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Bit error rate analysis of the *K* channel using wavelength diversity

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Abstract. The presence of atmospheric turbulence in the free space causes fading and degrades the performance of a free space optical (FSO) system. To mitigate the turbulence-induced fading, multiple copies of the signal can be transmitted on a different wavelength. Each signal, in this case, will undergo different fadings. This is known as the wavelength diversity technique. Bit error rate (BER) performance of the FSO systems with wavelength diversity under strong turbulence condition is investigated. *K*-distribution is chosen to model a strong turbulence scenario. The source information is transmitted onto three carrier wavelengths of 1.55, 1.31, and 0.85 μm. The signals at the receiver side are combined using three different methods: optical combining (OC), equal gain combining (EGC), and selection combining (SC). Mathematical expressions are derived for the calculation of the BER for all three schemes (OC, EGC, and SC). Results are presented for the link distance of 2 and 3 km under strong turbulence conditions for all the combining methods. The performance of all three schemes is also compared. It is observed that OC provides better performance than the other two techniques. Proposed method results are also compared with the published article. [DOI: 10.1117/1.OE.56.5.056106]

Keywords: *K* distribution; bit error rate; optical; selection combining; equal gain combining; wavelength diversity.

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1 Introduction

Free space optics (FSO) is a suitable technology in many applications such as point-to-point communication, intercampus link, disaster recovery link, and intersatellite link due to its main advantage of a license free channel and less setup time.[1,2] The performance of an FSO system degrades prominently due to atmospheric turbulence.[3] Atmospheric turbulence occurs due to the temperature and pressure variations in the free space. This variation affects the refractive index and causes rapid fluctuation of the propagated signal at the receiver input. This phenomenon is known as scintillation.[4] The received intensity fluctuation is characterized in terms of the scintillation index (SI). This parameter helps to decide whether the turbulence category is weak, moderate, or strong.[5,6]

Many channel models have been evolved over the years, to deal with weak to strong atmospheric turbulence induced fading in an FSO system. Due to simplicity, the log-normal channel model is more preferred. But this model is applicable only for weak turbulence conditions, as this model fails to handle scattering effects occurring in the strong turbulence.[3,7] It is reported in the literature[8,9] that gamma–gamma and $I-K$ distribution channel models provide the best-fit irradiance statistics for moderate to strong turbulence conditions. Also, *K* distribution has been found to be a suitable model under strong turbulence conditions since it demonstrates strong correlation between theoretical and practical data.[9,10] Uysal et al.[11] and Kiasaleh[12] have used this model to evaluate the bit error rate (BER) performance under a strong turbulence regime. The results in these papers indicate that the deployment of an FSO channel (with one pair of the transceiver) for practical applications requires a large signal-to-noise range for the targeted BER under strong turbulence. This clearly demands powerful turbulence mitigation techniques.

Various mitigation techniques have been proposed in the literature on FSO communication, some of which are based on the use of error codes with interleavers,[13,14] adaptive optics,[15] and aperture averaging.[16] However, each of these approaches has some limitations.[17] Diversity techniques are also considered as an alternative to mitigate the effect of turbulence. Diversity in the atmosphere refers to sending multiple copies of data to overcome the turbulence effect. Diversity can be explored in terms of time, space, and wavelength. Nistazakis and Tombras[18] have applied time diversity over gamma–gamma distribution and evaluated BER and outage probability performance for the FSO link. They have shown that the performance improvement in time diversity is achieved at the cost of lower bit rate transmission. Performance of the FSO link with the spatial diversity technique over *K* channel is examined in Ref. 19. Tsiftsis et al. have observed that better performance for the FSO link in the practical range of signal-to-noise ratio (SNR) can be obtained with more than five transceiver pairs.

Wavelength diversity is another prominent solution to mitigate the turbulence effect. In this method, source information is transmitted on more than one wavelength, considering turbulence induced fading will not be the same for different wavelengths. In the existing literature,[18,20] the wavelength diversity technique has been applied over the gamma–gamma,[18] lognormal[20] and exponentiated

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Weibull[21] channel model for the performance improvement of the FSO link. In this paper, we have applied wavelength diversity over strong turbulence. The K channel is used to model strong atmospheric turbulence. We have applied optical combining (OC), equal gain combining (EGC), and selection combining (SC) schemes at the receiver end to combine the signals and have also derived the expressions to calculate BER for each method. A comparison of the different combining methods is also presented.

