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Performance Analysis of 25 Gbps DP-QPSK Based CO-OFDM-FSO Link Incorporating Spatial Diversity under Climate Conditions and Atmospheric Turbulence

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Abstract—Attenuation caused by various weather conditions and atmospheric turbulence significantly reduces the performance and reliability of free space optics (FSO) link. This paper employs simulations to analyze the signal quality of the proposed FSO link under various climate conditions. The performance analysis and parametric evaluation of the proposed 25 Gbps DP-QPSK based CO-OFDM FSO link is carried out with and without the spatial diversity technique. Also, we have compared the proposed FSO link with the 16-QAM-based OFDM FSO link for vivid atmospheric conditions. The simulation results are analyzed in terms of key performance metrics such as bit error rate (BER), signal-to-noise ratio (SNR), link distance, received power, and reliability. The results show that the FSO link with spatial diversity is more effective towards mitigating the adverse effects of atmospheric attenuation and turbulence in comparison with FSO link without diversity and 16-QAM OFDM-based FSO link. In total, this results in lower BER, higher SNR, improved received power, and increased reliable distance for practical FSO communication system.

1. INTRODUCTION

Free space optics (FSO) communication system is a well-known wireless communication system that has seen significant growth and interest over the past ten years. Due to its enormous bandwidth, low bit error rate, license-free operation, and simple implementation, FSO is becoming more and more important in both the commercial and scientific communities. These characteristics of FSO communications are particularly appealing for uses such as free web browsing, e-commerce, data library access, business networking, work-sharing capabilities, real-time medical imaging transfer, and high-speed interplanetary connectivity [1]. However, the FSO communication link's quality of service is strongly influenced by weather conditions like haze, fog, smoke, rain, and thermal gradient. Scattering and turbulence, two well-known weather phenomena, degrade the transmitted signal in the FSO link, resulting in a high bit error rate or signal loss at the receiving end [2].

Researchers have recently proposed and investigated a variety of methods, including advanced modulation techniques, aperture averaging, spatial diversity, Orthogonal Frequency Division Multiplexing (OFDM), hybridizing FSO with radio frequency (RF) link, and forward error correction (FEC), to mitigate the negative impacts of atmospheric effects in FSO links. A study in [3], investigates the performance assessment of a 6.24 Gb/s spectrum slicing-wavelength division multiplexing (WDM)-FSO link under diverse climatic situations. A hybrid Polarization Division Multiplexing (PDM)-Coherent OFDM-based FSO system is analyzed, and the study reveals that data transmission with a distance ranging from 0.1 km to 15 km is achievable [4]. Differential phase shift keying (DPSK)-based

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FSO links using 10 Gbps-WDM was modeled and simulated under a variety of weather phenomena [5]. Under heavy fog conditions, this system successfully achieved the maximum link range of 0.5 km at 85 dB/km attenuation. A high-speed mode division multiplexing (MDM) based FSO links with non-return-to-zero (NRZ) scheme is evaluated in a variety of atmospheric weather scenarios for the 200 m to 2500 m range [6]. A simulation of a 4-QAM OFDM-based FSO system that successfully transmits 10 Gbps data across an 1800 m transmission distance is discussed in [7]. The influence of various atmospheric conditions on a 10 Gbps–10 GHz 4-QAM OFDM-RoFSO transmission link is investigated in [8]. The results show that the maximum link range is limited whenever the weather changes from haze to dry snow, dropping from 4000 m to 325 m. However, in the proposed Dual Polarization (DP) Quadrature Phase Shift Keying (QPSK) based Coherent OFDM FSO link with the spatial diversity system successfully mitigates the effect of fog attenuation and turbulence for a link range of 0.16 km to 71 km at a 25 Gbps data rate and with considerably low transmitted power. The designed system significantly improves the link availability even under harsh weather conditions like fog, rain, haze, and thermal gradient.

The paper is organized as follows. In Section 2, mathematical modeling of the atmospheric channel is presented. Section 3 represents a simulation setup of the proposed FSO communication system in Optisystem 19. Section 4 shows the experimental results and analysis. Section 5 represents a comparative analysis of the proposed FSO link results with the literature. The conclusions and future works are discussed in the final Section.

2. ATMOSPHERIC CHANNEL CHARACTERISTICS

Atmospheric channel characteristics play a crucial role in the performance of FSO communication systems. Some of the key atmospheric channel characteristics that affect FSO include scintillation, attenuation, multipath interference, angle of arrival fluctuations, and atmospheric absorption. Because of various climatic factors including rain, haze, fog, and thermal gradient, the medium characteristics between the transmitter and receiver fluctuate over time and reduce system performance.

2.1. Fog/Haze Weather Condition

Fog is a well-known weather phenomenon defined as a cloud of either water or smoke particles that affects vision and induces attenuation, which reduces the quality of the signal received. When a quantity of microscopic water droplets suspended in the atmosphere rises, the attenuation of fog also increases, resulting in a denser fog. Fog attenuation, Υ_a, in dB/km that depends on visibility range, V, in km, can be expressed as [6].

$$\Upsilon_a = \frac{17}{V}\left(\frac{\lambda}{550\,\text{nm}}\right)^{-p} \tag{1}$$

Because the solar spectrum's peak intensity is at 550 nm, this wavelength is used as the reference wavelength. λ is the operating wavelength in (nm), and p is the size distribution of the scattering particles that can be calculated according to Kim's model [9].

$$p = \begin{cases} 1.6, & V > 50 \\ 1.3, & 6 < V < 50 \\ 0.16V + 0.34, & 1 < V < 6 \\ V - 0.5, & 0.5 < V < 1 \\ 0, & V < 0.5 \end{cases} \tag{2}$$

Similarly, the values of p for the Kruse model are given as [8],

$$p = \begin{cases} 1.6, & for, \quad V > 50 \\ 1.3, & for, \quad 6 < V < 50 \\ 0.5858V^{\frac{1}{3}} & for, \quad V < 6 \end{cases} \tag{3}$$

Aerosols and air molecules, which scatter signals, cause losses even in conditions of clear air and adequate vision.

