Free space optical communication system in the presence of atmospheric losses

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Article Info	ABSTRACT
	Free space optical communication is gaining importance in the field of optical communication due to its high speed and high bandwidth applications. Free space optical communication system (FSOCS) provides many benefits as compared to traditional wireless communication system and fiber optic cables. This makes this technology the reasonable extension of metropolitan area network and also provides the quick recovery during natural disaster. This system performance is limited due to the atmospheric turbulence effect and various atmospheric losses such as rain, and fog. Gamma gamma atmospheric turbulent model is used to analyze the system performance in the presence of moderate to strong atmospheric turbulence. We have designed the FSO gamma gamma turbulent model with non-return to zero (NRZ) modulation format employing wavelength division multiplexing (WDM), spatial diversity multiple input multiple output (MIMO) (8×8) at various atmospheric turbulence levels and attenuation loss of 10 dB/km at the distance of 2-4 km. Using the proposed model, the link distance is enhanced up to 4km in the presence of turbulence and atmospheric losses with minimum laser transmitted power. *This is an open access article under the <u>CC BY-SA</u> license.*

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1. INTRODUCTION

Free space optical communication links provide high directivity, high power efficiency, easy installation and multi gigabyte applications. Wireless connection issues due to traditional methods are overcome by free space wireless optical communication links which deliver high quality signals, large bandwidth and high-speed data rate. These days free space optical (FSO) communication technology attracted lot of attention because of its several advantages over the traditional radio frequency (RF) based wireless communications [1].

FSO system uses light to transmit the signal in free space. There are various atmospheric turbulence distribution models like log normal, gamma gamma, malaga and K distribution [2]. Wireless signal transmission at the rate of 10 GHz and more affected by the atmospheric hydrometer particles. Rain is the major contributor for the fading of wireless signal [3]. Usage of massive multiple-input-multiple-output (MIMO) shows the signal improvement and minimum user interference [4]. Device to device communication is most promising technology in 5G networks [5].

5G network demands extremely high data rates in wireless backhaul over distances up to few kilometers. Link availability degradation due to fog can be minimized by using mid-IR (10.6 µm) signal [6]. To increase this distance, various techniques are used such as increasing the transmitter power, using multiple antennas and hybrid FSO/RF technology [7]–[9]. Though, optical fiber cables have tremendous advantages for

several years. Their performance was limited to the backhaul network [10]. Optical fibers are wired connections which require digging, and trenching. FSO is a wireless connection which doesn't require digging. It provides fast implementation during disaster recovery when other network fails [11]. The connection between the access networks and the end – user was not benefited from the optical fiber cables.

Performance of FSO system is degraded in unfavorable atmospheric weather conditions such as fog, snow, and rain. This reduces the capacity of FSO channel. Optical wireless mesh network which uses terrestrial links composed of several parallel full duplex FSO links [12]. Fog causes attenuation up to hundreds of decibels per kilometer. In the presence of fog FSO channel typically used for short range communication, therefore FSO has its future in wireless 5G/6G networks having cell sizes less than a kilometer [13], [14]. Charge coupled device (CCD) camera and laser diode at 0.55 µm can be used for the FSO link when the visibility reduces below 50m due to fog [15]. 5G network demands extremely high data rates in wireless backhaul over distances up to few kilometers. Link availability degradation due to fog can be minimized by using mid-IR (10.6 µm) signal [16]. Hybrid RF/FSO link can solve the system degradation due to dense fog and pointing errors [17]–[19]. Array of receivers could provide the better solution to the challenges due to atmospheric effects [20]. The SISO and MIMO analysis of FSO system is carried out in. MIMO shows the better performance in presence of strong atmospheric turbulence [21]. Coherent OFDM techniques are used for the link to improve the system performance of the system [22]. Hybrid MMW RF and FSO could be used for the future technologies [23]. Atmospheric scattering does not hamper short range FSO but aperture averaging can be used for FSO in atmospheric turbulence regime [24]. Carrier suppressed return to zero format can be used for the better performance of the system [25]. Visible light communication is emerging as one of the emerging technologies of optical wireless communication. Non-return to zero (NRZ) on-off-keying (OOK) and 4 Quadrature 02 (QAM) orthogonal frequency division multiplexing (OFDM) modulation techniques are used for visible light communication [26], [27].

