and EW with $C_n^2 = 5 \times 10^{-}14m^{-2/3}$

a) : It is apparent from table III that BER performance obtained considering EW channel with different diversity order is much higher compared to LN channel at both the distance under different C_n^2 values. As LN channel underestimates the behavior in the tail region where the turbulence impact is higher [11]. It is also observed that turbulence condition characterized with EW channel achieves the BER in the range of 10^{-8} without wavelength diversity which is sufficient for wireless communication system with data rates in the range of 100 Mbps [26].

B. Comparison under Moderate to Strong turbulence conditions

The comparison of the BER performance improvement of wavelength diversity based FSO system using EW channel and Gamma-Gamma channel for moderate to strong turbulence is presented in this section. The performance improvement of FSO system with wavelength diversity under moderate

TABLE III
BER RESULTS OBTAINED WITH WAVELENGTH DIVERSITY CONSIDERING LN AND EW CHANNEL

Diversity order	D = 10 mm ,	SNR = 20 dB , $Cn2 = 1 \times 10^{-14}$		
	$Cn2 = 1 \times 10^{-14}$			
	L = 1 km		L = 1.5 km	
	Lognormal	EW	Lognormal	EW
W=1	6.28×10^{-6}	2.41×10^{-11}	1.16×10^{-3}	1.70×10^{-10}
W=2	2.51×10^{-10}	3.88×10^{-14}	9.74×10^{-6}	4.66×10^{-13}
W=3	2.69×10^{-13}	1.73×10^{-15}	3.45×10^{-7}	2.35×10^{-14}
	$C_n^2 = 5 \times 10^{-14}$			
W=1	2.28×10^{-2}	2.41×10^{-8}	8.20×10^{-2}	9.09×10^{-8}
W=2	4.47×10^{-4}	2.16×10^{-10}	1.44×10^{-2}	1.29×10^{-9}
W=3	4.98×10^{-6}	2.10×10^{-11}	2.60×10^{-3}	1.40×10^{-10}

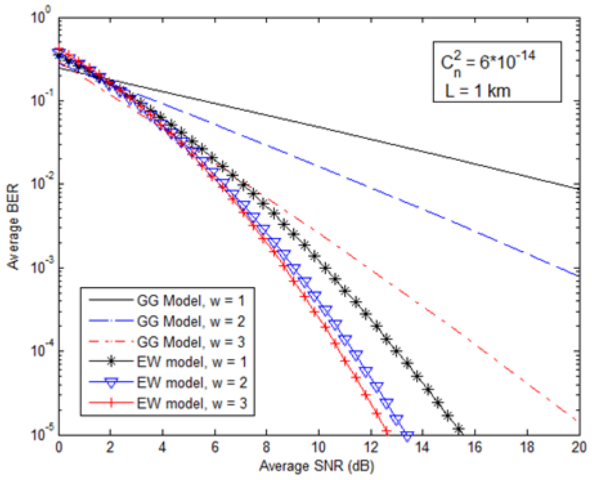

Fig. 5. Performance compassion of GG and EW for moderate turbulence condition

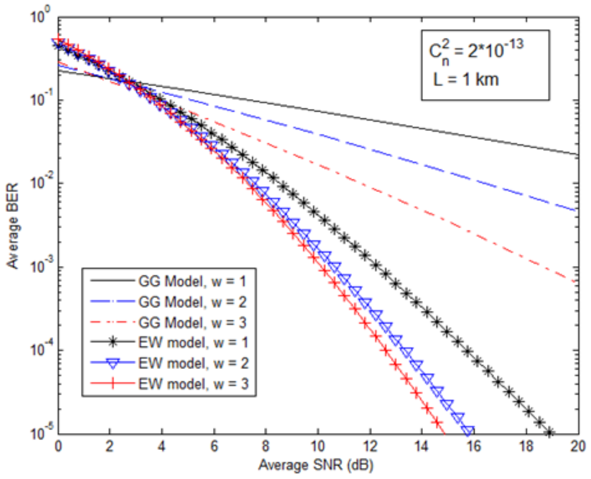

Fig. 6. Performance compassion of GG and EW for strong turbulence condition

to strong turbulence condition using Gamma-Gamma (GG) channel model is reported in he Ref. 19. In this article, average BER results are presented for the distance 1 and 2 km under moderate ($C_n^2 = 6 \times 10^{-14} m^{-2/3}$) and strong turbulence ($C_n^2 = 2 \times 10^{-13} m^{-2/3}$) conditions. Average BER results with GG channel is plotted from Eq. 16 of Ref. 19.