2.2. Rain Attenuation

One of the causes of attenuation in an FSO system is rain. Because an optical signal's wavelength is much shorter than a raindrop, rain has a lower impact than fog [10]. Rain affects optical signal intensity through a scattering effect. A linear relationship between specific attenuation and rain rate is given by [8].

$$\beta_{rain} = 1.076\, R^{0.67} \tag{4}$$

where R (mm/hr) represents rainfall rate. The following equation can be applied to approximate the attenuation due to rain in FSO links,

$$\Upsilon_{rain} = \frac{2.8}{V} \tag{5}$$

where V denotes the visibility in km, and its value depending upon the rainfall rate is presented in Table 1 [8, 10].

Table 1. Visibility ranges depending on rainfall rates.

Type of rainfall	Rainfall rate (mm/hr)	Visibility (km)
Light rain	0.25	18–20
Moderate rain	12.5	2.8–40
Heavy rain	25	1.9–2

Specific attenuation for various atmospheric conditions can be computed using visibility by Equations (1) & (5) as shown in Table 2 [4, 9]. The Kruse model has limitations in accurately estimating specific attenuation under low visibility conditions, whereas the Kim model offers alternative values for the size distribution parameter p in such situations, resulting in more accurate predictions.

Table 2. Specific attenuation for various weather conditions.

Climate type	Visibility (km)	Kim model: Specific attenuation (dB/km)	Kruse model: Specific attenuation (dB/km)
Clear	32	0.14	0.14
Low haze	3.40	2	2.01
Mild haze	2.10	4	3.73
Heavy haze	1.01	10	9.15
Light rain	1.49	6.27	5.71
Medium rain	1.04	9.64	8.83
Heavy rain	0.71	19.28	13.93
Light fog	0.50	34	20.97
Moderate fog	0.20	85	59.47
Dense fog	0.05	340	271.21

2.3. Atmospheric Turbulence Model

An optical beam may encounter distortions and fluctuations in intensity, phase, and direction due to atmospheric turbulence, which is brought on by random variations in the atmosphere's refractive index. This phenomenon is known as scintillation and can cause fading and fluctuations in the received signal strength [11]. The turbulence in the atmosphere has been studied by researchers, and several channel models have been put forth. The major models are (1) log normal model (weak turbulence) (2) Gamma-Gamma (weak to strong turbulence) (3) Negative exponential model (strong turbulence). This work considers the log-normal model for weak turbulence and the gamma-gamma model for moderate and strong turbulence. The optical irradiance I is calculated by the log-normal distribution channel model as follows:

$$I = e^X \tag{6}$$

where X-Gaussian random variable has mean μ and variance σ^2. The receiving irradiance fluctuation's probability density function (PDF) is given as [12].

$$p(I) = \frac{1}{\sqrt{2\pi}}\frac{1}{\sigma I}\exp\left\{\frac{-(\ln I + \mu)^2}{2\sigma^2}\right\} \tag{7}$$

where the normalized channel effect causes the I signal intensity to assume a mean of 1 [13]. The PDF of the intensity fluctuation for gamma-gamma is given as follows.

$$p(I) = \frac{2(\alpha\beta)^{\frac{(\alpha+\beta)}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I^{\left(\left(\frac{\alpha+\beta}{2}\right)-1\right)} k_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \tag{8}$$

where $\Gamma(.)$ is the Gamma function, $k_{\alpha-\beta}$ a second order Bessel function, I the irradiance. α is the number of large eddies and β the number of small eddies, and they are given as [14],

$$\alpha = \left[\exp\left(\frac{0.49\sigma_R^2}{\left(1+1.11\sigma_R^{\frac{12}{5}}\right)^{\frac{7}{6}}}\right)-1\right]^{-1} \tag{9}$$

$$\beta = \left[\exp\left(\frac{0.51\sigma_R^2}{\left(1+1.11\sigma_R^{\frac{12}{5}}\right)^{\frac{5}{6}}}\right)-1\right]^{-1} \tag{10}$$

Assuming plane wave propagation, the Rytov variance parameter σ_R^2 is given by,

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

In above equation, $k = \frac{2\pi}{\lambda}$ is the optical wave number, L the link length, and C_n^2 $(m^{-\frac{2}{3}})$ the altitude dependent index of the refractive structural parameter dictating the turbulence strength. According to the degree of atmospheric turbulence, C_n^2 typically ranges from 10^{-17} to 10^{-12} $(m^{-\frac{2}{3}})$. To simplify the procedure, the measure of turbulence strength known as σ_R^2 is utilized. It combines the parameters C_n^2, wavelength λ, and distance L [15]. The σ_R^2 is crucial in characterizing the scintillation effect caused by atmospheric turbulence on FSO link. C_n^2 determines the σ_R^2 value, which reflects the level of signal degradation and fluctuations. Higher C_n^2 values lead to a stronger scintillation effect, higher σ_R^2, and reduced link performance, while lower values lead to weaker scintillation, lower σ_R^2, and improved link performance. Careful design and optimization of FSO systems are essential to account for the impact of the C_n^2 on the σ_R^2 under varying atmospheric conditions.

3. SIMULATION SETUP

Several techniques have been studied in order to simulate an FSO communication link under actual circumstances. It has been decided to use OptiSystem 19 from Optiwave Systems Inc. for this project after assessing the viability of various simulation systems. Systems are designed with building blocks that are connected with each other. In addition to providing a variety of modulation methods, the OptiSystem building block libraries also allow to simulate the propagation of a laser beam through space. Table 3 illustrates the FSO link design parameters.

Table 3. Design parameter of proposed FSO system.