FSO communication system provides the alternative solution to last mile access problem with the same bandwidth and speed provided by the optical fiber cables. But, FSO performance is limited due to various atmospheric challenges. In this paper, the methodology is discussed to mitigate the losses occurred by the atmospheric turbulence and attenuation due to environmental factors.The effect of atmospheric turbulence is reduced by using multiple transmitters and receivers with wavelength division multiplexing technique. In this paper, we discussed the effects of atmospheric losses such as turbulence induced fading on the performance of FSO communication system using gamma gamma distribution. Using wavelength division multiplexing (WDM), MIMO, various modulation techniques and receivers improve the performance of system. Various modulation techniques like RZ and NRZ are used to evaluate the system performance. Simulation is carried out using MATLAB 21 and optisystem 19 tool.

2. METHODS

The atmospheric turbulence and fog are major delimiting factors of FSO system. The channel capacity of FSO communication link is evaluated using gamma gamma turbulence model for weak to strong atmospheric turbulence. Capacity equation is derived for the turbulence levels in the atmosphere shown in section 2.1. The channel is determined for the other atmospheric losses such as rain, haze, and fog. The transmitter section consists of RZ/NRZ modulation formats with WDM. The WDM output is given to 4×4 and 8×8 MIMO channel. The received signal is demultiplexed and combined using power combiner shown in section 2.2.

2.1. FSO channel capacity evaluation using gamma gamma turbulent channel

The probability density function for moderate to strong atmospheric turbulence is modelled by gamma gamma distribution and is given by:

$$p_I(I) = \frac{2(ab)^{(a+b)/2}}{\Gamma(a)\Gamma(b)} I^{(a+b)/2-1} K_{a-b}\left(2\sqrt{abI}\right) \tag{1}$$

where $K_v(.)$ is modified Bessel function, $\Gamma(.)$ is the gamma function, a and b parameters are dependent on the atmospheric turbulence:

$$a = \left[\exp\left(\frac{0.49\delta^2}{\left(1+0.18d^2+0.56\delta^{12/5}\right)^{7/6}}\right) - 1\right]^{-1} \tag{2}$$

and,

$$b = \left[\exp\left(\frac{0.51\delta^2}{\left(1+0.9d^2+0.62d^2\delta^{12/5}\right)^{5/6}}\right) - 1\right]^{-1} \tag{3}$$

in (4), δ^2 is known as Rytov variance which is expressed as:

$$\delta^2 = 1.23 C_n^2 k^{7/6} L^{11/6} \tag{4}$$

where C_n^2 is the strength of the atmospheric turbulence, which depends on height from the ground level and wind speed.

$$C_n^2(h) = 0.00594 \left(\frac{v}{27}\right)^2 (10^{-5}h)^{10} \exp\left(-\frac{h}{1000}\right) 2.7 \times 10^{-16} \exp\left(-\frac{h}{1500}\right) + A \exp\left(-\frac{h}{100}\right) \tag{5}$$

Where h is altitude in meters, v is wind speed measured in meters per second and $A=C_n^2(0)$ gives the value of C_n^2 at ground level. The parameters A and v are assumed to be taken as 1.7×10^{-14} and 21 m/s respectively. C_n^2 is varies from $10^{-17} m^{-2/3}$ to 10^{-13} $m^{-2/3}$.

In (3), d is given as $= \sqrt{kD^2/4L}$, where k is the optical wave number given as $k = 2\pi/\lambda$, L is the distance between the transmitter and receiver, λ is the operational wavelength and D is aperture diameter of the receiver. The Average channel capacity is given by (6):

$$\langle C \rangle = \int_0^\infty B \, log_2^{(1+\gamma)} P_\gamma(\gamma) \tag{6}$$

the probability density function of gamma gamma turbulent model is expressed as (7):

$$p_\gamma(\gamma) = \frac{(ab)^{(a+b)/2}}{\Gamma(a)\Gamma(b)} \frac{\gamma^{(a+b)/4-1}}{\Gamma^{(a+b)/4}} K_{a-b}\left(2\sqrt{ab\sqrt{\frac{\gamma}{\Gamma}}}\right) \tag{7}$$

