Enhancing Free Space Optical System Performance through Fog and Atmospheric Turbulence using Power Optimization

Vijayashri V. Belgaonkar
Department of Electronics & Communication Engineering, Visvesvaraya Technological University, Belagavi, India
vijayashree_ec@sirmvit.edu (corresponding author)

Ramakrishnan Sundaraguru
Department of Electronics & Communication Engineering, Visvesvaraya Technological University, Belagavi, India
sugursg@sirmvit.edu

C. Poongothai
Department of ECE, Sir M. Visvesvaraya Institute of Technology, Bengaluru, India | Visvesvaraya Technological University, Belagavi, India
pungathai_ec@sirmvit.edu

Received: 24 July 2024 | Revised: 20 September 2024 | Accepted: 20 November 2024

 DOI: https://doi.org/10.48084/etasr.8487

ABSTRACT

Free Space Optical (FSO) communication is gaining traction as a pivotal technology for next-generation communication systems, offering extremely high data rates, unlicensed bandwidth, and rapid transmission capabilities. However, its performance is significantly hindered by atmospheric factors such as turbulence and fog. This paper presents a comprehensive model for FSO communication designed to optimize performance under various atmospheric conditions. We assess channel capacity across a spectrum of weak to strong atmospheric turbulence using a Gamma-Gamma channel distribution. To mitigate channel losses, our system employs Wavelength Division Multiplexing (WDM) and multi-beam Multiple Input Multiple Output (MIMO) technologies. Results indicate that the integration of diversity techniques and WDM substantially enhances system performance in adverse weather conditions. Furthermore, power optimization is achieved through the implementation of optical amplifiers and feedback mechanisms from the receiver to the transmitter to adjust the transmitter power in accordance with received Bit Error Rate (BER). The proposed power-optimized WDM MIMO system demonstrates a remarkable BER of 1.48884e-15, while extending the transmission link distance to 2500 meters with a Q factor of 21.5 even under strong atmospheric turbulence conditions.

Keywords-Gamma-Gamma distribution; Rytov variance; atmospheric turbulence; channel capacity

I. INTRODUCTION

Free Space Optical (FSO) technology is considered a promising wireless technology for point-to-point and backhaul links for the next generation (5G and beyond) communications. Fiber optic links cannot be implemented for the floating base stations and high speed, high data rate wireless technologies must be considered. Compared to RF wireless communication, FSO offers high data rates, longer link distance, lower power consumption and is best suited for wireless data transmission between 5G floating base stations. When Distributed Feedback (DFB) laser diodes are used for FSO links, the performance of the system is significantly improved with a transmission rate of 40 Gb/s at the optical wavelength of 1550 nm [1]. If the FSO link fails due to severe weather conditions, the RF link can be used as an alternative [2]. Evaluating the impact of climate change on rainfall rates and rain fade distributions can help make long-term predictions for signal performance in 5G systems and high-frequency radio links, especially in relation to hydrometeor effects [3]. Massive Multiple-Input-Multiple-Output (MIMO) systems can be used in high-speed communications to improve system performance. Among the optical technologies, FSO is an essential element to achieve wireless optical transmission according to the requirements of future technologies due to easy installation, high bandwidth, and security [4]. Device-to-Device (D2D) communication has the potential to reduce communication latency while improving spectrum efficiency and system capacity [5]. Dust storms do not significantly degrade the RF links compared to the FSO links, which can be extremely attenuated. Therefore, RF links provide the backup for FSO links during severe sand and dust storms [6, 7]. In addition, fog and smoke degrade the signal strength of an FSO system [8]. By considering suitable wavelengths from visible NIR for the FSO system, the link distance can be increased in a dense fog environment. Spatial and wavelength diversity can be used to increase the FSO link distance [9].