Sr. No.	Parameter	Value
1.	Operating wavelength, λ	1550 nm
2.	Data rate	25 Gbps
3.	Symbol rate	6.25 Gbps
4.	Laser input power	4 dBm
5.	Laser line width	0.1 MHz
6.	Beam Divergence	0.25 mrad
7.	Transmitter aperture diameter	5 cm
8.	Receiver aperture diameter	10 cm
9.	Range	0.16 to 71 km
10.	Specific attenuation	0.14 to 340 dB/km
11.	Addition loss	1 dB
12.	Geometric loss	Considered
13.	Responsivity	1 A/W
14.	Dark current	10 nA
15.	Ionization ratio of photo detector	0.9
16.	Sequence length	20480
17.	OFDM-max possible sub-carriers	128
18.	OFDM-No. of sub-carriers per port	80
19.	OFDM-number of training symbols	10
20.	OFDM-PAPR range	6.76 to 7.62 dB
21.	Optical amplifier gain, G	20
22.	Modulation	QPSK

The proposed FSO system has been simulated using these simulation parameters over a range of climatic conditions and turbulence regimes. The schematic diagram of Dual Polarization-QPSK Coherent OFDM FSO link with spatial diversity is shown in Figure 1. The FSO system model has three sections, mainly transmitter, FSO channel, and receiver. The transmitter section consists of an RF to optical converter, continuous wave (CW) laser diode, polarization beam splitter, phase shift keying (PSK) sequence generator, and OFDM modulator. The mapping of serial data from the BER test set is done by PSK sequence generator. A serial to parallel converter is integrated inside the OFDM modulator to generate parallel data from serial data streams. In OFDM, the carriers are made to be orthogonal to one another via the inverse fast fourier transform (IFFT). To minimize inter-symbol interference, guard interval is used. However, an OFDM has a drawback of high peak to average power ratio (PAPR), which can lead to nonlinear distortion and degrade system performance. Our analysis revealed that the PAPR values of the OFDM signals ranged from 6.76 dB to 7.62 dB. Importantly, these values are within an acceptable limit that is below 10 dB. The laser power is separated into two polarized signals, X polarized and Y polarized, using the polarization beam splitter. Two dual port Mach-Zehnder modulators (MZMs), electrical gain, electrical bias, a cross-coupler, and a phase shifter constitute the RF to optical converter block. The MZM modulator is set off at its null point for operation. The signals are combined by using a polarization beam combiner, which are then transmitted through four beam FSO link using spatial diversity technique.

Spatial diversity utilizes multiple independent optical paths to transmit multiple data streams simultaneously, achieved by splitting the beam into multiple beams using power or beam splitters. Spatial combining techniques at the receiver combine the streams to improve signal quality. In FSO links, the diversity gain against atmospheric turbulence increases with the number of optical paths used,

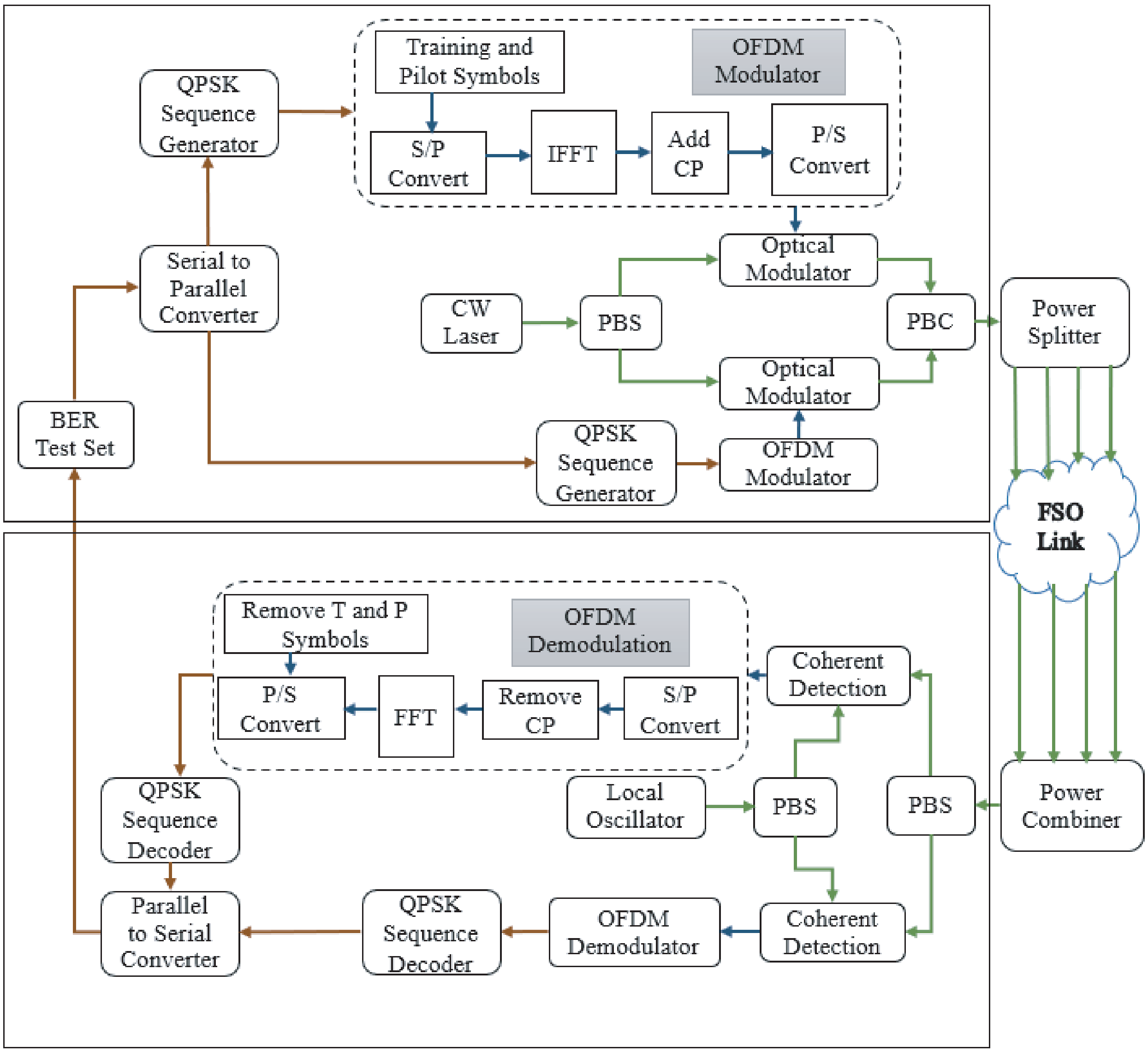


Figure 1. Schematic diagram of DP-QPSK CO-OFDM FSO system incorporating spatial diversity.

with 2×2, 4×4, and 8×8 order spatial diversity systems providing varying levels of performance at the cost of increased complexity and resources. This paper focuses on a 4×4 order spatial diversity system that balances performance, complexity, and suggests that the selection of spatial diversity order should consider specific requirements such as distance, data rate, and atmospheric conditions.