The rest of this paper is structured as follows: Sec. 2 describes the system model of the FSO system with wavelength diversity. Derivation of the mathematical expressions computes the average BER considering three different combining techniques, respectively, OC, EGC, and SC in Sec. 3. Section 4 presents numerical results. Finally, the conclusion of the work is given in Sec. 5.

2 System Model

In the FSO literature,[20,21] the wavelength diversity setup has been applied with composite transmitters and receivers. The transmitters broadcast the signal at different wavelengths simultaneously. Each receiver detects a signal of a particular wavelength. In this paper, the same approach is adopted to apply the wavelength diversity. Each receiver experiences an independent fading channel if located a few centimeters apart.[22] Figure 1 shows the block diagram of the FSO system with wavelength diversity. Considering the above scenario, the expression of the system model can be given as

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

where y_w is the output signal at each of W receivers, $h_w = \eta_w I_w$ is the intensity gain, η_w represents the conversion ratio of the photon to electric current of each receiver, and x is a binary modulated signal that takes the value "0" or "1" (considering on-off keying modulation). "n" represents the additive white Gaussian noise (AWGN) with zero mean and variance $N_0/2$ (AWGN is normally preferred in wireless communication[23]) and I_w is the normalized irradiance seen at each receiver. We have assumed that perfect channel knowledge is available at the receiver end.

In this paper, K distribution is considered to model strong turbulence conditions. The probability density function (PDF) of the K distribution[11] using wavelength diversity is modified by

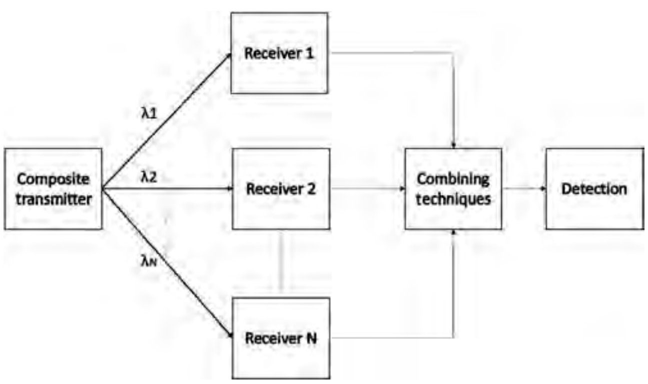

Fig. 1 Block diagram of FSO system with wavelength diversity.

$$f_{I_w}(I_w) = \frac{2(a_w)^{(a_w+1)/2}}{\Gamma(a_w)} I_w^{\frac{a_w-1}{2}} K_{a_w-1}(2\sqrt{a_w I_w}), \quad I_w > 0, \tag{2}$$

where a_w is the effective number of the discrete scatters with wth wavelength. $K_v(.)$ represents the v_{th} order modified Bessel function and $\Gamma(\cdot)$ denotes the gamma function. When $a_w \to \infty$, Eq. (2) approaches the negative exponential distribution. $K_v(.)$ can be written in form of the Meijer G-function as[24]

$$K_v(x) = \frac{1}{2} G_{0,2}^{2,0}\left(\frac{x^2}{4}\Big|_{\frac{v}{2},\frac{-v}{2}}^{-}\right). \tag{3}$$

Using the above conversion, the cumulative distribution function (CDF) of I is given by

$$F_{I_w}(I_w) = \int_0^\infty f_{I_w}(I_w)\mathrm{d}I_w, \tag{4}$$

or

$$F_{I_w}(I_w) = \int_0^\infty \frac{(a_w I_w)^{(a_w+1)/2}}{\Gamma(a_w)} I_w^{0-1} G_{0,2}^{2,0}\left(a_w I_w\Big|^{-}_{\frac{a_w-1}{2},\frac{-(a_w-1)}{2}}\right)\mathrm{d}I_w. \tag{5}$$

Using [Ref. 24; Eq. (26)] and [Ref. 25; Eq. (07.34.16.0001.01)], Eq. (5) can be written as

$$F_{I_w}(I_w) = \frac{1}{\Gamma(a_w)} G_{1,3}^{2,1}(a_w I_w|^{1}_{a_w,1,0}). \tag{6}$$