FSO communication is cost effective, non-invasive, does not require digging or trenching of cable lines, and is an alternative or complementary solution to fiber optic links. Gamma-Gamma turbulence distribution is suitable for predicting the FSO link in turbulent conditions [10]. The performance of FSO systems is degraded by adverse atmospheric weather conditions such as fog, snow, rain, etc., which reduce the capacity of FSO channels. Authors in [11] study the use of Orthogonal Quadrature Phase Shift Keying (OQPSK) to improve the Bit Error Rate (BER)of the received signal [11]. In the presence of weak atmospheric turbulence, the log-normal model with MIMO gives satisfactory performance [12, 13]. Quadrature Amplitude Modulation (QAM) does not reduce the link distance in the presence of strong atmospheric turbulence [14]. Various modulation schemes can be implemented in FSO to improve the received signal quality and increase data rate [15, 16]. 5G networks require extremely high data rates in wireless backhaul over distances up to a few kilometers. Therefore, FSO has its future in wireless 5G /6G networks with cell sizes less than one kilometer [17]. In addition, a fog link attenuation model has been developed based on Kim distribution and Monte Carlo simulation [18]. The effect of weather conditions on FSO channels is modeled using the Beer-Lambert law. Increasing the number of detectors reduces the received BER. Using Intensity Modulation and Direct Detection (IM/DD) and an 850 nm and 1550 nm optical signal, a link distance of 500 m is achieved in a foggy environment [19, 20]. Authors in [21] demonstrate improved transmission in a MIMO Dense-Wavelength Division Multiplexing (DWDM) FSO link to counteract the effects of turbulent weather conditions. The performance of Wavelength Division Multiplexing (WDM) in Passive Optical Networks (PON) within hybrid fiber/free space optical communication systems is improved by using modified On-Off Keying (OOK) for IM/DD techniques [22].

Terrestrial FSO transmission is subject to losses due to rain, fog, haze, snow, and atmospheric turbulence, with the latter having a significant impact on system performance. Atmospheric turbulence results from variations in atmospheric pressure and temperature caused by wind and solar radiation and causes refractive index inconsistencies along the signal path. Techniques such as multi-beam MIMO spatial diversity, WDM, and adaptive transmission power mitigate turbulence effects in FSO systems. Our study evaluates these impacts using Gamma-Gamma Distribution to assess channel capacity under varying turbulence and fog conditions at 1550 nm wavelength using Non-Return-to-Zero (NRZ) modulation and WDM technology.

II. FOG MODELS INDICATING ATTENUATION

Fog is one of the predominant degradation factors contributing to FSO signal attenuation. Fog has a particle size similar to the wavelength used in FSO communications, making it the dominant factor in optical signal attenuation in free space. The fog model shown in (1), proposed by Kruse, is considered for all wavelengths in the visible and near infrared bands [18].

$$\beta_a(\lambda) = \frac{3.912}{x}\left(\frac{\lambda}{0.55}\right)^{-q}, \quad \text{dB/km} \tag{1}$$

where x is the visibility in km, λ is the wavelength in μm and q is the particle size distribution dependent coefficient as shown in (2).

$$q = \begin{cases} 1.6 & x > 50 \text{ km} \\ 1.3 & 6 \text{ km} < x < 50 \text{ km} \\ 0.585x^{1/3} & x < 6 \text{ km} \end{cases} \tag{2}$$

Kim proposed a remedy for Kruse model by moderately modifying the parameter values of q coefficient as shown in (3). This model is independent of wavelength λ and is effective for visibility x<500 m [15].

$$q = \begin{cases} 1.6 & x > 50 \text{ km} \\ 1.3 & 6 \text{ km} < x < 50 \text{ km} \\ 0.16x + 0.34 & 1 \text{ km} < x < 6 \text{ km} \\ x - 0.5 & 0.5 \text{ km} < x < 1 \text{ km} \\ 0 & x < 0.5 \text{ km} \end{cases} \tag{3}$$

Kruse and Kim models did not consider particle size distribution data. Al-Nabulsi model was designed based on Gamma-Gamma distribution for fog with Mie scattering. Attenuation with respect to advection fog is given by [18]:

$$\beta_a(\lambda)_{adv} = 4.343\left(\frac{0.11478\lambda + 3.8367}{x}\right), \text{dB/km} \tag{4}$$

Ijaz model has been proposed for fog in real time environments. The model considers the visibility range from 15 m to 1 km and is described by [15]:

$$\beta_a(\lambda) = \frac{17}{x}\left(\frac{\lambda}{0.55}\right)^{-q(\lambda)}, \text{dB/km} \tag{5}$$

where q is shown in (6).