the average capacity of FSO gamma gamma turbulence is obtained by substituting (7) in (1) which is expressed by (8):

$$\langle C \rangle = \frac{B\left(\frac{ab}{\sqrt{\Gamma}}\right)^{(a+b)/2}}{\Gamma(a)\Gamma(b)\ln(2)} \times \int_0^\infty \ln(1+\gamma)\gamma^{(a+b)/4-1} K_{a-b}\left(2\sqrt{ab\sqrt{\frac{\gamma}{\Gamma}}}\right) d\gamma \tag{8}$$

the above equation indicates the average channel capacity of FSO communication system in the presence of moderate to strong atmospheric turbulence.

2.2. Design of FSO system using WDM and MIMO technology

FSO system requires line of sight communication, transmitter and receiver system to be aligned on the same axis. We have designed Spatial diversity MIMO system under moderate to strong atmospheric turbulent condition. The design of FSO layout of the link simulation is illustrated in Figure 1. Transmitter section consists of pseudo random bit sequence (PRBS) Generator which generates the data to be sent over the optical channel. Continuous Wave laser is used which generates the signal at 1550 nm with transmitter power as 20 dbm. WDM multiplexer used at the transmitter sector.

FSO system in Figure 2 design is the system which uses WDM concept to improve the performance of the system in the presence of turbulent atmosphere and losses. In this single input and single output configuration, continuous wave laser with the transmitter power of 30 dBm is used. As the transmitter power is reduced the effect of atmospheric turbulence is more.

Proposed FSO system in Figure 3 makes use of spatial diversity MIMO technology. This technology offers the advantages as compared to single-input and single-output (SISO) which is shown in Figure 2. This design is suitable when there is strong atmospheric turbulence during the windy day. This design gives better performance when there are other atmospheric losses such as rain, fog, haze, and snow. FSO channel is considered with 10 dB attenuation due to various atmospheric losses such as atmospheric turbulence, rain, fog, and haze. WDM Mux and optical amplifier is used at the transmitter section. FSO 8x8 channels are used to transmit the optical signal. At the receiver section power combiner is used to combine the received signal. WDM demultiplexer used to demultiplex the signal received. Avalanche photodiode (APD) is used to recover the data from the received optical signal. The FSO link system is analyzed for RZ, NRZ modulation formats at various level of laser power, APD and PIN photodiodes. Optical amplifier with 20 dB gain is considered to reduce the effect of various atmospheric losses.
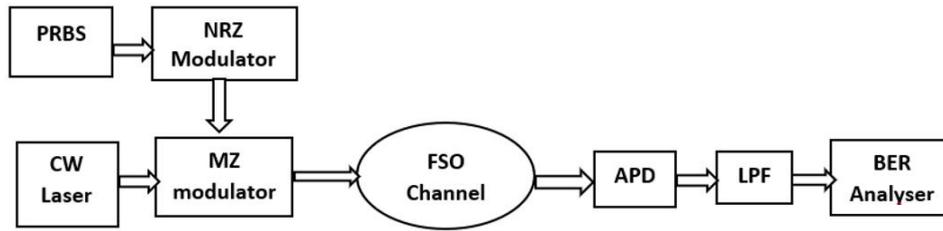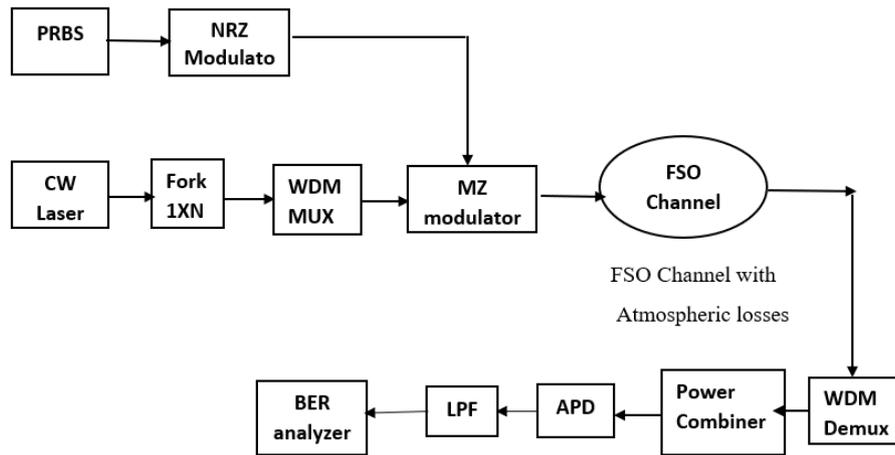
Figure 1. FSO link using NRZ modulator

