Performance Enhancement of FSO Communication Under Complex Weather Environment

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Abstract Free space optical communication is a well-known line of sight technology with the use of lasers for optical bandwidth connections. Bad weather conditions like dust storms in the Middle-East affect the performance in free space. These weather conditions lead to an increase in the bit error rate (BER) and decrease the Q-factor to low levels in FSO channel. To improve the performance of the system in such conditions a dual FSO channel has been proposed in which each channel includes optical amplifiers (specifically, an Erbium-doped fiber amplifier (EDFA)). This system shows performance improvement in terms of both BER and Q-factor. Additional communicating distance can be realized by exploiting 1550 nm by multiple channels and EDFA.

Keywords Free space optical communication (FSO) · Q-factor · Bit error rate (BER) · Atmospheric attenuation · Laser · Dust attenuation · Erbium-doped fiber enhancer (EDFA) · Optisystem

1 Introduction

Free Space Optical Communication (FSO) can be referred as an optical communication revolution that operates on light propagation in free space in order to transmit information for broadcast wireless communications. This appears differently in relation to wired medium, for example, optical fiber links. This free space optical research is of great importance when the physical connections are seen to be unreasonable because of significant expenses or different considerations [1].

FSO has become popular because of its ability to carry high bandwidth data for long distances (up to 8 km) with low BER. Weather conditions must be considered while using FSO channels because FSO channels get disturbed by carrier medium and dust storms result in suspended particles in air. Complex weather conditions like fog, dust storm, snow, rain, haze, etc. have a degrading effect on FSO channel. Absorption and scattering have a reciprocation effect on laser photons. Numerous

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methods have been proposed to overcome the setbacks of bad weather conditions, Optical Amplifying, Wavelength Division Multiplexing (WDM), etc. WDM has been observed to overcome the problem of beam divergence [2–7].

In this paper, FSO models have been executed using an optical amplifier (Erbium-doped fiber amplifier (EDFA)) at the transmitter and receiver end to obtain performance comparison in terms of BER and Q-factor values along with a distance up to 1 km. The weather conditions have been simulated using Kim's Model aimed at laser beam propagation. Dual-channel FSO system and then three-channel FSO system have been implemented. The comparison of the parameters for the different systems proposed above has been summarized [2].

The paper is organized as follows: Sect. 2 discusses the attenuation by dust particles for FSO link. Next, the effect of turbulence is studied. System models in order to optimize the output have been proposed and implemented. Later, the results obtained from the proposed models have been compared and analyzed in Sect. 3. Finally, appropriate conclusions have been obtained in Sect. 4.

2 Effect of Dust Storms in FSO Link Communication

2.1 Attenuation Condition

Attenuation refers to weakening of signal strength during propagation. It occurs due to absorption, scattering and scintillation of laser photons. Water particles and carbon dioxide are responsible for the absorption of optical signals. Beer's Law can be utilized in order to realize the relation which is present between the powers of the transmitted and the received signals, when atmospheric attenuation is taken into account [3]. This Law can be given as expressed in (1):

$$\tau = P_L = P_0 \times \text{EXP}(-\alpha \times L) \tag{1}$$

where,

τ = Atmospheric attenuation.
P_L = Laser Power at length L.
P_0 = Laser Power at the source.
L = Distance.
α = Atmospheric Attenuation Constant.

The atmospheric attenuation will be calculated (in dB) by using (2)

$$\tau_R = 4.3429 \times (\alpha \times L) \tag{2}$$

For the calculation of the Atmospheric Attenuation Coefficient of (2) as per Kim's formula, the value of α will be

Table 1 Attenuation by FSO link (Kim model) [3]

Visibility (km)	dB/km (785 nm)	dB/km (1550 nm)	Weather
0.05	340	340	Heavy fog
0.07	242	242	Heavy dust
0.2	85	85	Moderate
0.5	34	34	Dust-fog
1	14	10	Rain
2	7	4	Haze
4	3	2	
10	1	0.4	Clear
23	0.5	0.2	

$$\alpha = \frac{3.91}{V}\left(\frac{550\,\text{nm}}{\lambda}\right)^{-q} \tag{3}$$

where,

λ = Wavelength in nm.

q = Size distribution of scattering particles.

V = Visibility.

Scattering is a phenomenon under the condition of the optical signal in collision with a scatterer in the medium. As a result, there is an occurrence of a directional redistribution of energy [8]. This results in the loss of beam power in the direction of propagation which is highly dependent on the relative size of the scatters in the medium with reference to the optical signal wavelength [3].