$$q(\lambda) = 0.1428\lambda - 0.0947 \tag{6}$$

III. AVERAGE CHANNEL CAPACITY

An FSO system link is designed by evaluating the channel capacity in the presence of atmospheric turbulence. Weak atmospheric turbulence is modeled by a log-normal distribution, while weak to strong atmospheric turbulence is modeled by Gamma-Gamma distribution model. The average channel capacity is given by:

$$\langle C \rangle = \int_0^\infty B \, log_2^{(1+\gamma)} P_\gamma(\gamma) \tag{7}$$

where γ is the instantaneous electrical SNR and B is the channel bandwidth. The PDF of Gamma-Gamma distribution is given by [22]:

$$p_I(I) = \frac{2(ab)^{\frac{(a+b)}{2}}}{\Gamma(a)\Gamma(b)} I^{\frac{(a+b)}{2-1}} K_{a-b}\left(2\sqrt{abI}\right) \quad (8)$$

where $K_v(.)$ is the modified Bessel function, $\Gamma(.)$ is the gamma function, and the values of a and b depend on the refractive index structure parameter which is the atmospheric turbulence [9]. The atmospheric turbulence strength C_n^2 in (9), also known as the refractive index structure parameter, depends on wind velocity and altitude [17].

$$C_n^2(h) = 0.00594\left(\frac{v}{27}\right)^2 (10^{-5}h)^{10}\, exp\, exp\left(-\frac{h}{1000}\right) 2.7 \times 10^{-16}\, exp\, exp\left(-\frac{h}{1500}\right) + A\, exp\, exp\left(-\frac{h}{100}\right) \quad (9)$$

where h is the altitude in meters, v is the rms value of wind speed (21 m/sec), and A=$C_n^2(0)$ is the value of C_n^2 at ground level, which is estimated to be $1.7 \times 10^{-14} m^{-\frac{2}{3}}$. For weak to strong turbulence C_n^2 is varied from $10^{-17} m^{-\frac{2}{3}}$ to $10^{-13}\ m^{-\frac{2}{3}}$. The PDF of Gamma-Gamma turbulent model is expressed as [11]:

$$p_\gamma(\gamma) = \frac{(ab)^{\frac{(a+b)}{2}}}{\Gamma(a)\Gamma(b)} \frac{\gamma^{\frac{(a+b)}{4-1}}}{\Gamma^{\frac{(a+b)}{4}}} K_{a-b}\left(2\sqrt{ab\sqrt{\frac{\gamma}{\Gamma}}}\right) \quad (10)$$

The average capacity of the FSO Gamma-Gamma turbulence is obtained by substituting (10) in (7) as shown in (11).

$$< C > = \frac{B\left(\frac{ab}{\sqrt{\Gamma}}\right)^{\frac{(a+b)}{2}}}{\Gamma(a)\Gamma(b) ln\, ln\,(2)} \times \int_0^\infty \ln(1+\Upsilon)\, \gamma^{(a+b)/4-1} K_{a-b}\left(2\sqrt{ab\sqrt{\frac{\gamma}{\Gamma}}}\right) d\gamma \quad (11)$$

The above equation determines the capacity of the FSO channel in weak to strong atmospheric turbulence.

IV. PROPOSED FSO SYSTEM AND POWER OPTIMIZATION

FSO systems utilize high-bandwidth unlicensed spectrum, employing up to 30 dbm Continuous Wave (CW) laser power for highly attenuated channels due to turbulence and dense fog. As shown in Figure 1, the proposed system consists of a pseudo-random bit sequence generator feeding random bits to an NRZ modulator, followed by modulation using a Mach-Zender modulator at 1550 nm wavelength. Atmospheric turbulence and fog are mitigated by a spatial diversity MIMO system. The transmit power of CW laser ranges from 20 dbm to 30 dbm in dense fog conditions, supporting FSO designs with WDM and spatial diversity MIMO channels. The channels used have a frequency spacing of 0.1THz. The first channel frequency is 193.1 THz, the second channel frequency is 193.2 THz, the third channel frequency is 193.3 THz, and the eighth channel frequency is 193.8 THz. A total of 80 Gbps of data can be transmitted. Power optimization is achieved by implementing optical amplifiers and feedback mechanisms from the receiver to the transmitter to adjust the transmitter power according to the received BER.

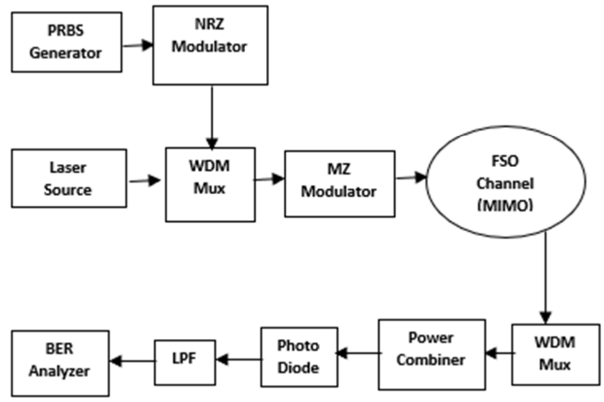

Fig. 1. Proposed WDM MIMO FSO System design for strong turbulence and fog weather conditions.

