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An Improved Wavelength Diversity Based Free Space Optical Link: Effects of Fog and Atmospheric Turbulence

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Free-space optical (FSO) communication systems have received a lot of attention from academia and industries due to their low cost, high security and data rates for various wireless communication applications. However, factors such as fog and atmospheric turbulence degrade the performance of the FSO communication system. Therefore, this study presents an improved wavelength diversity based free space optical link using a single channel approach. The authors employed both Kim and Al-Naboulsi's models to model the attenuation-induced FSO link. Furthermore, the Gamma-Gamma turbulent model was utilized to explain the turbulent nature of the FSO communication link. Experimental results showed improved performance in terms of Bit Error Rate (BER) and Quality factor of the FSO link up to a distance of 7km compared to the multiple channel approach that gives a signal output for distances less than 3km only. Hence, the impact of attenuation on the FSO link was reduced and the performance of the system was enhanced under fog and atmospheric turbulence conditions.

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Keywords: Al-Naboulsi's model; BER; FSO communication; Gamma-Gamma; Kim model; single and multiple channels.

1. INTRODUCTION

Presently, the rate of increase in data transmission necessitates an efficient communication link with high bandwidth, good channel quality, minimum errors, and maximum performance as well as security. This can be achieved through the utilization of a Free Space Optical (FSO) communication system. The FSO communication system is a Line of Sight (LOS) wireless transmission in which data is transmitted via free-space in the form of laser beams or infrared rays to obtain broadband communication [1]. This system exhibits a high immunity against Electromagnetic Interference (EMI) and provides highly secured transmission [2].

The FSO communication system is an existing alternative in contrast to fiber optics technology due to its capability to handle full-duplex data transmission. Although, light information can be routed through fiber cables efficiently, however various applications require the free-space to establish a communication link between the transmitter and receiver [3]. Furthermore, the system provides high data rates in the range of gigabits per second and hence, solving the problem of last mile connectivity [2].

In addition, FSO technology offers the potential of broadband communication capacity using unlicensed optical wavelengths. However, problems associated with atmospheric turbulence, such as fog, rain, and haze emerges between the transmitter and the receiver from time to time, resulting in fading. These fading links impose power loss on the optical signal, producing distortion and degrading bit error rate (BER) and throughput [4].

Therefore, this study presents an improved wavelength diversity based free space optical link using a single channel approach. This approach is a Multiple-Input Single-Output (MISO) based approach that enables multiple lasers with varying wavelengths to transmit similar signals via a single channel. The time variation in the refractive index and atmospheric temperature will vary at different wavelengths. Furthermore, the impact of attenuation reduces as a result of its variation for different wavelengths at similar period of time. In addition, an optical amplifier is installed at the receiver end in order to amplify the noise power as well as recover a very high quality of the transmitted signal.

The rest of the paper is structured as follows: Section 2 presents the review of related studies, section 3 presents the system model and design parameters. The experimental results obtained are presented in section 4, while conclusions are done section 5.

2. RELATED WORKS

This section presents the review of existing studies that have been carried out in the area of FSO link. In this regard, the Bit Error Rate (BER) performance of a Free-Space Optical (FSO) communication links over solid turbulence fading channels collectively with misalignment (pointing error) impacts was investigated [5]. The authors assessed the average BER in a closed form operating in the channel environment, assuming intensity modulation or direct detection with on-off keying. However, atmospheric turbulence and the building sway which are the two prevailing variables influencing the performance of optical wireless communications were not considered.

A spectral model of optical scintillation to design a terrestrial FSO communication link was presented in [6]. This helped to estimate in a current optical wireless channel, the power spectral density of optical scintillation when weather parameters and time zone such as rainfall and temperature intensity are provided. However, due to the constraint in the experimental site, the extension of the proposed model was not verified.

The influence of turbulence effects on Free-space Optical Interconnection (FSOI) channels inside a server framework was experimentally examined in [7]. The authors discovered that the fading statistics follow the notable log-normal distribution that is generally utilized for turbulent fading portrayals. However, the measured spatial and temporal correlation functions do not fit the frequently acknowledged turbulence theory predictions. Thus, decreasing the inter channel spacing for achieving an efficient diverse communication, thereby decreasing the spatial inter channel correlation.

In [8], an investigation of the performance of FSO communication systems under the impacts of bad weather conditions particularly for fog, heavy rain, dry and wet snow was presented. The performance of link was analyzed for these conditions and was enhanced by a method of using array of receivers. However, the system can be improved at higher data rate over a longer link range under all weather conditions along with atmospheric turbulences to improve the usage of free space optics technology.