Using Ref. 5, the SI can be computed as

$$\mathrm{SI} \triangleq \frac{E[I_w^2] - E^2[I_w]}{E^2[I_w]} = \frac{a_w + 2}{a_w}, \tag{7}$$

where $E[.]$ gives the expected value of the enclosed. The scintillation strength can also be described by the Rytov variance[11,18] and it is calculated by $\delta_w^2 = 0.5 C_n^2 k_w^{7/6} L^{11/6}$, where $k_w = \frac{2\pi}{\lambda_w}$, is the optical wavenumber, λ_w is the wavelength related to each of the W channels, and L is the link distance. C_n^2 characterizes the refractive index structure parameter. It depends on the atmospheric conditions and height. The instantaneous electrical SNR can be defined as $\gamma_w = \frac{(\eta_w I_w)^2}{N_0}$. The average electrical SNR is calculated as[26,27] $\mu_w = \frac{(\eta_w E[I_w])^2}{N_0}$, where $E[I_w] = 1$ since I_w is normalized. Taking the power transformation of the random variable I_w, the PDF for the instantaneous electrical SNR γ_w can be calculated as

$$f_{\gamma_w}(\gamma_w) = \frac{(a_w)^{\frac{a_w+1}{2}}(\gamma_l)^{\frac{a_w-3}{4}}}{\Gamma(a_w)(\mu_w)^{\frac{a_w+1}{4}}} K_{a_w-1}\left(2\sqrt{a_w\sqrt{\frac{\gamma_w}{\mu_w}}}\right), \quad \gamma_w > 0, \tag{8}$$

and the corresponding CDF of the instantaneous electrical SNR γ_w is

$$F_{\gamma_w}(\gamma_w) = \frac{1}{\Gamma(a_w)} G_{1,3}^{2,1}\left(a_w\sqrt{\frac{\gamma_w}{\mu_w}}|_{a_w,1,0}^{1}\right). \tag{9}$$

3 Average BER

In this section, a mathematical expression is derived for computation of average BER of the proposed FSO system. The BER for the single transceiver link with equal probability of transmitting bit 1 and 0, with respect to I, is given by

$$P(I) = P(e|1, I) + P(e|0, I) = P\left(n > \frac{\eta I}{2}\right) = P\left(n > \frac{-\eta I}{2}\right) = Q\left(\frac{\eta I}{\sqrt{2N_0}}\right) = Q\left(\sqrt{\frac{\gamma}{2}}\right), \tag{10}$$

where $P(e|1, I)$ and $P(e|0, I)$ denote conditional error probability with respect to I and $Q(.)$ is the Gaussian Q-function defined as $Q(x) = \left(\frac{1}{\sqrt{2N_0}}\right)\int_x^\infty \exp\left(\frac{t^2}{2}\right)\mathrm{d}t$ and it is related to the complimentary error function erfc(.) by $\mathrm{erfc}(x) = 2Q(\sqrt{2}x)$.

The average BER of the FSO system with one transceiver P_{av} is calculated by taking the average of Eq. (10) over the I, i.e.,

$$P_{av} = \int_0^{+\infty} P(I) f_I(I)\mathrm{d}I = \int_0^{+\infty} Q\left(\frac{\eta I}{\sqrt{2\pi}}\right) f_I(I)\mathrm{d}I = \int_0^{+\infty} f_I(I)\left[\frac{1}{2}\mathrm{erfc}\left(\frac{\eta I}{2\sqrt{N_0}}\right)\right]\mathrm{d}I. \tag{11}$$

The above integral can be expressed by the second kind of v_{th} order modified Bessel function $K_v(.)$ and complementary error function erfc(.) as Meijer G-functions[22] $[\mathrm{erfc}(\sqrt{x}) = \frac{1}{\sqrt{\pi}} G_{1,3}^{2,0}(x|_{0,1/2}^{1})]$. Thus, Eq. (11) can be expressed as

$$P_{av} = \frac{(2)^{(a-2)}}{\sqrt{\pi^3}\Gamma(a)} \mathrm{G}_{5,2}^{2,4}\left(\frac{4\eta^2}{N_0 a^2}|_{0,\frac{1}{2}}^{\frac{1-a}{2},\frac{2-a}{2},0,\frac{1}{2},1}\right). \tag{12}$$