The goal of power optimization for FSO communications is to adjust the transmitter power to ensure optimal performance while adhering to constraints. The process begins by defining the maximum *Pmax* and minimum *Pmin* allowable transmitter power. Atmospheric conditions, calculated by the refractive index structure parameter C_n^2 and atmospheric attenuation *A*, are evaluated to assess their impact on signal quality. Using these parameters, the received power *Rp* and *BER* are calculated. If *BER* is found to be high and the received signal power is insufficient, the transmitter power is increased to a required level *Preq*. However, *Preq* must remain within the defined limits of *Pmax* and *Pmin*. Specifically, if *BER* is significantly below the permissible limit, *Preq* is increased; otherwise, the current transmitter power *Ptx* is retained. To ensure compliance with the power constraints, the adjusted power *Padj* is calculated as the maximum of *Pmin* and the minimum of *Pmax* and *Padj*. Finally, the optimized power output *Pout* is returned. The proposed power optimization algorithm is the following:

```
Define Pmax, Pmin
Evaluate C_n^2 and A
Find Rp, BER
Compute Preq
Adjust Transmitter power based on BER
If BER <<permissible limit, then
Increase the Preq
Else
Retain the same Ptx
Ensure power is within limits, Pout =
max(Pmin, min(Pmax, Padj))
Return Pout
```

V. RESULTS AND DISCUSSION

Results simulate channel capacity and BER under atmospheric turbulence and fog conditions using Gamma-

Gamma Channel distribution. FSO communications utilize near-infrared waves (700 nm to 2500 nm) to transmit data and are primarily constrained by atmospheric channel limitations. The graphs in the following figures compare average channel capacity against SNR as impacted by diverse climatic conditions. Key system parameters are detailed in Table I.

TABLE I. SYSTEM PARAMETERS USED IN SIMULATION

Parameters	Values
Wavelength	1550 nm
Height	25 m
Wind speed	21 m/s
Atmospheric turbulence	Low, Medium, and Strong
Attenuation due to fog	22 dB/km
Transmitter power	5-30 dBm
Receiver aperture diameter	20 cm
Beam divergence angle	0.25 dbm/rad

Figure 2 shows the average channel capacity values with respect to different levels of received SNR. The wavelength used for this analysis is 1550 nm and the link distance between the transmitter and receiver is 4 km. The analysis is performed for the following levels of atmospheric turbulence; $C_n^2 = 1 \times 10^{-15} m^{-\frac{2}{3}}$ is weak atmospheric turbulence, $C_n^2 = 9 \times 10^{-15} m^{-\frac{2}{3}}$ is moderate turbulence, and $C_n^2 = 3 \times 10^{-14} m^{-\frac{2}{3}}$ is strong turbulence.

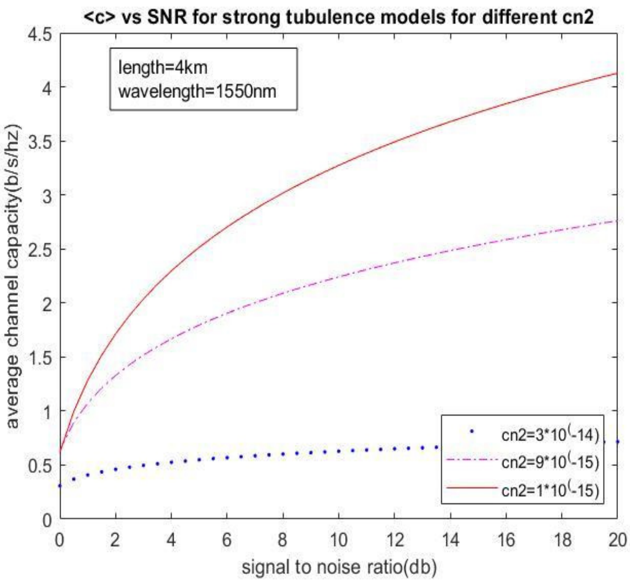

Fig. 2. Average channel capacity.