For the constant wavelength, attenuation is only a factor of visibility. In this paper, the comparison of two different wavelengths has been done and the attenuation effect on each one of them has been analyzed. The atmospheric attenuation coefficient has been summed up as shown in following Table 1.

2.2 Turbulence Condition

The signal loss caused due to Turbulence can be described with two parameters of intensity fluctuation [9]: (1) Correlation length, (2) Correlation time.

The performance of any FSO link gets detoriated due to atmospheric turbulence, which leads to the temporal and spatial fluctuation of light intensity. The Space Diversity Reception Technique (SDRT) as well as the Advanced Modulation formats help in order to remove the impairments of the atmospheric turbulence [10].

When the aperture of the receiver is larger than the length of correlation then loss can be reduced significantly by using aperture averaging technique. But this might not always be a practical solution. In such cases, there can two approaches [4]:

1. Temporal domain technique—In this technique, only one receiver is used. If the receiver has knowledge of marginal fading distribution but has no knowledge of the temporal fading correlation and instantaneous fading state then the technique employed is Maximum Likelihood Detection (MLD). But if the receiver has knowledge of joint temporal fading distribution and has no knowledge of instantaneous fading state then Maximum Likelihood Sequence Detection (MLSD) is employed.
2. Spatial domain technique- In this technique, a minimum of two receivers are used at different locations or at different spatial angles. For improving the gain of reception, these two receivers should be kept at large distance.

Temporal pulse broadening results in an aliasing effect if the duration of temporal pulse is more than that of bit time. This causes loss of signal and hence results in higher BER [5]. The receiver SNR can be expressed as given in (4):

$$\text{SNR}(z) = \frac{(P_r(z)R_d)^2}{\sigma_n^2} \tag{4}$$

where,

R_d = Receiver responsivity.
σ_n^2 = Dark Noise, thermal noise and shot noise.
$P_r(z)$ = Received power under pulse broadening.
z = Distance at which receiver is kept.

The power received at distance z under pulse broadening is given by (5):

$$P_r(z) = P(0)\frac{\sigma_0}{\sigma(z)} \int \exp\left(-\frac{t^2}{4\sigma^2(z)}\right) \mathrm{d}t \tag{5}$$

One of the techniques that can be employed to reduce the effect of Attenuation and Turbulence is Co-operative diversity. In this technique, virtual arrays are created for transmission and reception of the signal [11]. Relay-assisted communication technique can also be applied which receives a signal, passes it through an amplifier (optical) and finally this signal is passed down to the consecutive node [6].

2.3 Literature Survey on Existing Systems

In FSO communication technology high bit rate of laser beams are transmitted. Since light in a laser follows a straight line, anything obstructing its path would cause loss of signal [7]. Therefore, this becomes a limitation of this system. Obstruction caused by rain, haze, fog, temperature, pressure, etc. lower the range of such devices to only a few kilometers.

Some parameters have to be highlighted to optimize the model. The best priority order for various parameters is as illustrated in Fig. 1 [11]. Under hazy weather

Fig. 1 Priority order for FSO performance
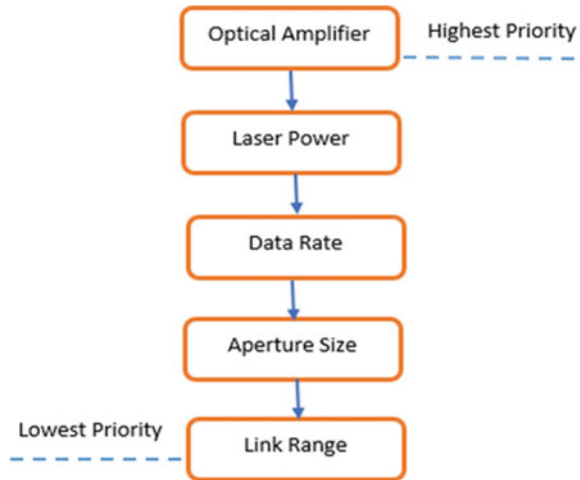
conditions (visibility > 2 km), 1550 nm and 785 nm light differ in their value of atmospheric attenuation, but in foggy weather, the laser light attenuation is not dependent on the wavelength. All the wavelengths get attenuated equally by fog. Mie scattering calculations results show this condition [12].