Furthermore, the performance of FSO communication links under weak atmospheric turbulence was studied and analyzed [9]. The authors designed and presented a flow chart for the evaluation of the performance of the FSO communication links based on the obtained mathematical expressions. However, the system performance in terms of outage probability can be enhanced different diversity schemes. Furthermore, Multi Input Multi Output (MIMO) can be introduced to help improve the system capacity.

In addition, the impacts of fog, rain, and snow on the performance of FSO communication link was analyzed by employing Gamma-Gamma turbulence model in terms of attenuation coefficient [10]. The authors employed Kim and Kruise model to investigate the attenuation of different wavelengths in the presence of fog. The experimental results obtained showed that higher wavelengths experiences less atmospheric attenuation in comparison to smaller wavelengths. However, the attenuation turns out to be wavelength independent for visibility range of less than 500 meters.

In view of these limitations identified from the review of related works, this study seeks to investigate and improve the impacts of fog and atmospheric turbulence on the performance of FSO communication systems using wavelength diversity.

3. SYSTEM MODEL

The attenuation-induced FSO link was modelled using the Kim and Al-Naboulsi's model. The Gamma-Gamma turbulent model was used to explain the turbulent nature of the FSO communication link. These models were utilized to model the channel through which the signal will pass.

3.1 Kim Model

The attenuation according to Kim model is presented in equation 1 [11].

$$\mathrm{A} = \frac{3.192}{\mathrm{V}}\left(\frac{\lambda}{550}\right)^{-\mathrm{q}} \ \text{dB/km} \tag{1}$$

Where V is the visibility in km, and λ is the wavelength in nm.

The model estimates the attenuation in the visible and near infrared bands. The coefficient 'q' which depends on the particle size distribution, is determined from experimental data and presented in equation 2 [12].

$$\mathrm{q} = \begin{cases} 1.6 \text{ for } \mathrm{V} > 50km \\ 1.3 \text{ for } 6\mathrm{km} < V < 50km \\ 0.16\mathrm{V} + 0.34 \text{ for } 1\mathrm{km} < V < 6km \\ \mathrm{V} - 0.5 \text{ for } 0.5\mathrm{km} < V < 1km \\ 0 \text{ for } \mathrm{V} < 0.5km \end{cases} \tag{2}$$

3.2 Al-Naboulsi Model

Two models of attenuation prediction for convection and advection fog types have been proposed from this model namely; Al-Naboulsi's convection fog model and Al-Naboulsi's advection fog model

3.2.1 Al-Naboulsi's convection fog model

Convection fog is formed when the temperature drops close to the dew point, thereby forming water vapour in the atmosphere which condenses and obstructs visibility. This fog appears when the air is adequately cool and becomes saturated. It usually arises at the end of the day or at night when meteorological conditions are favorable. The convection fog attenuation prediction is presented in equation 3 [13].

$$\sigma_{\mathrm{convection}=} 4.343\left(\frac{0.18126\lambda^2+0.13709\lambda+3.7502}{\mathrm{V}}\right) \tag{3}$$

Where V is the visibility in km, and λ is the wavelength in nm.

3.2.2 Al-Naboulsi's advection fog model

Advection fog is formed when wet, hot air passes over a cooler or terrestrial surface, the air associated with the surface area is cooled inferior to its dew point, thereby forming condensation of water vapour to condense and obstruct visibility. The advection fog attenuation prediction is equation 4 [13].

$$\sigma_{\mathrm{advection}=} 4.343\left(\frac{0.11478\lambda+3.8367}{\mathrm{V}}\right) \tag{4}$$

Where V is the visibility in km, and λ is the wavelength in nm.

3.3 Gamma-Gamma Turbulence Model

The gamma-gamma turbulence model is centered on the modulation process where the variation of light radiation passing through a turbulent atmosphere is assumed to contain large-scale (refraction) and small-scale (scattering) impacts. The small-scale variations include contributions due to cells or eddies lesser than Fresnel zone while the large-scale variations are created by turbulent eddies greater than that of the initial Fresnel zone. Subsequently, the normalized received irradiance I_t is expressed as the product of two independent processes I_x and I_y as presented in equation 5.

$$\mathrm{I_t} = \mathrm{I_x}\,\mathrm{I_y} \tag{5}$$

Where I_y and I_x comes from small-scale and large-scale turbulent eddies respectively and are equally anticipated to obey the gamma-gamma Probability Distribution Function (PDF). Their PDF is presented equation 6 [14].

$$\mathrm{p(I_t)} = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)}\mathrm{I_t}^{\left(\frac{\alpha+\beta}{2}\right)^{-1}}\ \mathrm{K}_{\alpha-\beta}\left(2\sqrt{\alpha\beta \mathrm{I}}\right);\ \mathrm{I_t} > 0 \tag{6}$$

Where α and β are the actual number of large-scale and small-scale eddies of the scattering process, $K_{\alpha-\beta}$ represent the Bessel function and Γ is the gamma function.