In terms of the average electrical SNR of single transceiver system μ, Eq. (12) can be written as

$$P_{av} = \frac{(2)^{(a-2)}}{\sqrt{\pi^3}\Gamma(a)} G_{5,2}^{2,4}\left(\frac{4\mu}{a^2}|_{0,\frac{1}{2}}^{\frac{1-a}{2},\frac{2-a}{2},0,\frac{1}{2},1}\right). \tag{13}$$

The considered channel mode is similar to a single-input multiple-output (SIMO) diversity case. Based on this assumption and considering Ref. 28, the detection rule for OOK will be off

$$P(\vec{y}|\mathrm{off}, I_w) \lessgtr P(\vec{y}|\mathrm{on}, I_w), \tag{14}$$

on where $\vec{y} = (y_1, y_2, \ldots, y_W)$ is the vector signal of W channels at the receivers. In this respect, we have derived the equations to calculate the average BER of the FSO system with W different channels by using OC, EGC, and SC methods, respectively, at the receiver end.

3.1 *Optimal Combining*

In the OC method, different diversity branch signals are cophased and weighted as per their signal strength prior to the combination. Using Ref. 19, the BER of the FSO link with wavelength diversity can be written as

$$P_{W,\mathrm{OC}} = \int_{\vec{I}} f_{\vec{I}}(\vec{I}) Q\left[\frac{1}{\sqrt{2WN_0}}\sqrt{\sum_{w=1}^{W}(\eta_w I_w)^2}\right]\mathrm{d}\vec{I}, \tag{15}$$

where $\vec{I} = (I_1, I_2, \ldots, I_W)$ is the vector representation of the irradiance of W receivers. In order to integrate Eq. (15), we have taken an approximation for the Q-function,[29] i.e., $Q(x) \approx \frac{1}{12}\exp\left(\frac{-x^2}{2}\right) + \frac{1}{4}\exp\left(\frac{-2x^2}{3}\right)$ and substituted it into Eq. (15), to obtain the BER expression. It is given as

$$P_{W,\mathrm{OC}} \approx \frac{1}{12}\prod_{w=1}^{W}\int_0^\infty f_{I_w}(I_w)\exp\left[\frac{-(\eta_w I_w)^2}{4WN_0}\right]\mathrm{d}I_w + \frac{1}{4}\prod_{w=1}^{W}\int_0^\infty f_{I_w}(I_w)\exp\left[\frac{-(\eta_w I_w)^2}{3WN_0}\right]\mathrm{d}I_w. \tag{16}$$

To get the closed form of Eq. (16), we have expressed Eq. (16) as the exponential function, $e^{-x} = G_{0,1}^{1,0}(x|_{0}^{-})$ and represented in the form of Meijer G-function.[24] After performing integration, the obtained closed equation for Eq. (16) is given as

$$P_{W,\mathrm{OC}} = \frac{1}{12}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)} G_{4,1}^{1,4}\left[\frac{4\eta_w^2}{(a_w)^2 WN_0}|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\} + \frac{1}{4}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)} G_{4,1}^{1,4}\left[\frac{16\eta_w^2}{3(a_w)^2 WN_0}|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\}. \tag{17}$$

For the average electrical SNR, Eq. (17) can be rewritten as

$$P_{W,\mathrm{OC}} = \frac{1}{12}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)} G_{4,1}^{1,4}\left[\frac{4\mu_w}{(a_w)^2 W}|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\} + \frac{1}{4}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)} G_{4,1}^{1,4}\left[\frac{16\mu_w}{3(a_w)^2 W}|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\}, \tag{18}$$

where a_w defines the number of discrete scatter of the w_{th} channel and μ_w signifies the average electrical SNR of the w_{th} channel.

3.2 *Equal Gain Combining*

The EGC method combines all the incoming signals at different receivers with scaling. The average BER with W different channels for the case of EGC can be calculated as[19]

$$P_{W,\mathrm{EGC}} = \int_{\vec{I}} f_{\vec{I}}(\vec{I}) Q\left(\frac{\sum_{w=1}^{W}\eta_w I_w}{W\sqrt{2N_0}}\right)\mathrm{d}\vec{I}. \tag{19}$$

Applying the same calculation procedure as done in the case of the OC method, the final average BER expression for EGC can be written as

$$P_{W,\mathrm{EGC}} = \frac{1}{12}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)}G_{4,1}^{1,4}\left[\frac{4\mu_w}{(a_w)^2W^2}\Big|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\} + \frac{1}{4}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)}G_{4,1}^{1,4}\left[\frac{16\mu_w}{3(a_w)^2W^2}\Big|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\}. \tag{20}$$

