International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 2, April 2025, pp. 1745~1753
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i2.pp1745-1753

High speed space division multiplexing based integrated fiber transmission system and its impact on atmospheric conditions

Kakarla Phaneendra Kumar, T. Sreenivasulu Reddy
Department of Electronics and Communication Engineering, Sri Venkateswara University College of Engineering,
Sri Venkateswara University, Tirupati, India

Article Info

Article history:

Received Apr 12, 2024
Revised Aug 31, 2024
Accepted Oct 23, 2024

Keywords:

Free space optical communication
Transmission
Wireless communication
Atmospheric conditions
Space division multiplexing

ABSTRACT

With several advantages over traditional wireless and fiber optic cables, free space optical communication is becoming more and more popular because of its high speed and bandwidth applications. In particular, the high transmission capacity of free space optics (FSO) communication systems makes them preferred, which enables them to handle the growing amount of internet traffic. Because FSO has no regulatory limitations, operates over large distances with high levels of security, and transmits data faster than radio frequency communication technologies are widely utilized. However, given different atmospheric conditions, the availability and capacity of FSO optical bands represent a major concern. For next-generation information transmission networks to satisfy end users high-capacity demands, the transmission technology known as space-division multiplexing (SDM) has become essential. Hence in this work, High speed space division multiplexing based integrated fiber/FSO transmission system and its impact on atmospheric conditions is presented. The SDM transmission system developed in this study is based on an integrated multimode fiber (MMF)/ FSO link with linear polarized (LP) spatial modes. This approach takes into consideration extreme climate conditions like snow and turbulence while evaluating performance. Utilizing bit error rate (BER) and received optical power (ROP) are the performance of FSO is evaluated in different weather conditions.

Corresponding Author:

Kakarla Phaneendra Kumar
Department of Electronics and Communication Engineering, Sri Venkateswara University College of Engineering, Sri Venkateswara University
Tirupati, Andhra Pradesh, India
Email: phanieceobvp@gmail.com

1. INTRODUCTION

Nowadays, large bandwidths and high-quality signals are needed for communication, which is radio frequency (RF) communications are not used in place of optical lasers and free space optics (FSO). Finding alternatives to the current RF infrastructure is essential to a combination of the rapidly increasing number of people using mobile phones and the need for high-speed data services has increased exponentially. In order to meet the requirements of optical network design, FSO is able to provide a viable point-to-point solution. Being a line of sight (LOS) technology, FSO requires alignment between the transmitter and the receiver. High-speed wireless networks commonly use FSO because of its great efficiency for continuous high-throughput and low interference. In comparison to RF systems, because of its wide bandwidth and low interference, FSO systems have become more and more popular [1]. In order to enable short-range fifth generation (5G) wireless communications, directivity, power efficiency, installation simplicity, and multigigabyte applications are offered by free space optical communication cables [2]. Wireless optical communication lines in free space offer fast data speeds, a large bandwidth, and high-quality signals, solve wireless connection problems caused by traditional technologies. Recently, numerous benefits of FSO communication technology over traditional radio frequency based wireless communications have been addressed widely [3].

Increasingly high data rates are required for 5G network wireless backhaul over several kilometers. Through using the mid-IR (Infra-Red-10.6 μm) transmission, one can limit the decrease of link availability caused by fog. Several methods are used to increase this range, using several antennas, using hybrid FSO/RF technology and increasing the transmitter power are two of the methods that are used. However, optical fiber cables have several benefits for a number of years [4]. They could only operate on the backhaul network. Digging and trenching are necessary for wired connections such as optical fibers. FSO is a wireless connection that can be made without digging. When another network fails, it offers easy setup during disaster recovery [5]. These geographical limitations, such as mountains, rivers, and other obstacles, have been overcome by the development of FSO transmission channels, allowing the transmission of optical and sensor signals. FSO technology is a technique that sends data through free space or the atmosphere using light [6]. The critical properties of FSO are colossal bandwidth, enhanced security, and low installation costs. For this reason, FSO-based communication system architecture is frequently used in deep space and terrestrial applications. The architecture of an optical network is connected to the foundation of FSO; these inputs are received at the photodiode-based receiver from laser-based transmitters [7].