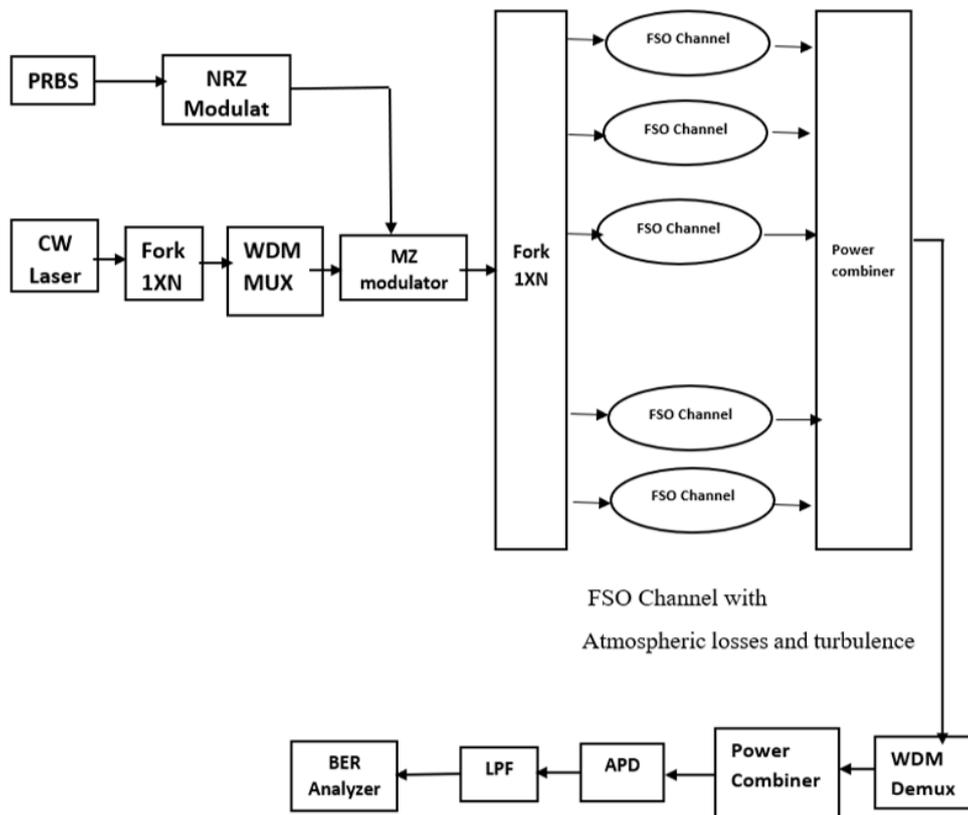Figure 2. FSO system with WDM and SISO

Figure 3. Proposed FSO link with WDM MIMO in strong atmospheric turbulence and atmospheric losses

3. RESULTS AND DISCUSSION

FSO link is designed to analyze the effects of atmospheric losses and improve the performance using WDM and multiple laser beam techniques. RZ and NRZ both the formats are used to analyze the FSO link. It shows that NRZ modulation scheme performs better as compared to RZ modulation. At the receiver section, either of APD or PIN photodiode is used to convert optical signal to its electrical version. It shows from the results that, APD photodiode performs better as compared to PIN photodiode in terms of bit error rate (BER) and quality factor. The system is evaluated for single channel, multiple channels, with or without optical amplifier, RZ, NRZ format, various levels of transmitter power, different atmospheric turbulence levels and link distance. It is observed that, as the link distance increases the system performance degrades therefore optical amplifiers are efficient to restore the performance of the FSO link. 10 dB atmospheric loss is considered due to rain, dust, and fog. Gamma gamma turbulent channel is considered for moderate to strong atmospheric turbulence.