3.3 *Selection Combining*

The SC method uses a simple implementation procedure. It selects the branch with the highest SNR out of all available branches at the receiver. Consequently, the selection of irradiance and average electrical SNR are made as per

$$I_{\mathrm{SC}} = \max(I_1, I_2, \ldots, I_l), \tag{21}$$

and

$$\mu_{\mathrm{SC}} = \max(\mu_1, \mu_2, \ldots, \mu_l). \tag{22}$$

The average BER of the FSO link with SC can be obtained as

$$P_{W,\mathrm{SC}} = \int_0^{\infty} f_{I_{\mathrm{SC}}}(I_{\mathrm{SC}})Q\left(\frac{\eta_{\mathrm{SC}}I_{\mathrm{SC}}}{\sqrt{2WN_0}}\right)\mathrm{d}I_{\mathrm{SC}}, \tag{23}$$

where $f_{I_{\mathrm{SC}}}(I_{\mathrm{SC}})$ is the PDF of the highest value of the irradiance. For W wavelength channel, the final average BER equation in terms of μ_{SC} can be expressed as

$$P_{W,\mathrm{SC}} = \frac{1}{12}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)}G_{4,1}^{1,4}\left[\frac{4\mu_{\mathrm{SC}}}{(a_w)^2W}\Big|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\} + \frac{1}{4}\prod_{w=1}^{W}\left\{\frac{2^{(a_w-1)}}{\pi\Gamma(a_w)}G_{4,1}^{1,4}\left[\frac{16\mu_{\mathrm{SC}}}{3(a_w)^2W}\Big|_{0}^{\frac{1-a_w}{2},\frac{2-a_w}{2},0,\frac{1}{2}}\right]\right\}, \tag{24}$$

where μ_{SC} is the maximum average SNR achieved by the system for the irradiance I_{SC}. In the wavelength diversity, the atmospheric turbulence channel between each transceiver pair is statistically independent for different wavelengths. So, the combined error probability of all receivers is always less as compared to the error probability of a single channel.

4 Results and Discussion

We have calculated the average BER of an FSO link with wavelength diversity over the K distribution. BER graphs are plotted for OC, EGC, and SC, for a link having distances of 2 and 3 km, respectively, over strong turbulence conditions. For strong turbulence, the refractive index structure parameter $C_n^2 = 2 * 10^{-13}\ \mathrm{m}^{-2/3}$ is chosen. The receiver aperture diameter D is kept fixed at 0.01 m. To apply the wavelength diversity, three wavelengths are chosen as $\lambda_1 = 1.55\mu$m, $\lambda_2 = 1.31\mu$m, and $\lambda_3 = 0.85\ \mu$m. The sensitivity threshold and electrical SNR for all the W receivers are considered as identical, i.e., $\mu_1 = \mu_2 = \ldots = \mu_W = \mu$ and $\gamma_{\mathrm{th},1} = \gamma_{\mathrm{th},2} = \ldots = \gamma_{\mathrm{th},W} = \gamma_{\mathrm{th}}$. The BER performance of all three diversity schemes is also compared for the diversity of the order of 2. Finally, the performance of the proposed scheme is compared with the spatial diversity over K channel published by Tsiftsis et al.[19]

The graphs of average BER with and without wavelength diversity using SC, EGC, and OC are plotted in Figs. 2, 3, and 4, respectively. In these graphs, $W = 1$ represents without diversity case with an operational wavelength of 1.55 μm, whereas $W = 2$ and 3 signifies the wavelength diversity orders of 2 and 3, respectively. For the diversity of the order of 2, 1.55 and 1.31 μm wavelengths are chosen. The information is transmitted on 1.55, 1.31, and 0.85 μm in the case of a diversity order of 3.

From Fig. 2, it is evident that in order to achieve the BER of 10^{-4}, the required maximum SNR is 55 and 68 dB at distances of 2 and 3 km, respectively, in no diversity scenario, whereas the same is 41 and 49 dB, respectively, with wavelength diversity of the order of 3 using the SC method. Similar results using the EGC method are shown in Fig. 3. A maximum of 2 and 9 dB improvement is achieved by applying wavelength diversity at distances of 2 and 3 km, respectively.