A communication technology called FSO sends an information-carrying signals through empty space. In terms of optical modulated signal transmission, it is extremely near to optical fiber communication (OFC) technologically. In FSO, the sending and receiving ends of the communication signal are connected by a direct LOS link, this is categorized as optical wireless communication (OWC) in general. Through the channel or the atmosphere, the signal is transferred. Since it utilizes light, it supports unlicensed spectrum, high data transmission, and very secure communication. The possibility that it can be utilized is another advantage in areas where the physical layout makes optical fiber installation challenging [8].

Since optical fiber links and FSO communication share many technological similarities, the two have many similar transmission characteristics. Transmitting optically modulated signals, can have a transmission speed of up to terabits per second (Tbps), is one such capability. Additional characteristics include impeccable signal security, plug-and-play installation features, and license-free optical spectrum further increase the attraction of FSO in its quest to provide high-speed and cost-effective last-mile connection. FSO is an interesting option for creating an extensive communication infrastructure since placing optical fiber in urban locations is very expensive and RF bandwidth is becoming increasingly limited [9].

However, there are still a number of difficulties with FSO systems. Beam wandering and scintillation are caused by atmospheric turbulence, which presents the greatest problem. These effects have the possibility to significantly reduce the FSO signal's quality, this leads to bit-error rates that are too high to transmit data properly. Rain, fog, and haze are only a few of the weather conditions that affect the FSO network. While FSO communication has numerous advantages, its efficiency is sometimes impacted by external challenges like weather [10]. For instance, the information signal gets reduced by varying weather conditions, which increases the bit error rate (BER). Rain, haze, and fog are examples of external weather conditions that can change quickly and decrease optical signals during transmission by scattering and absorbing signal strength, which lowers the quality of the signal that is received [11].

The attenuation value varies according on the climate; in clear weather, it is less than 1 dB/km, while during heavy dust (HD) storms, it can reach hundreds of dB/km. The air attenuation resulting from molecular absorption, scattering, and the scintillation phenomenon, which significantly decreases the transmission link, are the main difficulties in transmitting optical signals using open space channels. The performance of the high-speed FSO link during various atmospheric conditions has been examined by numerous research organizations, including heavy rain, smoke, snow, fog, and dust. In the previously described weather conditions, several techniques have been developed to increase the FSO link's data rate. [12]. However, still there is a need for effective system for FSO transmission during various weather conditions.

To improve the FSO channel's capacity and allow multiple users to send data simultaneously, researchers now employ a number of multiplexing techniques. Wavelength division multiplexing (WDM), polarization division multiplexing (PDM) [13], and orthogonal frequency division multiplexing (OFDM) [14] are a few of these methods. Although WDM systems transfer large amounts of data, the fiber access network's stability and reliability are essential. Consequently, if the linked fiber line is destroyed while high-speed and wide-capacity signal transmission is occurring in such passive optical network (PON) networks, it will impact the associated end-users' network connection [15].

A possible method for effectively sending asynchronous data signals from numerous users through a network is optical code division multiple access (OCDMA). Data from each individual user is coded uniquely, in order to enhance user security and privacy, all data from numerous users is multiplexed and transferred simultaneously. Various codes can be used, such dynamic cyclic shift (DCS), random diagonal (RD), diagonal permutation shift (DPS), and enhanced double weight (EDW). The usage of these codes is complicated by the existence of phase-induced intensity noise (PIIN) caused by multiple access interference (MAI), even though these codes can provide encryption, which needs to be illuminated by suitable detection techniques [16].

However, the spatial intensity distribution property of the optical carrier signal was used by space division multiplexing (SDM) techniques for transmitting multiple information signals simultaneously [17]. In order to increase transmission capacity, various independent information messages can now be communicated utilizing two or more overlapping orthogonal modes due to a technique called Mode division multiplexing, or mode division multiplexing (MDM). A more modern approach to spatial diversity is called SDM, it uses many optical fiber eigenmodes as independent channels to generate multiple-input multiple-output systems. In the event that one connection fails during harsh conditions, SDM makes it possible to provide multiple links and extends the maximum link distance [18].