Figure 4 shows the result of SISO FSO system with link distance 2 km, 30 dbm transmitted power using NRZ modulation technique. The maximum Q factor achieved for this configuration is 8.80584 and BER of 6.244×10^{-19}. Continuous wave laser with the transmitted power of 20 dBm and RZ pulse generator is used for the system. Avalanche photo diode with 3R generator is used at the receiver end to recover the information signal. In this configuration, no multibeam in transmitted signal channel FSO link is used. Here, this system does not function well with the higher levels atmospheric turbulence, the channel performance degrades significantly. As compared to RZ modulated signal at the transmitter section, NRZ modulation performs better in terms of bit error rate generated at the receiver end. The maximum Q factor achieved in this configuration is 9.73378 and minimum bit error received is 8.5360×10^{-23}. Avalanche photodiode is used at the receiver section.
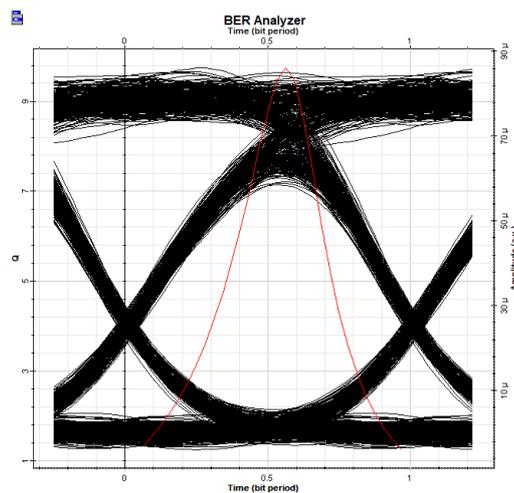

Figure 4. Single beam FSO system with a link distance of 2km using NRZ modulation

In the configuration shown in Figure 5, continuous wave laser of 30dBm is used at the transmitter end and APD photodiode is used at the receiver end. The channel is affected by strong atmospheric turbulence. The maximum Q factor achieved for this configuration is 3.89343 and minimum bit error rate is 4.9267×10^{-5}. The use of avalanche photodiode at the receiver section performs better in terms of quality factor and minimum bit error rate as compared to PIN photodiode.

With the use amplifier in multi beam FSO, the performance of the system is further improved. Figure 6 shows spatial diversity WDM MIMO with the use of optical amplifier. The minimum bit error rate achieved is 6.1341×10^{-185}. The maximum quality factor is 28.972. This is achieved using optical amplifier. The BER rate achieved using MIMO with optical amplifier is improved as compared to single beam FSO. Achievable link distance in the presence of turbulence and atmospheric losses is 4 km. Table 1 shows the results obtained for various atmospheric turbulence levels and attenuation loss of 10 dB. Gamma gamma atmospheric turbulent model is used to analyze the results

Figure 7 shows plot of min logarithm of BER Vs transmitted laser power. As the laser power is increased the minimum BER rate decreases. Therefore, when there is higher attenuation due to atmospheric losses such as turbulence, rain, and fog. Usually, the transmitter power is increased. The optimal laser power required is 20-30 dBm.
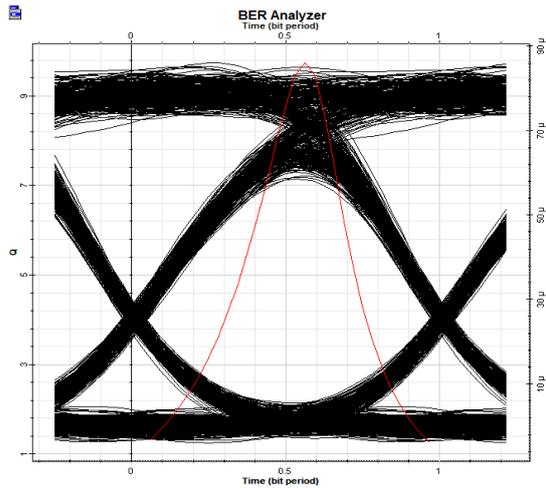
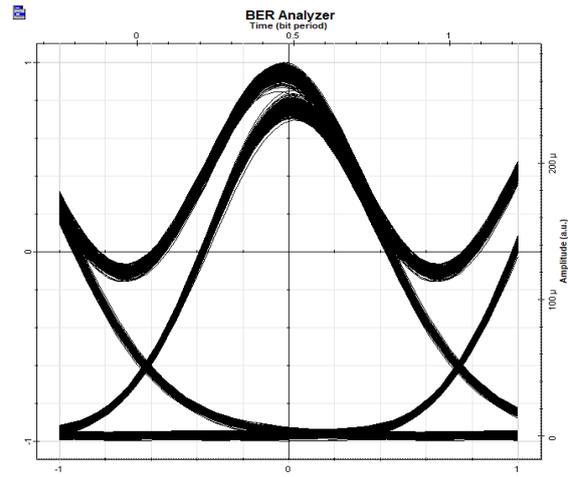Figure 5. FSO link with avalanche Photodiode at the receiver