If the optical radiation at the receiver is anticipated to be a plane wave, hence, the two parameters α and β which characterize the irradiance fluctuation PDF can be expressed in equations 7 and 8 respectively [15].

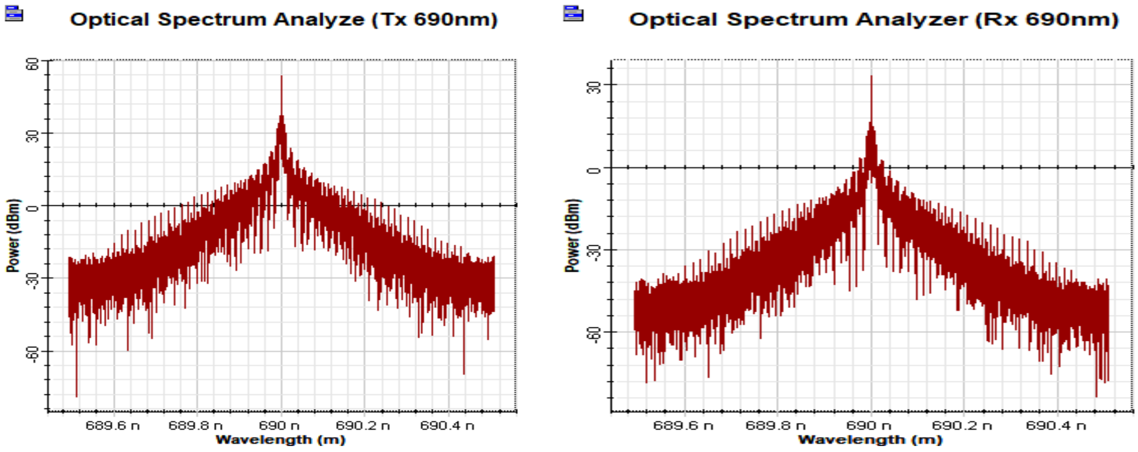
$$\alpha = \exp\left[\left(\frac{0.49\sigma_l^2}{\left(1+1.11\sigma_l^{12/5}\right)^{7/6}}\right) - 1\right]^{-1} \tag{7}$$

$$\beta = \exp\left[\left(\frac{0.51\sigma_l^2}{\left(1+0.69\sigma_l^{12/5}\right)^{5/6}}\right) - 1\right]^{-1} \tag{8}$$

4. RESULTS AND DISCUSSION

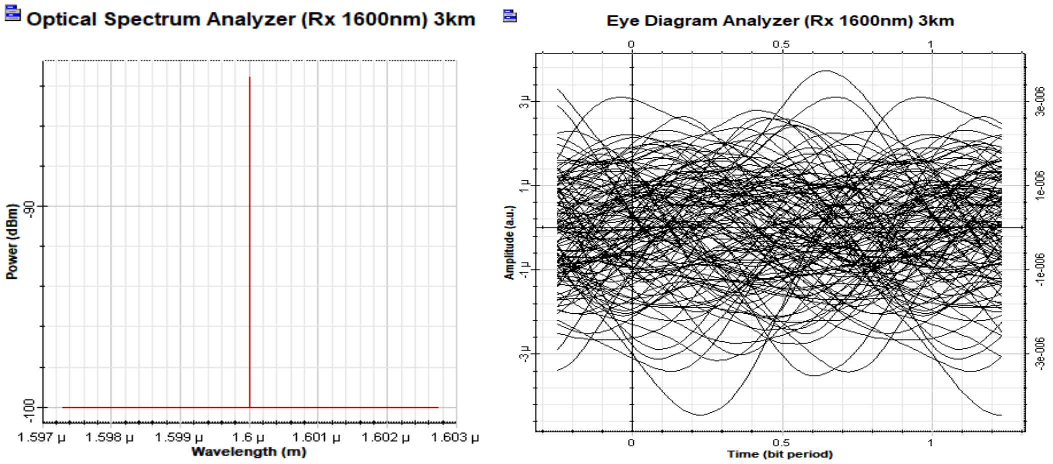
This section presents the simulation results obtained based on the impact of fog and atmospheric turbulence on the performance of FSO communication link. The performance of the link was analyzed in terms of BER and Q-Factor using both single and multiple channels approach. In addition, the attenuation coefficients were varied from 0.25dB/km to 160dB/km. This is called for all possible attenuations using Kim, Al-Naboulsi and Gamma-Gamma turbulence model at 1km-10km range of visibility.