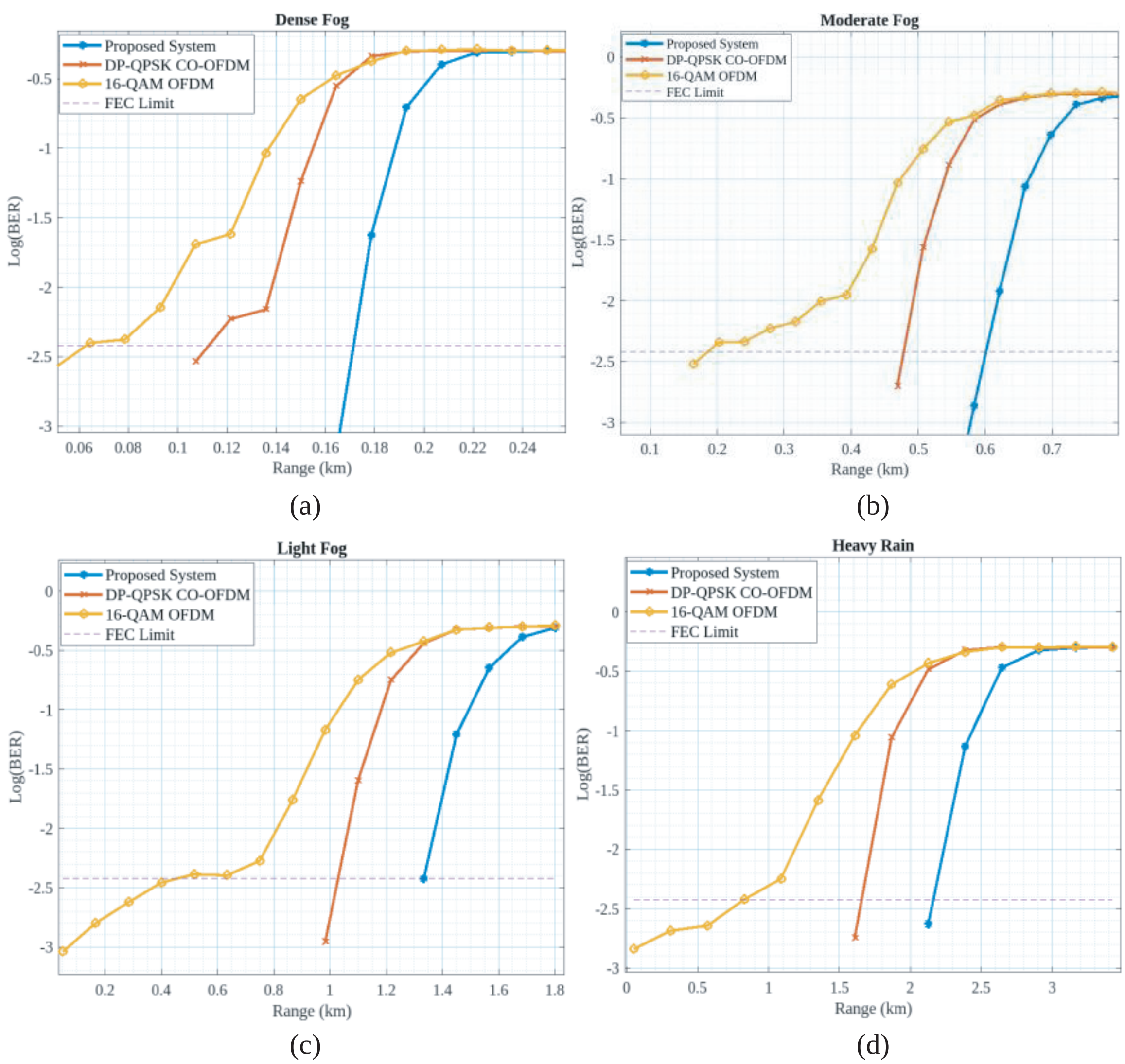
The received signal is processed in the receiver section using an optical Gaussian filter with a 25 GHz bandwidth. The polarization beam splitter splits the received signal into two orthogonal polarization states. A dual-polarization optical coherent PSK receiver is used to retrieve the signal. Based on a homodyne receiver design, it uses balanced photodetectors, electrical amplifiers, and a local oscillator. A CW laser source with the same specifications as the transmission laser serves as the oscillator. High signal-to-noise ratio (SNR), laser noise cancellation, and signal variation detection are all possible with balanced photodetectors. An OFDM demodulator is employed to recover the data, then a coherent sequence decoder. The PSK decoder then completes the demodulation of the signal. The simulation results are obtained by an electrical carrier analyzer, WDM analyzer, BER test set, and Optical Spectrum Analyzer.

4. RESULT AND DISCUSSION

The performance and capabilities of the proposed DP-QPSK based CO-OFDM FSO link with spatial diversity, DP-QPSK based CO-OFDM FSO link without spatial diversity, and 16-QAM-OFDM FSO link have been compared. BER as function of link distance, SNR and received power have been considered as comparison parameter under different weather conditions (as given in Table 2) at 25 Gbps data rate and 4 dBm transmitted power. It is perceived that the increase in BER is due to the increased transmission distance as well as the attenuation factor. This is due to the optical signal's fading and power loss resulting from atmospheric attenuation and turbulence, which deteriorate the link's reliability as the link's length increases. The analysis of simulation results has been done to consider the maximum distance and required SNR to achieve a faithful log (BER) of −2.42 (i.e., FEC Limit [4]).