Figure 3 shows the average channel capacity achieved for the strong turbulence level of $C_n^2 = 3 \times 10^{-14} m^{-\frac{2}{3}}$ for various link distances. Channel capacity decreases as the link distance increases. Channel capacity is plotted for the link distance of 1 km, 2 km, and 4 km. An optical wave with wavelength 1550 nm is considered in this configuration.

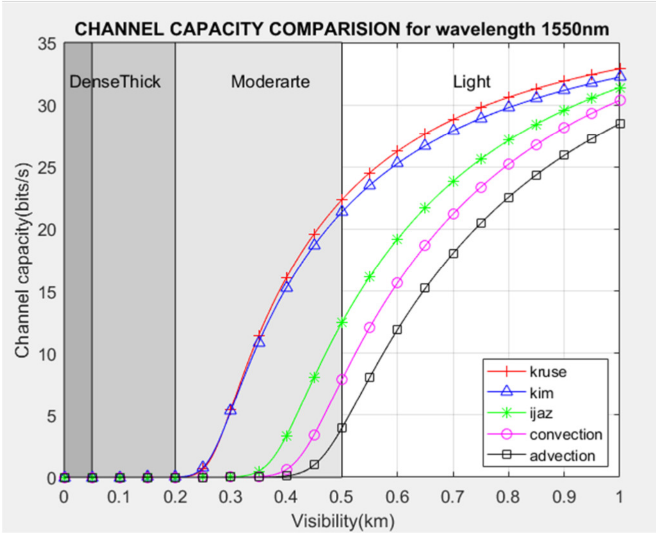

Fig. 3. Average channel capacity <c> of a wireless communication link for different link distance.

Simulation results show that there is no significant difference between the attenuation coefficient of Al-Nabulsi and Ijaz models and that of Kim and Kruse models. Kim and Kruse models provide better attenuation as compared to the other models as shown in Figure 4. FSO channel capacity *C* is the dominant factor influencing the visibility in FSO systems. Simulation analysis shows that the channel capacity is minimal in dense and thick fog.

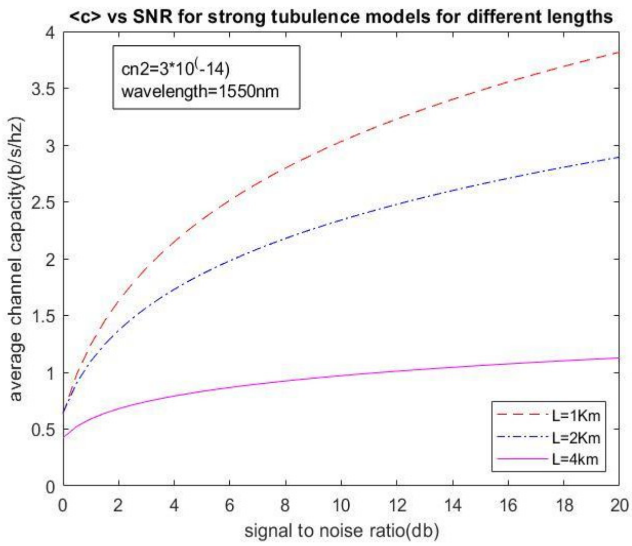

Fig. 4. Comparative analysis on attenuation coefficient.

The results shown in Figure 5 clearly indicate that as the visibility decreases, the channel capacity also degrades. In addition, channel capacity is severely impacted in the presence of dense fog. Channel capacity assessment at 850 nm optical wavelength in the presence of fog is illustrated in Figure 6. Comparative analysis shows that Kim and Kruse fog models provide superior channel capacity estimates compared to other models. Table II presents FSO system performance results for multiple transmitter and receiver configurations with *N* denoting the number of channels. Figure 7 shows the performance of the WDM FSO system in dense fog and turbulence, highlighting the increased link distance by 600 m. Under atmospheric turbulence and dense fog, the achievable link distance reaches 1200 m, achieving a minimum BER of 1.15351e-020 and a maximum Q factor of 9.24537.