Figs. 1 and 2 presents sample of the simulation results obtained at different wavelengths and distances using the multiple channel approach.



(a) Transmitted Power **(b) Received Power**

Fig. 1. Transmitted and Received Power at 690nm (1km)



(a) Received Power **(b) Quality Factor**

Fig. 2. Received Power and Quality Factor at 1600 nm (3 km)

Table 1(a). Results of transmitted optical powers using multiple channel approach

Range (km)	Attenuation (dB/km)	Transmitted power (dBm)	Transmitted optical power (dBm)
1	0.25	60	56.7816
2	18.00	60	56.7816
3	35.75	60	56.8521
4	53.50	60	56.7816
5	71.25	60	56.9214
6	89.00	60	56.9897
7	106.75	60	56.7100
8	124.50	60	56.8521
9	142.25	60	56.8521
10	160.00	60	56.7100

Table 1(b). Results of Received Optical Powers using Multiple Channel Approach

Range (km)	Received optical power (dB/km)								BER	Quality factor
	690nm	**780nm**	**850nm**	**980nm**	**1060nm**	**1140nm**	**1550nm**	**1600nm**		
1	36.173	36.388	36.173	36.457	36.388	36.388	36.388	36.317	0	10845.9
2	-5.3469	-5.4913	-5.3469	-5.2764	-5.2764	-5.3469	-5.2764	-5.3469	0	182.479
3	-80.012	-80.155	-80.012	-80.083	-80.155	-80.012	-80.083	-80.227	1	0
4	-100	-100	-100	-100	-100	-100	-100	-100	1	0
5	-100	-100	-100	-100	-100	-100	-100	-100	1	0
6	-100	-100	-100	-100	-100	-100	-100	-100	1	0
7	-100	-100	-100	-100	-100	-100	-100	-100	1	0
8	-100	-100	-100	-100	-100	-100	-100	-100	1	0
9	-100	-100	-100	-100	-100	-100	-100	-100	1	0
10	-100	-100	-100	-100	-100	-100	-100	-100	1	0

Fig. 1 shows the transmitted and received optical power using 690nm wavelength over a distance of 1km. The amount of power transmitted from each laser is 60dBm. However, after going through modulation process, the transmitted optical power dropped to about 56dBm as presented in Fig. 1(a). Furthermore, due to the amount of attenuation present in the FSO channel, the received optical signal dropped to about 36dBm as presented in Fig. 1(b).

Fig. 2 presents the received optical power and eye diagram using the 1600nm wavelength distance of 3km. The eye diagram presented in Fig. 2(b) shows a linear decline of BER and Q-Factor values due to the amount of attenuation present in the FSO channel and the increase in the distance range.

Table 1 presents the summary of results obtained for transmitted and received optical powers using multiple channel approach for a wavelength of 690nm, 780nm, 850nm, 980nm, 1060nm, 1140nm, 1550nm and 1600nm over 1-10km distance range respectively.

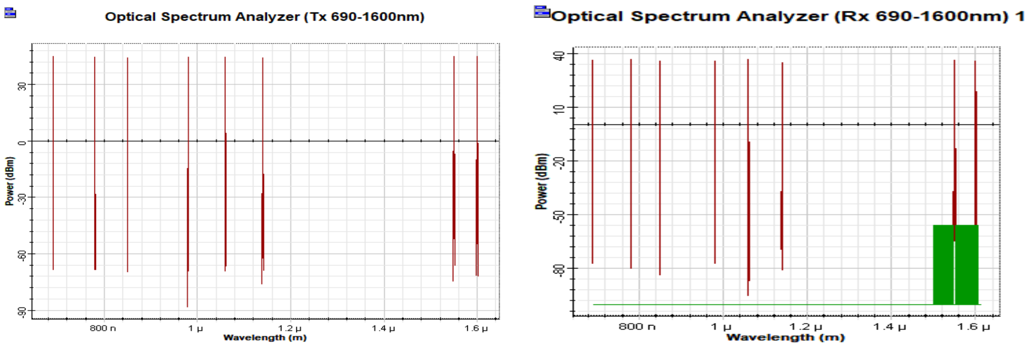
Table 1 presents the summary of results obtained for transmitted and received optical powers using multiple channel approach. Table 1(a) shows the results of the transmitted optical powers for wavelengths of 690nm, 780nm, 850nm, 980nm, 1060nm, 1140nm, 1550nm and 1600nm over a distance of 1-10km. While Table 1(b) shows the results of the received optical powers, BER and Quality factors obtained for these wavelengths.