2.4 System Model

The system has been modeled with the optical simulator software "Optisystem-17". This software allows the users in order to plan, test, as well as simulate optical links in the optical networks.

In this model, the transmitter has a pseudo-random bit generator, a non-return-to-zero pulse generator, Mach–Zehnder modulator and continuous wave laser diodes. This generates wavelengths 750 nm and 1550 nm. In order to reduce the jitter timing by 40%, an avalanche photodiode (APD) and a low-pass Gaussian filter are used at the receiver [3]. The parameters as specified in Table 2 had been taken into account.

Figure 2 shows the modeling of two-channel FSO system without any amplifier. In Fig. 3, two optical amplifiers EDFAs have been enforced in two FSO channels. This allows the benefit of the constructive combination of the light power [3].

The gain of the amplifiers is 20 dB. In Fig. 4, a three-channel FSO having amplifiers has been represented. The parameters are kept same in all the models.

Table 2 FSO link parameters

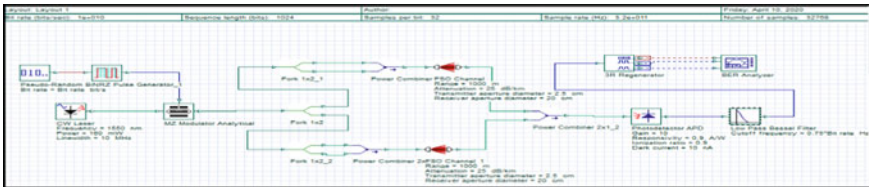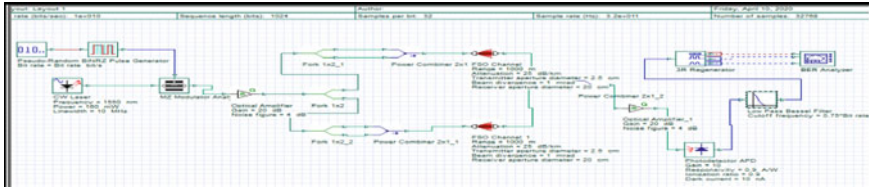| Channel configurations	Parameter
Dynamic Range	1000 m
Attenuation for dust storms	25 dB/km–200 dB/km
Diameter of the aperture of the receiver	20 cm
Diameter of the aperture of the transmitter	2.5 cm
Transmission power	160 mV
Wavelength	785 nm, 1550 nm
Beam divergence	1 mrad

Fig. 2 Two-channel FSO system

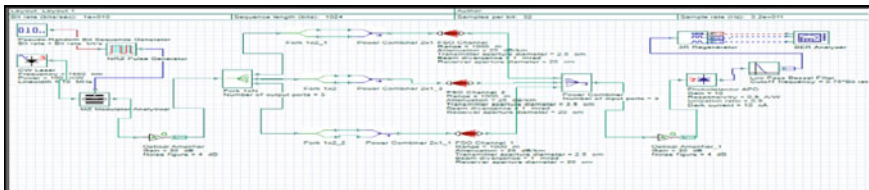**Fig. 3** Two-channel FSO system with amplifier

Fig. 4 Three-channel FSO system with amplifier

3 Results and Discussions

The parameters are set as per Table 2 and the following results for different wavelengths and different systems have been obtained.

Table 3 Q-factor and BER for various models-785 nm wavelength of laser beam

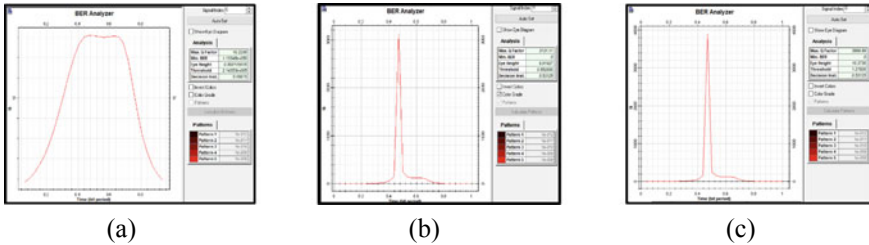| Model	Q-factor (max)	BER (min)
Two-channel without amplifier	16.22	1.13e−0.59
Two-channel with amplifier	3131.11	0
Three-channel with amplifier	3899.89	0

| (a) | (b) | (c) |

Fig. 5 **a** Two-channel-no amplifier; **b** Two channels with amplifier; **c** Three channels with amplifier

3.1   For 785 nm Wavelength Laser Beam

The Q-factor versus time graph of the systems after setting the wavelength as 785 nm has been shown. Table 3 shows the Q-factor (max) and BER (min) obtained.