4.1. Performance Analysis under Climate Conditions

FSO link can achieve up to 0.17 km range in the dense fog condition with the proposed system (DP-QPSK based CO-OFDM with spatial diversity) with a −2.42 log (BER) value as shown in Fig. 2(a). A 0.11 km communication distance can be achieved by DP-QPSK based CO-OFDM without spatial diversity FSO link, and 16-QAM OFDM-based FSO system can achieve a reliable distance up to 0.07 km at the same obtained BER. Fig. 2(b) compares the BER value obtained during moderate fog with and



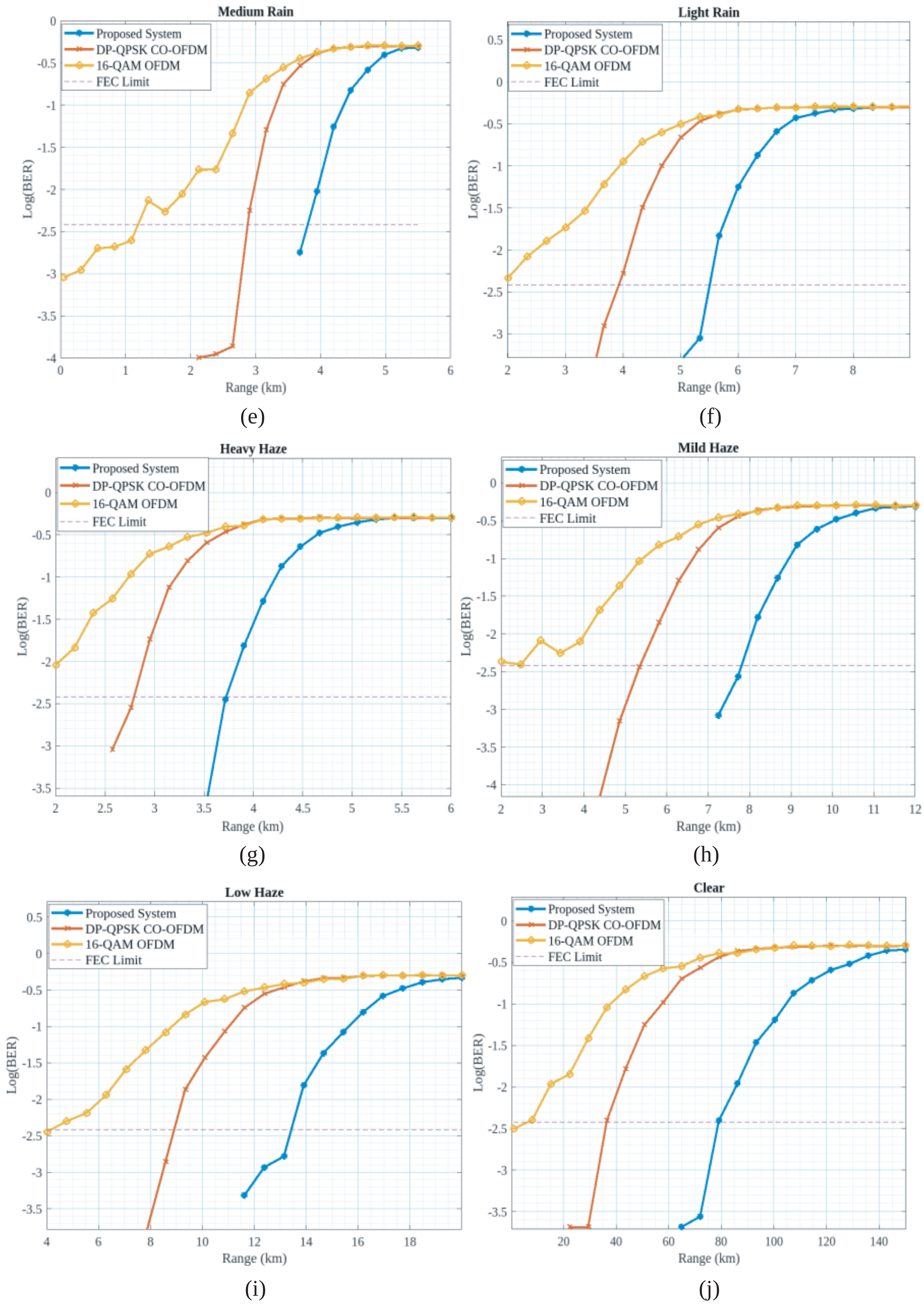


Figure 2. BER in terms of FSO link range for various climate conditions.

without spatial diversity. It is noticed that with the spatial diversity technique, the log (BER) achieved is −2.42 for the distance of 0.6 km. In the case without spatial diversity, the same log (BER) value is obtained at a link length of 0.48 km. It is noted that DP-QPSK based CO-OFDM with a spatial diversity system enables the establishment of longer connection setups than the DP-QPSK based CO-OFDM without spatial diversity technique. In the light fog, Fig. 2(c), the log (BER) value of −2.43 is achieved at a distance of 1.3 km with spatial diversity, while the log (BER) increased to −0.43 and −0.42 in the case of a system without spatial diversity and 16 QAM OFDM, respectively. It is observed that with spatial diversity an additional log (BER) of −2.01 improves the performance. In Figs. 2(d)-(e)-(f), the BER performance analysis of an FSO link during rainy conditions is displayed. In this paper, the rain attenuation factor is used to examine the impact of rain. Equation (5) can be applied to compute the specific attenuation of the FSO system, which depends on the value of rain intensity.