TABLE II. MULTI BEAM FSO WITH MODERATE FOG

N	Max. Q factor	Min BER	Eye Height
Without Diversity	9.53087	1.9e-022	1.50e-006
N=2	25.7471	3.5e-156	8.39e-006
N=4	35.9712	3.9e-292	1.47e-006
N=8 (1550 nm)	50.8133	0	2.73e-005
N=8 (850 nm)	44.5424	0	2.17e-005

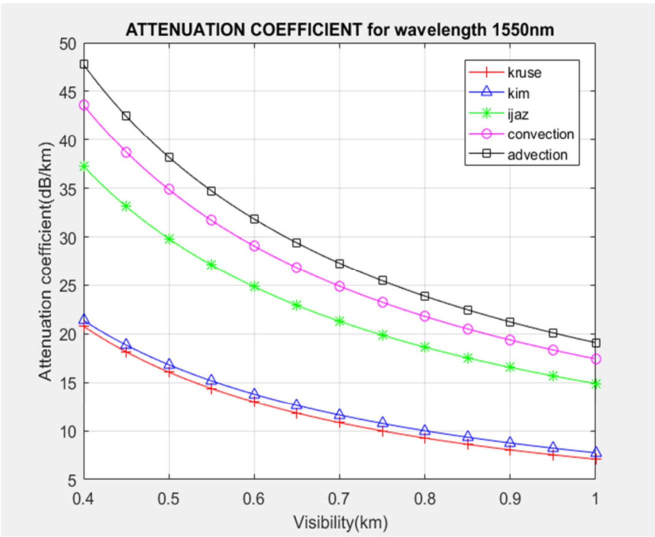

Fig. 5. Channel capacity for wavelength 1550 nm in fog.

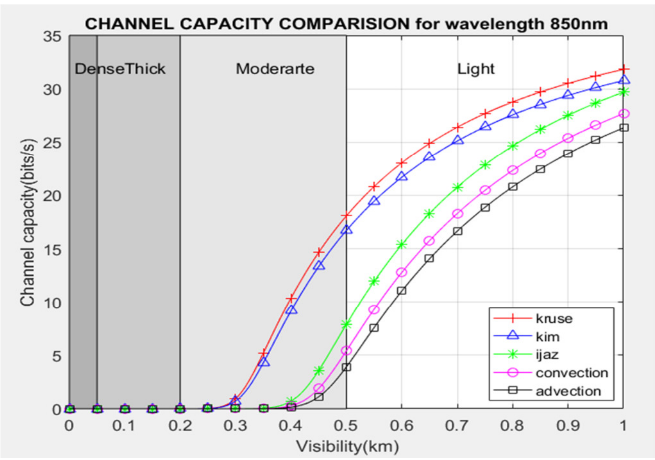

Fig. 6. Channel capacity for wavelength 850 nm in fog.

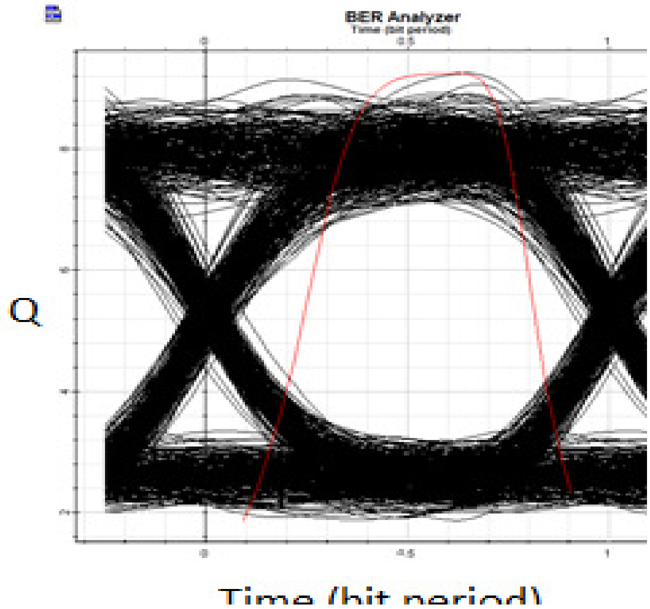

Fig. 7. 1550 nm WDM MIMO FSO turbulence.

The proposed design is evaluated for all the turbulence values from low to high levels and the results are shown in Table III. For strong turbulence 1×10^{-13}, the Q factor is reduced and the BER increases. In the presence of strong turbulence, the link distance is reduced to 1700 m. This can be improved by increasing the transmitter power to 30 dBm using the proposed power optimization algorithm. The link distance in the presence of strong turbulence is increased to 2500 m.