Figure 5a shows the resultant BER curve two-channel FSO system without amplifier. The result was having a Q-factor (max) of 16.22 and the BER's minimum value as 1.133e−0.59.

For further improvement of the result, it was implemented with the addition of amplifiers. This upgraded the result, as evident in Fig. 5b. The maximum value of Q-factor is 3131.11 and the BER value is 0. It can be seen that performance has been improved for three-channel FSO (Fig. 5c). The result is having Q-factor 3899.89 (higher than the latter ones), and BER is 0 as desired.

3.2   For 1550 nm Wavelength Laser Beam

Table 4 shows the results that were obtained by different proposed systems by setting the wavelength to 1550 nm.

Table 4 Q-factor and BER for various models-1550 nm wavelength of laser beam

Model	Q-factor (max)	BER (min)
Two-channel without amplifier	17.74	6.102e−0.71
Two-channel with amplifier	1137.37	0
Three-channel with amplifier	1344.04	0

In Fig. 6a, the methodology of finding this BER Analyzer is similar to that which is done in Fig. 5a, but the wavelength is 1550 nm. The result in Fig. 6a can be seen to be as 17.74 as Q-factor along with a BER value of 6.102e−0.71.

In Fig. 6b, Q-factor of the two-channel FSO with amplifier model comes out to be 1137.37 and the BER is 0. Therefore, the Q-factor of a two-channel FSO with amplifier is more than that of without amplifier. Also, the Q-factor of two-channel FSO with amplifier model of 1550 nm is lesser as compared to that of 785 nm. As demonstrated in Fig. 6c, Q-factor is found to be 1344.04 and BER is 0. Thus, the three-channel FSO with amplifier model can be seen to give the better results.

In Table 5, the eye diagram of the two-channel and three-channel model with amplifiers in two conditions at wavelength of 1550 nm has been analyzed.

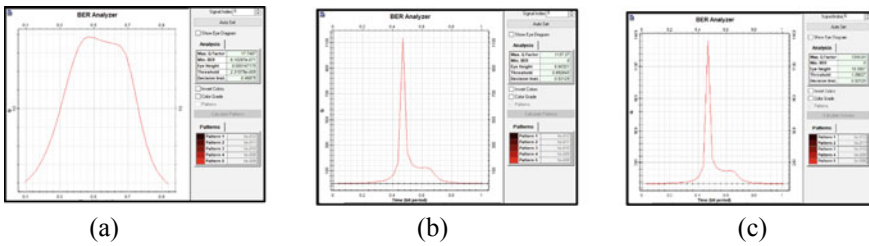Figure 7a demonstrates the eye diagram of a two-channel model when exposed to

Fig. 6 a Two-channel-no amplifier; b Two channels with amplifier; c Three channels with amplifier

Table 5 Q-factor and BER for various models-1550 nm wavelength of laser beam

Model	Q-factor (max)	BER (min)
Heavy dust 200 dB/km of two channels at 380 m	6.317	1.103e−0.10
Moderate dust 32 dB/km of two channels at 1.7 km	20.159	7.352e−0.91
Heavy dust 200 dB/km of three channels at 380 m	7.692	6.126e−0.15
Moderate dust 32 dB/km of three channels at 1.7 km	25.266	2.437e−141

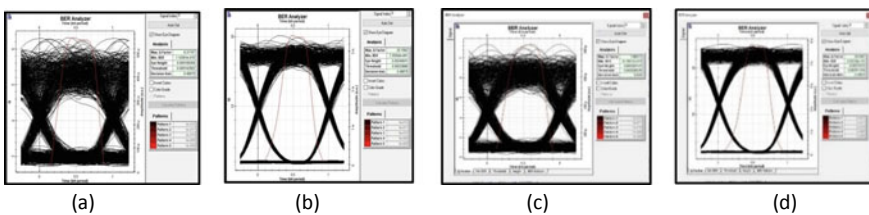**Fig. 7** **a** Eye diagram depicts Q-factor on heavy dust 200 dB/km of two channels and amplifier system at 380 m; **b** Eye diagram depicts Q-factor on moderate dust 32 dB/km of two channels and amplifier system at 1.7 km; **c** Eye diagram depicts Q-factor on heavy dust 200 dB/km of three channels and amplifier system at 380 m; **d** Eye diagram depicts Q-factor on moderate dust 32 dB/km of three channels and amplifier system at 1.7 km

heavy dust and high attenuation of 200 dB/km. The maximum Q-factor obtained in such a case is 6.317 and the minimum value of BER is found to be 1.103e−010. As per Fig. 7b, shows the eye diagram of a two-channel model in moderate dust. The maximum Q- factor obtained is 20.159 and the minimum BER is 7.352e−0.91.