From Figs. 2(d)-(e)-(f), the log (BER) then −2.42 is achieved at the transmission distance of 1.60 km, 2.8 km, and 3.9 km for heavy, medium, and light rain respectively without spatial diversity. In the case of the 16-QAM OFDM technique, the FSO link can achieve a range of 0.7 km, 1.2, and 1.9 km for the same criteria. The reliable distance is increased to 2.20 km, 3.78 km, and 5.6 km with spatial diversity in the same condition. So, for the same distance, better BER has been recorded using DP-QPSK based CO-OFDM with spatial diversity technique in the rainy condition. Figs. 2(g)-(h)-(i) display the log (BER) versus distance graph for haze weather conditions with spatial diversity, without spatial diversity and 16-QAM OFDM modulated FSO links. In Fig. 2(g), it has been observed that the log (BER) value of −2.45 can be achieved for the range 3.73 km, 2.76 km, and 1.96 km for heavy haze conditions by respective systems. Mild haze condition results in log (BER) values of −2.57 with spatial diversity, 0.44 without spatial diversity, and −0.41 with 16 QAM OFDM over a distance of 7.76 km in Fig. 2(h). Similar results are observed for the low haze weather condition as shown in Fig. 2(i). Hence, it is clear that using spatial diversity significantly reduces BER, which is a requirement for any system. In Fig. 2(j), we observe that with spatial diversity, a log (BER) value of −3.55 is obtained at a distance of 71 km, whereas without spatial diversity the same BER is obtained at a link length of 29.38 km. It is indicated that DP-QPSK based CO-OFDM with spatial diversity FSO system can extend the link range to 41.62 km in clear weather conditions as compared to DP-QPSK based CO-OFDM without spatial diversity FSO.

Table 4. Summary of performance analysis in terms of log (BER), SNR and received power in climate condition.

Climate condition	Attenuation (dB/km)	FSO link Range (km)	DP-QPSK-based CO-OFDM with Spatial Diversity			DP-QPSK-based CO-OFDM without Spatial Diversity			16-QAM OFDM based FSO link		
			Log (BER)	SNR	Received Power (dBm)	Log (BER)	SNR	Received Power (dBm)	Log (BER)	SNR	Received Power (dBm)
Clear	0.14	71	−3.55	30.83	−32.39	−0.56	18.39	−41.18	−0.44	19.45	−38.32
Low haze	2	13.21	−2.78	29.60	−34.73	−0.46	18.81	−42.30	−0.41	18.35	−39.25
Mild haze	4	7.76	−2.57	28.53	−35.03	−0.44	19.87	−42.36	−0.41	18.34	−39.42
Heavy haze	10	3.73	−2.45	31.49	−35.40	−0.46	16.99	−42.57	−0.40	17.29	−39.50
Light rain	6.27	5.60	−3.04	27.78	−34.27	−0.46	18.99	−42.12	−0.41	17.48	−39.15
Medium range	9.64	3.91	−2.74	27.79	−35.21	−0.53	19.04	−42.46	−0.44	19.39	−39.46
Heavy rain	19.28	2.15	−2.63	13.75	−33.64	−0.48	11.79	−41.89	−0.43	13.22	−38.79
Light fog	34	1.3	−2.43	28.55	−34.83	−0.43	17.63	−42.36	−0.42	17.25	−39.32
Moderate fog	85	0.6	−2.86	32.62	−34.76	−0.51	18.33	−42.31	−0.49	17.49	−39.34
Dense fog	340	0.16	−3.20	31.60	−33.84	−0.55	20.20	−41.84	−0.47	21.15	−38.97

Table 4 presents a summary of the performance analysis of DP-QPSK based CO-OFDM with spatial diversity, DP-QPSK based CO-OFDM without spatial diversity, and 16-QAM OFDM based FSO link. For maximum link range log (BER), SNR and received power in dBm are achieved and compared for various climate conditions. Results represent significant performance improvement in terms of BER, SNR, and received power by using the proposed FSO link with spatial diversity as compared to without spatial diversity and 16-QAM OFDM techniques.

4.2. Performance Analysis under Atmospheric Turbulence

Turbulence is more significant in clear weather condition at higher altitudes and can be caused by various factors, including temperature gradients, wind shear, and atmospheric pressure changes. The log normal distribution model as given in Equation (7) is employed to characterize the atmospheric turbulence under the weak regime in this work. The Gamma-Gamma distribution model (Equation (8)) is also introduced to characterize the turbulent channel, as it has been shown to give high accuracy under moderate-to-strong conditions.

BER performance analysis with respect to the range of communication for weak, moderate, and strong turbulence regimes is presented in Figs. 3(a)-(b)-(c). In Fig. 3(a), for weak turbulence conditions, it has been found that the log (BER) value of -2.52 can be achieved over ranges of 71.95 km with spatial diversity, 29.38 km without spatial diversity, and 8.09 km using a 16 QAM OFDM-based FSO system. A considerable amount of turbulence across a 57.76 km communication distance in Fig. 3(b) results in log (BER) values of -2.63 with spatial diversity, -0.65 without spatial diversity, and -0.50 with 16 QAM OFDM. Fig. 3(c) shows the performance -2.26 with 16-QAM OFDM and -1.92 without spatial diversity at the 43.57 km range.

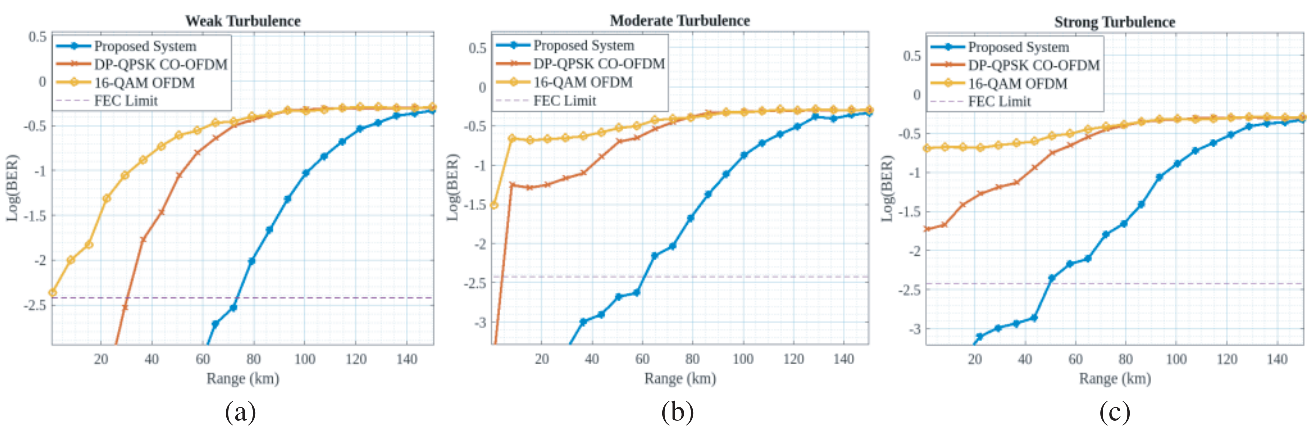


Figure 3. BER in terms of FSO link range for various atmospheric turbulence.