TABLE III. PERFORMANCE FOR VARIOUS LEVELS OF ATMOSPHERIC TURBULENCE

Turbulence	Q factor	BER	Transmission Distance (m)
1×10^{-17}	177.449	0	2000
5×10^{-16}	118.761	0	2000
1×10^{-15}	31.313	9.16307e-216	2000
6×10^{-15}	14.714	1.5067e-49	2000
1×10^{-13}	7.80613	1.48884e-15	1700 (Up to 2500 with Power Optimization)
7×10^{-14}	7.85893	9.9e-16	2000

Table IV shows the comparison of the existing literature and proposed design. In [13], the WDM MIMO system provides a communication link distance up to 1370 m. On the other hand, with the proposed design that includes power optimization, the link distance can be extended to 1600 m.

TABLE IV. COMPARISON WITH EXISTING LITERATURE

Comparison	Method used	Link Distance
[13]	WDM-MIMO	1370m
Proposed Design	Power Optimization WDM MIMO	1650m

VI. CONCLUSIONS

This study highlights the effectiveness of a Free Space Optical (FSO) communication link in transmitting signals amidst strong atmospheric turbulence and fog. Our simulation results demonstrate that the proposed design, which incorporates Wavelength Division Multiplexing (WDM), Multiple Input Multiple Output (MIMO) technology, and power optimization, significantly improves performance. We found that the 1550 nm optical wavelength reduces signal attenuation compared to the 850 nm wavelength, thereby improving reliability in challenging conditions. The integration of Non-Return-to-Zero (NRZ) modulation, WDM, spatial diversity MIMO, and power optimization provides an optimal solution for high-speed, high-data-rate communications. Notably, our system achieved a Q factor of 50.8133 under fog conditions, extending the link distance to 2500 m despite strong atmospheric disturbances. These results position our FSO design as a leading candidate for advancing future optical communication networks.

ACKNOWLEDGMENT

The authors are grateful to HR Universal Systems Inc. in Delhi, for sponsoring the license of Optiwave's Optisystem software tool to conduct the research.

REFERENCES

[1] W. S. Tsai *et al.*, "A 20-m/40-Gb/s 1550-nm DFB LD-Based FSO Link," *IEEE Photonics Journal*, vol. 7, no. 6, pp. 1–7, Dec. 2015, https://doi.org/10.1109/JPHOT.2015.2506172.

[2] N. Vishwakarma and S. R, "On the Capacity Performance of Hybrid FSO/RF System With Adaptive Combining Over Generalized Distributions," *IEEE Photonics Journal*, vol. 14, no. 1, pp. 1–12, Feb. 2022, https://doi.org/10.1109/JPHOT.2021.3135115.

[3] H. Basarudin *et al.*, "Evaluation of Climate Change Effects on Rain Rate Distribution in Malaysia Using Hydro-Estimator for 5G and Microwave Links," *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11064–11069, Aug. 2023, https://doi.org/10.48084/etasr.5552.

[4] S. M. Albadarn, "The Effect of Pilot Reuse Factor on Massive MIMO Spectral Efficiency," *Engineering, Technology & Applied Science Research*, vol. 13, no. 3, pp. 10703–10707, Jun. 2023, https://doi.org/10.48084/etasr.5605.

[5] S. Alotaibi, "Interference Mitigation Strategy for D2D Communication in 5G Networks," *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11318–11325, Aug. 2023, https://doi.org/10.48084/etasr.6008.

[6] B. Bag, A. Das, I. S. Ansari, A. Prokeš, C. Bose, and A. Chandra, "Performance Analysis of Hybrid FSO Systems Using FSO/RF-FSO Link Adaptation," *IEEE Photonics Journal*, vol. 10, no. 3, pp. 1–17, Jun. 2018, https://doi.org/10.1109/JPHOT.2018.2837356.

[7] A. Bekkali, C. B. Naila, K. Kazaura, K. Wakamori, and M. Matsumoto, "Transmission Analysis of OFDM-Based Wireless Services Over Turbulent Radio-on-FSO Links Modeled by Gamma–Gamma Distribution," *IEEE Photonics Journal*, vol. 2, no. 3, pp. 510–520, Jun. 2010, https://doi.org/10.1109/JPHOT.2010.2050306.

[8] N. A. Sarker *et al.*, "Secrecy Performance Analysis of Mixed Hyper-Gamma and Gamma-Gamma Cooperative Relaying System," *IEEE Access*, vol. 8, pp. 131273–131285, 2020, https://doi.org/10.1109/ACCESS.2020.3009026.

[9] V. V. Belgaonkar and R. Sundaraguru, "Performance Evaluation of OWC System in Different Weather Conditions Using Wavelength and Spatial Diversity," in *2022 IEEE International Conference on Electronics, Computing and Communication Technologies*, Bangalore, India, 2022, pp. 1–6, https://doi.org/10.1109/CONECCT55679.2022.9865848.