Fig. 5 and 6 show the comparison results at 1 km distance under moderate and strong turbulence, respectively. It is apparent from the plots that average BER decreases with increase in diversity order for both channel model. Moderate turbulence represented by Gamma-Gamma model has shown improvement of 20 dB with a diversity order of 3 compared to no diversity case.

The same is observed 30 dB with EW channel model which is 10 dB higher than the achieved results using GG model. In strong turbulence scenario, 20 dB improvement in the performance is observed with a diversity order of 3 compared to no diversity case with both channel models. However, the obtained BER considering EW channel is lesser than the achieved using GG channel. The similar results are observed at the distance of 2 km. The detailed results of average BER at 20 dB SNR for the distance of 1 and 2 km is shown in table IV.

As shown in table IV, moderate and strong turbulence characterized by GG channel shows a consistent 10 dB improvement with higher diversity level at both the distances. The performance improvement achieved at the distance of 1 km using EW channel is 10 dB and 20 dB higher than the achieved with GG channel under moderate and strong turbulence, respectively with a diversity order of 3 compared to no diversity. At the distance of 2 km, both the channel models achieve 20 dB improvement with a diversity order of 3 compared to diversity less scenario under both the turbulence conditions. However, the overall BER performance of wavelength diversity based FSO system using EW channel is much higher than that obtained with GG channel under both the turbulence condition at a different distance. The channel characterized by EW has a maximum performance gain of about 60 dB and 40 dB over GG channel under moderate and strong turbulence condition, respectively.

C. Comparison under Strong turbulence conditions

In this section, the BER results obtained under strong turbulence condition using EW channel is compared with the published results (OC method at receiver) considering K channel.20 In this article, the required SNR to obtained BER

TABLE IV
PERFORMANCE COMPARISON BETWEEN GAMMA-GAMMA AND EW

Diversity order	Turbulence condition	D = 10 mm, SNR = 20dB			
		L = 1 km		L = 2km	
		GG	EW	GG	EW
W = 1	Moderate	8.50×10^{-3}	4.68×10^{-8}	4.23×10^{-2}	4.60×10^{-7}
	Strong	2.18×10^{-2}	2.46×10^{-6}	5.32×10^{-2}	1.21×10^{-5}
W = 2	Moderate	7.72×10^{-4}	4.68×10^{-10}	3.88×10^{-3}	9.10×10^{-9}
	Strong	4.59×10^{-3}	6.13×10^{-8}	4.20×10^{-3}	6.10×10^{-7}
W = 3	Moderate	1.39×10^{-5}	5.25×10^{-11}	4.69×10^{-4}	1.29×10^{-9}
	strong	6.39×10^{-4}	1.07×10^{-8}	4.61×10^{-4}	1.37×10^{-7}

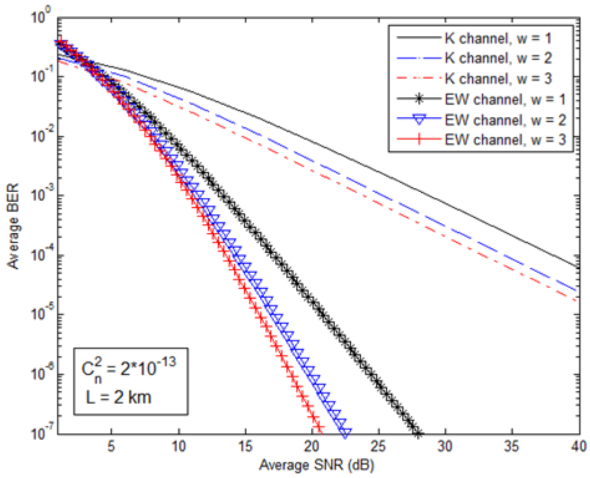

Fig. 7. Performance compassion using K and EW at 2 km

in the range of 10^{-4} is reported for the distance of 2 and 3 km. Fig. 7 shows the comparison of BER results achieved using K and EW channel at the distance of 2 km. The results of K channel is plotted using Eq. 18 of Ref. 20.