After implementation Fig. 7d in three channels, the Q-factor (maximum value) is 25.266 and the minimum value of BER is 2.437e−141. As can be seen from Fig. 7a and c, the two-channel model has low Q-factor as compared to the three-channel model in similar situations. Same can be seen with Fig. 7b and d. The eye diagram also suggests that the model gives better results when the attenuation is less, as seen by comparing Fig. 7a with b and Fig. 7c with d. The three-channel system gives the optimum output as compared to any other proposed model. The Q-factor obtained when the wavelength is 1550 nm is lower than that obtained when the wavelength is 785 nm in all models. This is valid as the dynamic range is kept as 1000 m.

4 Conclusion

The FSO system has a Q-factor performance which varies over diverse climatic conditions. As per the results, the FSO links can be made more effective for increased attenuations with the help of several channels which have EDFA amplifiers. The Q-factor performance can be increased with the help of the growing quantity of transmitting links added to the influence of amplifiers. The higher the transmission links and amplifiers, the better is the performance amplifiers.

The idea of multiple channels and the power of amplifiers to increase Q-factor has been proposed in this paper for the same. Extending the idea may lead to even better results, directing to better FSO performance even in adverse climatic conditions.

References

1. Kumar P (2018) Free space optics—a review. Int J Res Appl Sci Eng Technol 6(2). https://doi.org/10.22214/ijraset.2018.2087
2. Mohammed NA, El-Wakeel AS, Aly MH (2012) Performance evaluation of FSO link under NRZ-RZ line codes, different weather conditions and receiver types in the presence of pointing errors. Open Electr Electron Eng J 6(1):28–35. https://doi.org/10.2174/1874129001206010028
3. Alnajjar SH, Noori AA, Moosa AA (2017) Enhancement of FSO communications links under complex environment. Photonic Sens 7(2):113–122. https://doi.org/10.1007/s13320-017-0336-1
4. Mikolajczyk J, Bielecki Z, Szabra D (2018) Free-space laser communications. Prz Elektrotechniczny 94(8). https://doi.org/10.15199/48.2018.08.11
5. Malik A, Singh P (2015) Free space optics: current applications and future challenges. Int J Opt 2015. https://doi.org/10.1155/2015/945483
6. Burdah S, Alamtaha R, Samijayani ON, Rahmatia S, Syahriar A (2019) Performance analysis of Q factor optical communication in free space optics and single mode fiber. Univ J Electr Electron Eng 6(3). https://doi.org/10.13189/ujeee.2019.060311

7. Mikołajczyk J et al (2017) Analysis of free-space optics development. Metrol Meas Syst 24(4). https://doi.org/10.1515/mms-2017-0060

8. Raja AR, Kagalwala QJ, Landolsi T, El-Tarhuni M (2007) Free-space optics channel characterization under UAE weather conditions. In: ICSPC 2007 Proceedings of 2007 IEEE International conference on signal processing and communication, pp 856–859. https://doi.org/10.1109/ICSPC.2007.4728454

9. Zhu X, Kahn JM (2002) Free-space optical communication through atmospheric turbulence channels. IEEE Trans Commun 50(8):1293–1300. https://doi.org/10.1109/TCOMM.2002.800829

10. Wang Z, Zhong W, Fu S, Lin C (2009) Performance comparison of different modulation formats over free-space optical (FSO) turbulence links with space diversity reception technique. IEEE Photonics J 1(6):277–285. https://doi.org/10.1109/JPHOT.2009.2039015

11. Karimi M, Nasiri-Kenari M (2011) Free space optical communications via optical amplify-and-forward relaying. J Lightwave Technol 29(2):242–248. https://doi.org/10.1109/JLT.2010.2102003

12. Bouhadda M, Abbou FM, Serhani M, Boutoulout A (2019) FSO communication capacity in turbulent and dispersive channel with AWGN noise. In: 2019 International conference on wireless technologies, embedded and intelligent systems (WITS 2019), pp 1–4. https://doi.org/10.1109/WITS.2019.8723853