A free-space optical communication system using WDM and fast hybrid signal interaction are discussed. This paper presents and demonstrates a fast hybrid signal in a FSO communication system using WDM. For the first time, a single beam is used in this study to send a fast hybrid signal with rates of 10, 25, 28, and 32 Gb/s that mixes four different wavelengths that are modulated separately. Selecting parameters after considering the impact of the number of mixed light channels, the channel spacing, clear eye mappings are a positive bit error rate (BER) are provided by a tunable optical bandpass filter bandwidth on system performance. However, this system is cost-effective [19].

An optical communication system is described which is operating in free space with atmospheric losses. With spatial diversity, WDM is used at different atmospheric turbulence levels. The authors developed the FSO gamma turbulent model with non-return to zero (NRZ) modulation format and multiple input multiple output (MIMO) (8×8). Over a range of 2-4 km, it achieved attenuation loss of 10 dB/km. With substantial air turbulence and 10 dB/km atmospheric attenuation, the recommended model can increase the link distance by up to 4 km [20].

By utilizing the appropriate optical bands, a combination of free space optics and optical networks was created to enable high-speed communication in difficult conditions. Using optical bands conventional (C) short (S) and original (O) to combine optical and FSO lines, increasing network flexibility and wireless network coverage under difficult conditions are the objectives. When the Kim model was used to analyze BER values under different weather conditions, the S and C bands were continuously underperformed by the O band. The signal quality was assessed using eye diagrams, and even in adverse weather, the O band outperformed the other two bands. All things considered, using the O band in particular, the research suggests that FSO is an attractive choice for quick wireless communication [21].

The free-space vector-mode-division-multiplexing signal transmission of 228 Gb/s based on optical frequency comb technology is described. This technique is shown experimentally and creates a vector-mode division multiplexing (VMDM) over an 80-cm FSO connection using an optical frequency comb. To achieve the 228 Gbit/s data transmission rate, two basic vector modes with a direct detection OFDM (DD-OFDM) signal spanning 20 wavelengths have been used. According to the result, this VMDM system ought to be a viable option for high-capacity short-reach optical transmission networks [22].

For free-space optical chaotic communication at 20 Gbps, orbital angular momentum multiplexing is used. An orbital angular momentum (OAM) multiplexing free-space all-optical chaotic communication system that increases transmission capacity and security has been experimentally developed by the authors. Optical chaotic signals are used to discretely transmit two distinct OAM waveforms containing 20 Gbps ON-OFF keying signals over a 2 m free-space link. This study may open up new possibilities for structured light applications in optical chaos and lead to the development of safe, high-capacity free-space chaotic communication systems in the future [23].

Free-space optical communications with large capacity using mid-infrared wavelength-division-multiplexing and mode-division-multiplexing. The wavelength-division-multiplexing and mode-division-multiplexing techniques were experimentally demonstrated by the authors in a mid-IR FSO link at a distance of around 0.5 meters. Each of the three wavelengths (3.396, 3.397, and 3.398 μm) that multiplex on a single polarization carries two orbital-angular-momentum (OAM) beams. In order to get a 300 Gbit/s overall capacity, each beam transmits 50 Gbit/s quadrature-phase-shift-keying data [24].

Research on optical communications in real atmospheric circumstances conducted in free space is investigated. In this analysis, a simulation environment is constructed and presented for free space optical communications (FSOC) investigation under these conditions. The atmospheric channel, beam divergence that varies with distance, turbulence, applicable modulation techniques are explained an overall overview of the capabilities is provided. This paper's insights should help in determining cases under which the FSOC offers a relevant potential for use or the limiting considerations become too important and alternative technologies need to be taken into consideration [25].

It is shown that to design and evaluate a dense WDM FSO (DWDM FSO) for multiple input, multiple output (MIMO) applications utilizing free space optical systems. DWDM with MIMO is used to establish a free space optical transmitter and receiver link that can overcome the attenuation that is present in adverse weather situations. The purpose of utilizing this design methodology is to demonstrate that MIMO technology enhances the FSO system's efficiency. The advantages of utilizing MIMO over single input and single output (SISO) systems are demonstrated by a comparison of the results of the two design approaches [26].

Performance analysis of a mode division multiplexed, high data rate free space optics link in hard weather is investigated. In order to transmit data in different dust weather scenarios, the authors analyze a mode division multiplexing-based 2×10 Gb/s–10 GHz radio-over-free-space optics (RoFSO) transmission system and describe its design. The binary digital optical modulation techniques, namely NRZ and return to zero (RZ), are compared in the proposed system. The results show that the suggested system with NRZ modulation covers a transmission range of 14.5 km. At RZ modulation, the intended BER of 10−6 resulted in a significant link enhancement of 4.5 km when the transmission range was limited to 10 km [27].