Figure 4 shows the BER performance using the OC method. For the same BER, required SNR is 38 and

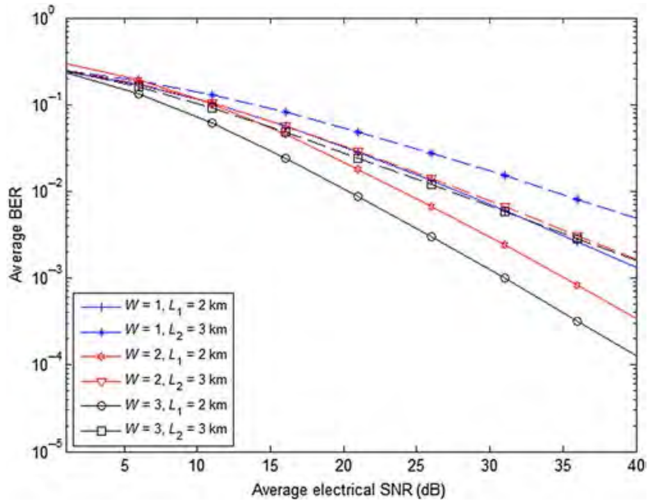

Fig. 2 BER performance of link with SC scheme.

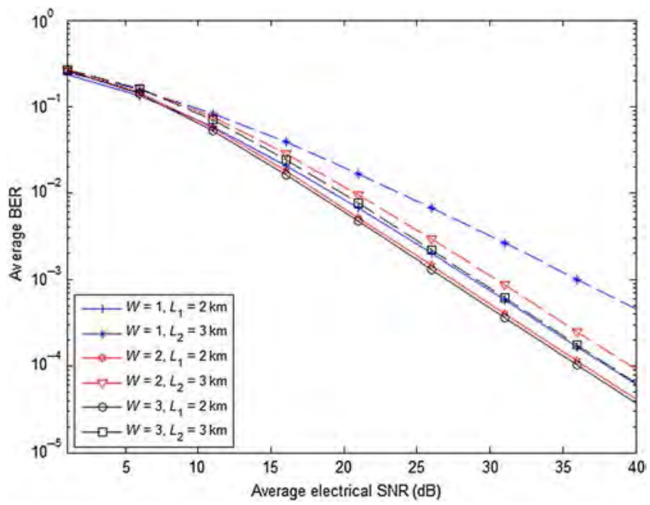

Fig. 3 BER performance of link with EGC.

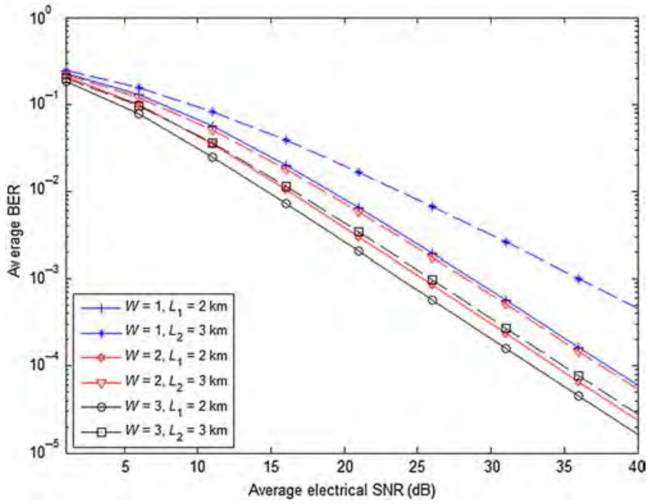

Fig. 4 BER performance of link with optimal combining scheme.

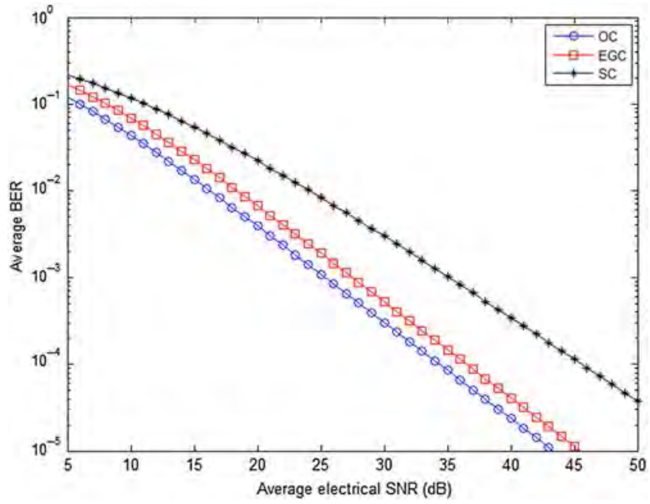

Fig. 5 Performance comparison of OC, EGC, and SC scheme with $W = 2$ at 2 km.