The obtained BER at 30 dB SNR is in the range of 10^{-4} and 10^{-5} using K and EW channel, respectively in no diversity case at the distance of 2 km. Deployment of wavelength diversity improves the performance with both the models. An improvement of around 4.5 dB is observed with a diversity order of 3 at same SNR compared to no diversity scenario when strong turbulence is represented by K channel. The same was of around 20 dB with EW channel. This trend continues even at a higher distance of 3 km. The BER performance of FSO system with wavelength diversity using K channel gives an improvement of about 10 dB with a diversity order of 3 compared to no diversity at 30 dB SNR at 3 km distance. While the use of EW channel for the same system achieves an improvement of 20 dB with a diversity order of 3 compared to no diversity at same SNR. The details results of BER performance comparison at 2 km and 3 km distance is shown in table V.

It is clearly evident that performance of FSO with EW is much better compared to K at the distance both the distance. This is due to fact that K channel model with one parameter to measure fluctuation in irradiance and do not clearly concentrate the tail portion of PDF. While EW channel has a specific parameter that controls the tail portion of PDF which expresses the error rate and the fading probability.

For a fair comparison, the result is also presented in the form of required SNR for the BER of 10^{-4} in table VI as reported in the published article [20] for OC method at receiver.

It is apparent that use of EW channel decreases the SNR requirement by 55% compared to K channel for the targeted BER in the case of without diversity at distance of 2 km. It decreases further by 5% with a diversity order of 3 at the same distance. The similar results are observed at distance of 3 km. Use of EW reduces the SNR requirement by 62% compared to K channel with a diversity order of 3 at the distance of 3 km for the targeted BER. From the table V and VI it is clear that use of EW channel for strong turbulence condition is recommended to take maximum performance gain through wavelength diversity.

VI. CONCLUSION

The performance of FSO communication system under different turbulence conditions using EW channel model with wavelength diversity schemes is investigated. The mathematical expression for the average BER has been derived considering OC method. The observed maximum improvement in the average BER with wavelength diversity of the order of 3 is of 14 dB, 30 dB and 20 dB under weak, moderate and strong turbulence, respectively at 1.5 km distance. A comparative BER performance analysis is also carried out. It indicates that weak and moderate turbulence condition defined by EW channel for the link distance up to 1 km achieves the BER in the range of 10^{-7} without applying diversity. Whereas turbulence conditions represented by LN and GG model for same link distance demands the wavelength diversity to achieve the same BER. At higher distance, significant performance improvement is observed using EW channel with wavelength diversity. Similarly for strong turbulence scenario, the channel represented by EW model achieves 30 dB higher performance than classical K channel model with wavelength diversity order of 3. It is clear from this comparative analysis that maximum BER improvement of FSO system with wavelength diversity under different turbulence conditions can be achieved when turbulence conditions are categorized by EW channel. So, use of EW channel to characterize different turbulence conditions

TABLE V
BER PERFORMANCE COMPARISON BETWEEN K AND EW

Diversity order	D = 10 mm , SNR = 30 dB , $C_n^2 = 2 \times 10^{-13}$			
	L = 2 km		L = 3 km	
	K	EW	K	EW
W=1	5.75×10^{-4}	1.57×10^{-5}	2.60×10^{-3}	3.38×10^{-5}
W=2	2.36×10^{-4}	8.50×10^{-7}	5.14×10^{-4}	2.29×10^{-6}
W=3	1.60×10^{-4}	1.95×10^{-7}	2.74×10^{-4}	5.91×10^{-7}

TABLE VI
REQUIRED SNR FOR THE BER OF 10^{-4}

Diversity order	L = 2 km		L = 3 km	
	K	EW	K	EW
W=1	38 dB	17 dB	47.5 dB	17.32
W=2	34 dB	14 dB	37.5 dB	14.96
W=3	33 dB	13 dB	35 dB	13.78

is strongly recommended to achieve better performance of FSO system with and without wavelength diversity.

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