Figure 6. Spatial diversity WDM MIMO with optical amplifier

Table 1. FSO performance in the presence of atmospheric turbulence

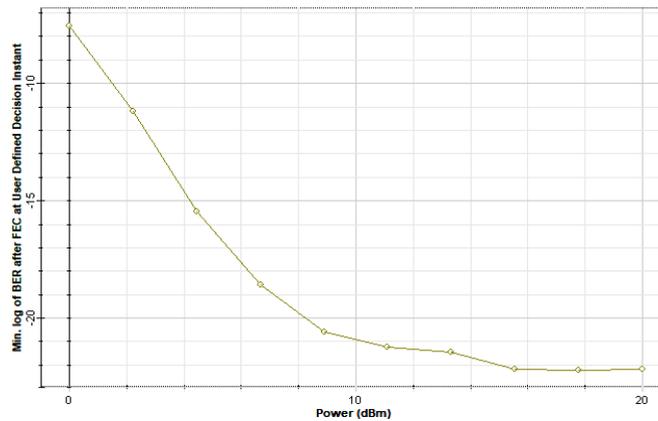| Atmospheric turbulence (in m-2/3)	Max. Q factor	Min BER	Eye height
8e-14	10.855	1.0156e-027	2.3158e-006
9e-15	15.742	1.8846e-056	4.6717e006
3e-15	17.2959	2.4665e-067	5.3416e-006

Figure 7. BER Vs continuous wave (CW) laser transmitter power variation

Table 2 shows the comparison between the proposed work and the previous work [19]. For the link distance of 1 km, the obtained Q factor is more efficient as compared to the previous work proposed. The previous work has considered only the atmospheric losses and neglected the atmospheric turbulence. The proposed design works better in the presence of both atmospheric turbulence and losses. Table 3 shows the results of proposed work in the presence of atmospheric turbulence of 6e-15 $m^{-2/3}$ and losses. As the proposed work gives better performance the link distance can be improved till 4 km.

Table 2. Comparison of proposed work and previous work [19]

Parameter	Attenuation dB/km	Work done by [19] Q– factor 4×4 MIMO	Proposed design (Q–factor 4×4 MIMO)	Proposed method (8×8 MIMO)
Clear air	0.44	67.965	278.56	280.657
Rain	4.6	32.4903	259.468	279.34
Fog	6.8	22.104	252.425	269.377
Haze	8.8	15.051	243.529	253.287

Table 3. Q factor obtained for proposed system in the presence of atmospheric turbulence and losses

Parameter	Proposed design Q factor (4×4 WDM MIMO with atmospheric turbulence)
Clear air	26.032
Rain	26.4391
Fog	27.1179
Haze	28.01

4.   CONCLUSION

Free space optical communication is emerging as an alternative wireless technology which provides high data rate, bandwidth and high-speed communication. In this paper, FSO performance is analyzed in the presence of moderate to strong turbulent atmosphere and 10 dB attenuation loss due to rain, fog and dust. The performance of the system is improved when WDM with multi beam laser is implemented. FSO performance is evaluated for various levels of transmitter power, RZ-NRZ formats, avalanche and PIN photodiode. It shows from the obtained results that using 20 dBm Laser power, NRZ format, WDM MIMO and avalanche photodiode the communication distance length is increased to 4km in the atmospheric attenuation of 10 dB/km and strong atmospheric turbulence.

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