Figs. 3 to 6 presents sample of the simulation results obtained at different wavelengths and distances using the single channel approach.

Fig. 3 shows the transmitted and received optical power at a wavelength of 690-1600nm over a distance of 1km. The amount of power transmitted from each laser is 60dBm. However, after going through modulation process, the transmitted optical power dropped to about 56dBm as presented in Fig. 3(a). Furthermore, due to the amount of attenuation present in the FSO channel, the received optical signal dropped to about 36dBm as presented in Fig. 3(b).

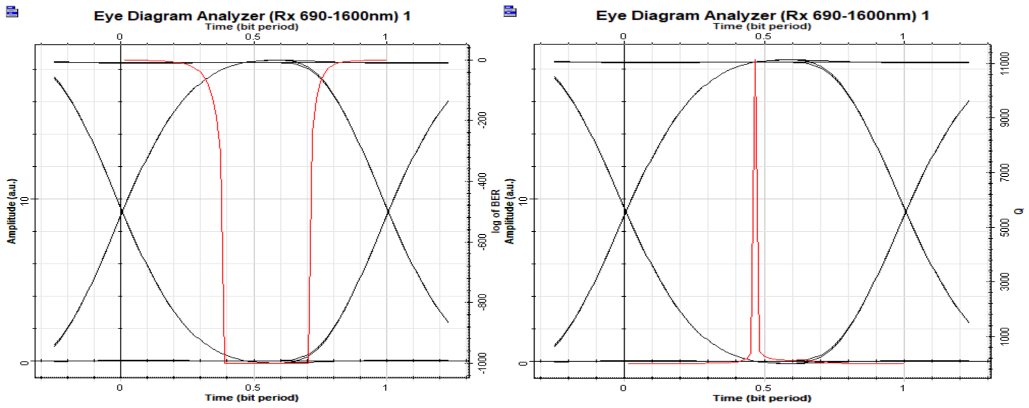
Fig. 4 present simulation result obtained for the Quality factor and BER for a wavelength of 690-1600nm over 1km distance range. The result depicts a minimum BER of 0 and a reliable Quality factor value of about 11133.1. This shows that the signal coming out from the receiver is of a very high quality and error free.

Figs. 5 and 6 presents the Quality factor obtained for a wavelength of 690-1600nm over distances of 7km and 9km respectively.



(a) Transmitted Power **(b) Received Power**

Fig. 3. Transmitted and Received Power at 690-1600nm (1km)



(a) Minimum BER **(b) Quality Factor**

Fig. 4. Mininum BER and Quality Factor for 690-1600nm (1km)

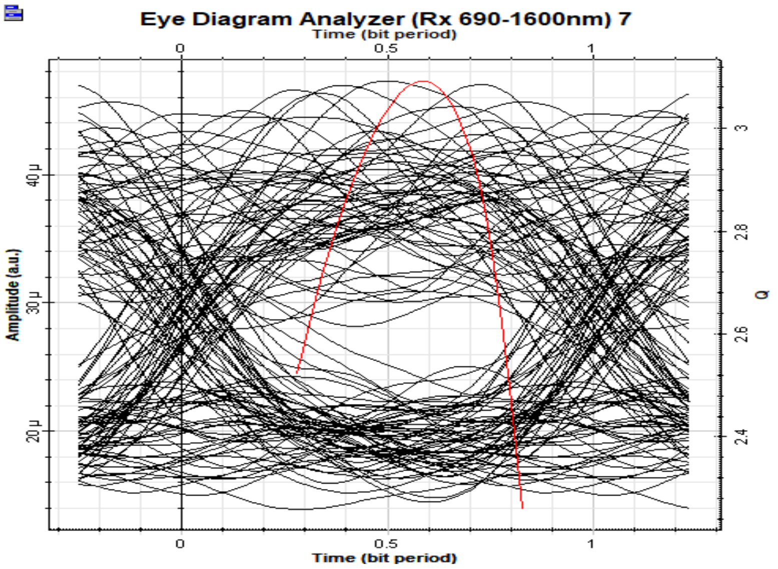


Fig. 5. Quality Factor for 690-1600nm (7km)