[10] T. Shang, R. Chen, Y. Liu, and Y. Gao, "Performance Analysis of IMC in FSO Systems Over Gamma–Gamma Channel," *IEEE Photonics Journal*, vol. 10, no. 3, pp. 1–13, Jun. 2018, https://doi.org/10.1109/JPHOT.2018.2842716.

[11] V. V. Belgaonkar, C. L. Triveni, and R. Sundaraguru, "Free Space Optical Communication Using OQPSK in the Presence of Strong Atmospheric Turbulence and Losses, " *Optical and Quantum Electronics*, vol. 56, no. 10, Oct. 2024, Art. no. 1669, https://doi.org/10.1007/s11082-024-07591-1.

[12] M. Miao and X. Li, "Novel Approximate Distribution of the Sum of Lognormal-Rician Turbulence Channels With Pointing Errors and Applications in MIMO FSO Links," *IEEE Photonics Journal*, vol. 14, no. 4, pp. 1–15, Aug. 2022, https://doi.org/10.1109/JPHOT.2022.3181041.

[13] Y. K. Gupta and A. Goel, "EDFA Controlled Spectral Efficient MIMO Free Space Optic Links for Mitigation of Climatic Turbulence Conditions," *Wireless Personal Communications*, vol. 132, no. 4, pp. 2563–2585, Oct. 2023, https://doi.org/10.1007/s11277-023-10732-6.

[14] V. V. Belgaonkar, R. Sundaraguru, J. U. Kumar Reddy, B. Mohan, K. U. Shridhar, and A. Gandham, "Weak to Strong Atmospheric Turbulence Analysis in Free Space Optical Communication and Mitigation Using M-ary QAM," in *2020 IEEE International Conference on Electronics, Computing and Communication Technologies*, Bangalore, India, 2020, pp. 1–6, https://doi.org/10.1109/CONECCT50063.2020.9198360.

[15] Z. Wang, W. D. Zhong, S. Fu, and C. Lin, "Performance Comparison of Different Modulation Formats Over Free-Space Optical (FSO) Turbulence Links With Space Diversity Reception Technique," *IEEE Photonics Journal*, vol. 1, no. 6, pp. 277–285, Dec. 2009, https://doi.org/10.1109/JPHOT.2009.2039015.

[16] N. Kathpal, A. K. Garg, P. Goyal, and Y. K. Awasthi, "Design of 16×100 Gbps Free-Space Optical System Using Advanced Modulation Techniques," *Journal of Optics*, vol. 52, pp. 1584–1601, Sep. 2023, https://doi.org/10.1007/s12596-022-01072-y.

[17] H. Singh, N. Mittal, R. Miglani, H. Singh, G. S. Gaba, and M. Hedabou, "Design and Analysis of High-Speed Free Space Optical (FSO) Communication System for Supporting Fifth Generation (5G) Data Services in Diverse Geographical Locations of India," *IEEE Photonics Journal*, vol. 13, no. 5, pp. 1–12, Oct. 2021, https://doi.org/10.1109/JPHOT.2021.3113650.

[18] A. Elfikky, M. Singh, A. I. Boghdady, S. A. Abd El-Mottaleb, S. A. H. Mohsan, and M. H. Aly, "Spatial Diversity-based FSO Links under Adverse Weather Conditions: Performance Analysis, " *Optical and Quantum Electronics*, vol. 56, no. 5, Mar. 2024, Art. no. 826, https://doi.org/10.1007/s11082-024-06625-y.

[19] V. V. Belgaonkar and S. Ramakrishnan, "Free Space Optical Communication System in the Presence of Atmospheric Losses," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 33, no. 1, pp. 159–166, Jan. 2024, https://doi.org/10.11591/ijeecs.v33.i1.pp159-166.

[20] A. Malik and P. Singh, "Comparative Analysis of Point to Point FSO System Under Clear and Haze Weather Conditions," *Wireless Personal Communications*, vol. 80, no. 2, pp. 483–492, Jan. 2015, https://doi.org/10.1007/s11277-014-2022-6.

[21] Elsayed, E.E., Yousif, B.B. Performance evaluation and enhancement of the modified OOK based IM/DD techniques for hybrid fiber/FSO communication over WDM-PON systems. *Opt Quant Electron* **52**, 385 (2020). https://doi.org/10.1007/s11082-020-02497-0.