47.5 dB at distances of 2 and 3 km, respectively. With the diversity of the order of 3, the required SNR is 33 and 35 dB. The detailed results of all methods are given in Table 1.

The achieved results show the improvement in the performance of the FSO system after applying wavelength diversity in all three schemes. A maximum improvement is observed in the case of SC but the required SNR is still very high to consider for any practical application, while OC demands less SNR for targeted BER compared to the other two techniques.

A performance comparison of all three techniques with a diversity order of 2 at 2-km distance is plotted in Fig. 5. This result also validates that the OC technique provides the best performance as compared to the other techniques. The difference in SNR with respect to the average BER remains almost constant for OC as well as EGC and the difference is around 2 to 3 dB. The performance of the SC is poorer compared to the other two techniques. Similar results were observed in the case of $W = 3$.

Figure 6 shows a comparison of the wavelength diversity with a spatial diversity scheme (presented in the Ref. 19, for SIMO case) over K channel model. Tsiftsis et al.[19] have transmitted information using single wavelength over multiple transceiver pairs. The comparison is presented for the receiver diversity orders of 2 and 3. It is observed that about 3 to 5 dB SNR improvement is achieved by wavelength diversity over spatial diversity. For both cases, the wavelength diversity performs better than spatial diversity.

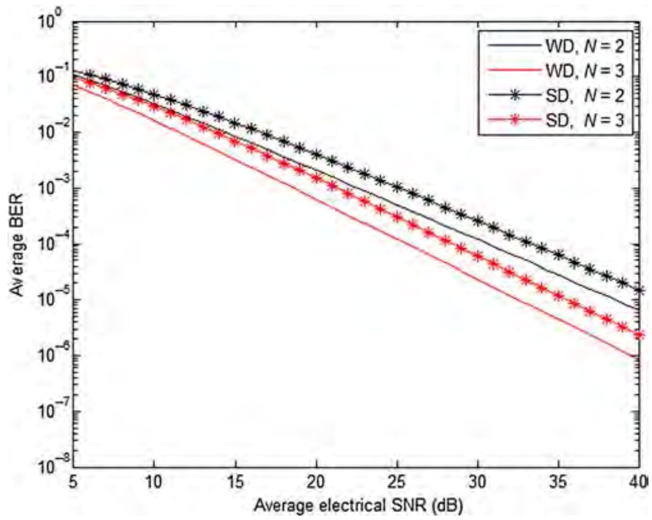

Fig. 6 Comparison of wavelength and spatial diversity using OC.

5 Conclusions

The performance of the FSO link under strong turbulence using the wavelength diversity is investigated. Mathematical expressions for the three different combining techniques namely OC, EGC, and SC are derived. It is observed that at a diversity order of 3, the OC method reduces the SNR by 13% and 26% for link lengths of 2 and 3 km for the

Table 1 Obtained SNR for the targeted BER of 10^{-4}.

Diversity order	OC (dB)		EGC (dB)		SC (dB)	
	$L = 2$ km	$L = 3$ km	$L = 2$ km	$L = 3$ km	$L = 2$ km	$L = 3$ km
$W = 1$	38	47.5	38	47.5	55	68
$W = 2$	34	37.5	36	39.5	46	57
$W = 3$	33	35	36	38.2	41	49

BER of 10^{-4}, respectively, as compared to without wavelength diversity. The same is 11% and 27% in the case of SC. SC provides better improvement than OC at a distance of 3 km. However, OC provides the targeted BER of 10^{-4} at lower SNR of 35 dB. EGC performance is 2 to 3 dB less than OC. Overall, OC provides better results than the other two combining methods, i.e., EGC and SC. Results are also compared with the spatial diversity scheme for the SIMO case and found to be better. Deployment of the wavelength diversity enriches the performance of the FSO system.

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