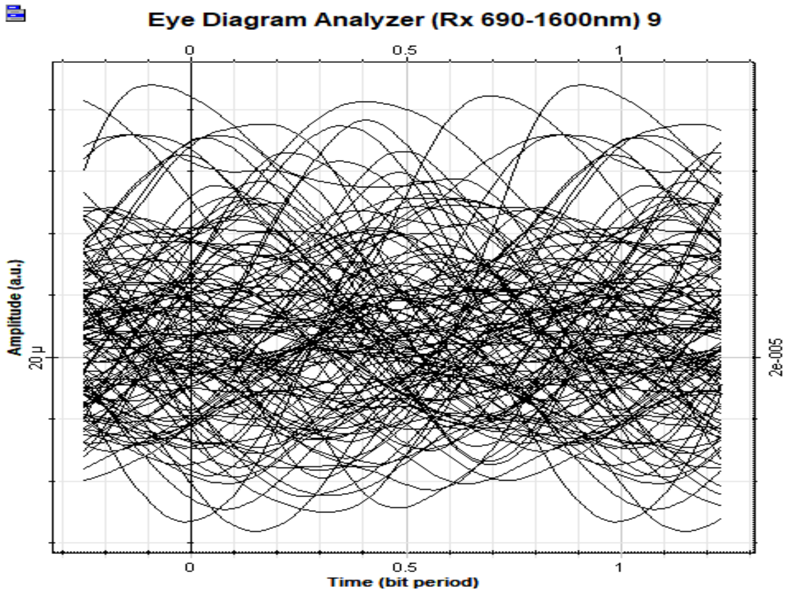


Fig. 6. Quality Factor for 690-1600nm (9km)

Fig. 5 shows the simulation result obtained for the Quality factor of a wavelength of 690-1600nm at a distance of 7km. The result shows that there is a Quality factor value, however the output is quiet noisy. While the simulation result presented in Fig. 6 shows the value of the Quality factor to be zero; and thus, shows no signal output at 9km range of visibility.

Table 2 presents the summary of the results obtained using single channel approach. at a wavelength of 690nm-1600nm over 1-10km distance range respectively.

From the result obtained, the single channel approach was able to minimize the BER performance of the FSO link as well as maximize the Quality factor efficiently up to a distance of 7km compared to the individual channel model which was able to give a signal output for distance ranges less than 3km only. Hence, the single channel model showed a promising approach to enhance the performance of the FSO link under fog and atmospheric turbulence condition.

Table 2. Simulation results using single channel approach

Range (Km)	Attenuation (dB/km)	Transmitted Power (dBm)	Transmitted Optical power (dBm)	Received optical power (dBm)	BER	Quality Factor
1	0.25	60	56.7905	38.4738	0	11133.1
2	18	60	56.8346	22.0761	0	9879.73
3	35.75	60	56.8082	14.5056	0	6770.79
4	53.5	60	56.7905	5.48131	0	3751
5	71.25	60	56.8346	-5.11432	0	1018.61
6	89	60	56.8258	-17.4902	1.49686e-133	24.5522
7	106.75	60	56.7994	-31.6689	0.000948054	3.09112
8	124.5	60	56.8082	-47.6352	1	0
9	142.25	60	56.7816	-65.486	1	0
10	160	60	56.7727	-85.1872	1	0

5. CONCLUSION

In this study, an improved wavelength diversity based free space optical link using a single channel approach was presented. The proposed approach enabled multiple lasers with varying wavelengths to transmit similar signal via a single channel. Also, an optical amplifier was installed at the receiving end in order to amplify the noise power and also to recover a very high quality of transmitted signal. The simulation results obtained shows that the single channel model minimizes the BER performance of the FSO link and maximizes the Quality factor efficiently up to 7km distance range compared to the multiple channel approach that gives a signal output for distances less than 3km only. Hence, the impact of attenuation on the FSO link was reduced and the performance of the system is enhanced under fog and atmospheric turbulence conditions. In addition, the single channel model is the most proficient model to transmit signals at high performance under fog and atmospheric turbulence condition. However, future work should focus on ways to modify the optical amplifiers in order to improve the noise power at the receiving end.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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