Table 5 summarizes the performance investigation of the 16-QAM OFDM-based FSO link, DP-QPSK CO-OFDM with spatial diversity, and DP-QPSK CO-OFDM without spatial diversity in the presence of atmospheric turbulence. Log (BER), SNR, and received power in dBm are obtained and compared for the longest link distance. The proposed DP-QPSK based CO-OFDM FSO link with spatial diversity significantly improves performance in terms of BER, SNR, and received power in comparison to DP-QPSK based CO-OFDM without spatial diversity and 16-QAM OFDM approaches.

4.3. Effect of Geometric Loss on Performance of FSO Link

The communication range has a significant effect on the geometric loss for the FSO communication link. The geometric loss increases as the distance between the transmitter and receiver increases. This is because the optical signal experiences attenuation and spreading as it travels through the atmosphere,

Table 5. Performance analysis in terms of Log (BER), SNR and received power in atmospheric turbulence.

Turbulence	C_n^2 $\left(m^{-\frac{2}{3}}\right)$	FSO link Range (km)	DP-QPSK based CO-OFDM with Spatial Diversity			DP-QPSK based CO-OFDM without Spatial Diversity			16-QAM OFDM based FSO link		
			Log (BER)	SNR	Received Power (dBm)	Log (BER)	SNR	Received Power (dBm)	Log (BER)	SNR	Received Power (dBm)
Weak	10^{-16}	71.95	−2.52	26.10	−32.39	−0.50	18.39	−41.19	−0.45	19.45	−38.33
Moderate	10^{-14}	57.76	−2.63	33.41	−29.24	−0.65	21.99	−39.12	−0.50	22.28	−36.08
Strong	10^{-12}	43.57	−2.86	39.62	−25.03	−0.94	35.63	−42.36	−0.60	26.27	−32.53

which results in a reduction in signal power. Geometric loss in dB can be defined as [5],

$$L_{GM} = 10 \log \left[\frac{d_r^2}{(d_t + R\theta_{div})^2} \right] \tag{12}$$

In Equation (12), d_r is the aperture diameter of receiver (m), d_t the aperture diameter of transmitter (m), θ_{div} the beam divergence (mrad), and R the link range (km).

Figure 4 illustrates the relationship between the FSO link range (km) and the geometric loss (dB). The plot demonstrates that the geometric loss escalates as the distance between the transmitter and receiver increases. This also shows that FSO links have a limited range of a few kilometers due to the rapid increase in geometric loss with increasing distance. The significant effect of the FSO link range on the geometric loss underscores the importance of meticulous system design to optimize performance for a given range.

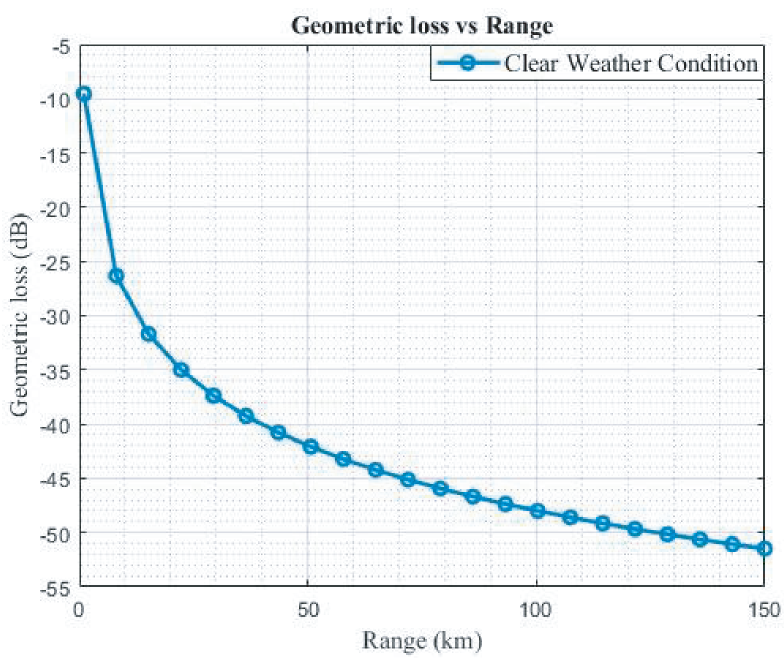


Figure 4. Geometric loss in terms of FSO link range under clear weather condition.

4.4. Effect of Transmitted Power on Performance of FSO Link

Fig. 5 provides insights into how the transmitted power affects the performance of the proposed FSO link. It shows that increasing the transmitted power results in improved signal quality and reduced bit error rates (BER). This indicates that higher power levels contribute to more reliable communication over longer distances. Higher power levels, such as 8 dBm and 16 dBm, enable the FSO link to cover greater distances with lower BER values. Conversely, lower power levels, such as −3 dBm and 0.5 dBm, limit the link range and can lead to higher BER values.

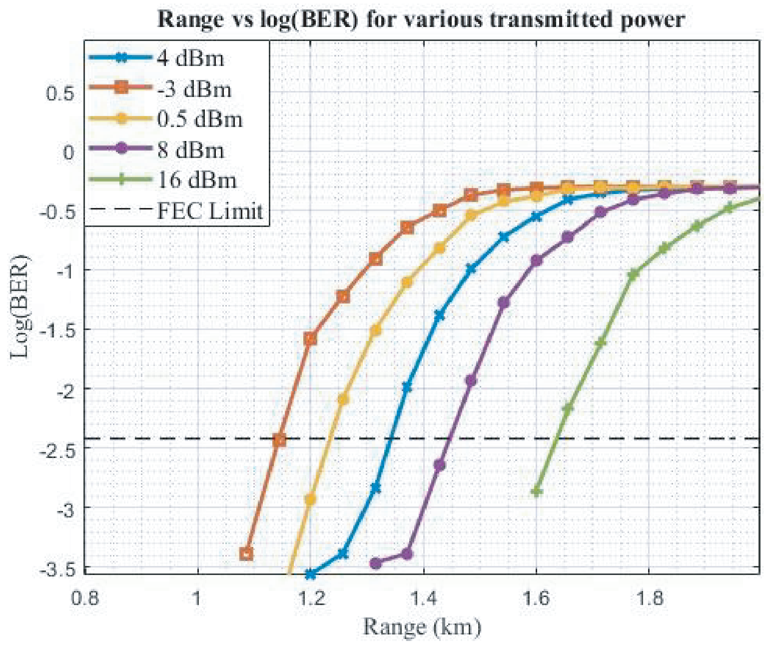


Figure 5. BER in terms of FSO link range for various transmitted power.

However, safety regulations and practical limitations must be considered when adjusting the transmitted power. Proper system design is essential to optimizing FSO link performance, accounting for components, modulation schemes, and error correction techniques.

5. COMPARATIVE ANALYSIS

Table 6 compares the performance of the proposed DP-QPSK based CO-OFDM with spatial diversity FSO link with contemporary works in the literature in terms of data rate, transmitted power, specific attenuation coefficient, and maximum supported transmission range.

The comparison shows that the proposed FSO link, operating at 25 Gbps data rate and 4 dBm transmitted power, demonstrates a significantly improved performance in contrast with the reported works. This is due to the incorporation of dual polarization QPSK modulation and CO-OFDM technology with spatial diversity. Compared to QAM modulation, DP-QPSK provides considerable spectral efficiency and is more resilient to noise. High-speed information transmission without inter-symbol and inter-carrier interference is made possible by CO-OFDM, which also offers resilience against multipath signal fading. Spatial diversity provides improved BER, SNR, and received power performance in varied climate conditions and turbulence. SS-WDM-based FSO link using NRZ encoding mentioned in [3] can achieve a longer distance than the proposed FSO link. However, the atmospheric attenuation coefficients for several weather scenarios were estimated by the authors to be significantly lower than actual values. For example, compared to 34 and 85 dB/km, the attenuation for low and heavy fog is considered to be 15.25 and 25.5 dB/km, respectively. In this work, the proposed FSO link has been simulated for the specific attenuation coefficients considered in [9].

Table 6. Performance comparison of the proposed work with reported literature.

Ref.	Method/ Technique	Data rate (Gbps)	Tx Power (dBm)	Climate Condition	Specific Attenuation (dB/km)	Maximum Link Length (km)
[3]	SS-WDM-based FSO link NRZ encoding	1.56	25	Clear	0.233	140
				Light Haze	0.55	66
				Heavy Haze	2.37	19
				Light rain	7.75	8.3
				Heavy rain	19.28	3.14
				Light fog	15.5	3.8
				Heavy fog	25.5	2.5
[4]	Hybrid PDM based CO-OFDM FSO link using 4-QAM scheme	100	15	Clear	1.14	15
				Low haze	2	5.5
				Medium haze	4	3.6
				Heavy haze	10	2
				Light rain	6.27	2.7
				Medium rain	9.64	2.02
				Heavy rain	19.28	1.22
				Low fog	34	0.8
				Moderate fog	85	0.4
				Dense fog	340	0.1
[5]	WDM-base d FSO link incorporating DPSK scheme	10	10	Clear	0.064	35
				Light fog	4.28	3
				Moderate fog	25.16	1.2
				Heavy fog	85	0.5
[6]	MDM based FSO link incorporating NRZ scheme	2.5	NA	Clear	0.14	2.5
				Thin fog	9	0.6
				Moderate fog	16	0.4
				Heavy fog	22	0.2
[7]	Four-QAM based OFDM FSO link	10	8	Clear	0 −3	1.8
				Light rain	3–6	1.2
				Heavy rain	6–17	0.6
				Light fog	17–70	0.3
				Heavy fog	80–200	0.1
[8]	4-QAM Based OFDM-Ro-FSO link	10	16	Haze	4	4
				Light rain	6.27	2.9
				Heavy rain	19.28	1.2
				Light fog	9	2.2
				Heavy fog	16	1.35

Proposed System	DP-QPSK based CO-OFDM FSO link incorporating spatial diversity	25	4	Clear	0.14	71
				Low haze	2	13.21
				Mild haze	4	7.76
				Heavy haze	10	3.73
				Light rain	6.27	5.60
				Medium range	9.64	3.91
				Heavy rain	19.28	2.15
				Light fog	34	1.3
				Moderate fog	85	0.6
				Dense fog	340	0.16

6. CONCLUSION

In this paper, we have done parametric evaluations of three different FSO systems, DP-QPSK based CO-OFDM with spatial diversity, DP-QPSK based CO-OFDM without spatial diversity, and 16-QAM OFDM systems. The performance evaluation is carried out for varying transmission ranges under various climate conditions and atmospheric turbulence. Under clear to dense fog weather conditions having specific attenuation coefficients ranging $\Upsilon_a \sim 0.14\,\text{dB/km}$ to $340\,\text{dB/km}$, the proposed FSO link achieves reliable communication distance $L \sim 71\,\text{km}$ to $0.16\,\text{km}$, respectively. Similarly, under weak to strong turbulence regimes having refractive index structure parameter $C_n^2 \sim 10^{-16}$ to 10^{-12}, the proposed FSO link achieves reliable communication distance $L \sim 43.57\,\text{km}$ to $71.95\,\text{km}$, respectively. In addition, the performance analysis in terms of Log (BER), SNR, and received power is shown for various climate conditions and turbulence scenarios. The simulated results achieve remarkable BER improvement of 10^{-2}. Finally, the proposed FSO link validates practical link and will help communication engineers to design a real-time reliable FSO system for varied atmospheric conditions and turbulence.

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