An analysis is conducted on how a decision feedback equalizer could improve the performance of a mode division multiplexing free space optical communication system under different atmospheric conditions. MDM utilizes a decision feedback equalizer (DFE) with minimal mean square error (MMSE) for the FSO system. The DFE is being looked into with varying tap counts. The DFE's feedforward and feedback filter coefficients are both optimized by the MMSE method. Using Hermite-Gaussian (HG) modes, there are four 2.5 Gbps channels in parallel in the suggested structure. The results show that the DFE equalization technique successfully transmits 10 Gbps in medium fog, medium haze, and medium rain in clear weather at 40 m, 800 m, 1400 m, and 2 km. Eye diagrams and BER are used for performance analysis, and the results are compared to those of the traditional approach [28].

Hence, this work presents high speed space division multiplexing based integrated fiber/FSO transmission system and its impact on atmospheric conditions is presented. The literature survey is discussed after the introduction. The section 2 demonstrates the methodology of high-speed space division multiplexing based integrated fiber/FSO transmission system and its impact on atmospheric conditions. In section 3, the result of the analysis is evaluated. Section 4 has the conclusion.

2. METHOD

In this work, high speed space division multiplexing based integrated fiber/FSO transmission system and its impact on atmospheric conditions is presented. Figure 1 displays the presented system's block diagram. This analysis presents the block schematic of an integrated fiber/FSO transmission system that uses two linear polarized (LP) modes and SDM for linear mode transmission. Two LP modes LP01 and LP11, are connected in order to offer 2-independent 10 Gbps, 10 Gbps data bits over 10.5 km multi-mode fiber (MMF) (fixed) and FSO channel under variable weather conditions. With a 10 Gbps speed, the transmitter gathers the data bits in an ON-OFF keying scheme known as NRZ. Next, using a Mach-Zehnder-modulator (MZM) and a spatial laser, Figure 1 shows that they are optically modulated into a separate LP modal beam. A 2-mode SDM multiplexer is then used to combine both of the optically modulated modal beams. Under changing weather conditions, the 10.5 km MMF link and the FSO channel are used to transport the 20 Gbps SDM signal.

Different atmospheric conditions exist in free space, where the modulated signals are transmitted:

a. FSO model:

The weather outside has a major impact on the FSO transmission system performs. In this research, various weather conditions which affect the system's functionality are investigated. To divide LP modes, a 2-mode SDM demultiplexer (DEMUX) is utilized. A low pass filter (LPF) and a PIN (positive-intrinsic negative diode) detector are used to extract the data. The optical SDM signal is collected at the receiver plane using a 2-mode SDM de-multiplexer. The received power ($P_{received}$), which depends on the transmitted power ($P_{transmitted}$), is expressed in (1) as:

$$P_{recieved} = P_{transmitted} \times \left[\frac{d_r^2}{(d_t+\theta R)^2}\right] \times 10^{-\rho R/10} \quad (1)$$

b. Rain attenuation

Rain is the primary component of attenuation that decreases the received signal and impacts the FSO link. It is expressed in (2) as:

$$\alpha_{rain} = \beta R_q \quad (2)$$

where α_{rain} represents the rain rate (mm/hr) and attenuation of rain (DB/km), respectively. The frequency and surrounding temperature affect the coefficients b and q.

c. Haze and fog attenuation

Particles of smoke and dust remain in the atmosphere for longer than rain due to atmospheric phenomena such as haze and fog weather. Therefore, they significantly worsen the FSO transmission systems perform. The expression for the attenuation of haze and fog is expressed in (3) as:

$$\alpha_{haze,fog} = \frac{3.912}{V}\left(\frac{\lambda}{550nm}\right)^{-z} \quad (3)$$

where z is the scattering particle's size distribution, k is the wavelength in nm, V is the visibility (km), and $\alpha_{haze,fog}$ is the haze/fog attenuation (dB/km). Equation (4) defines the attenuation in snow conditions as:

$$\alpha_s = \begin{cases} 0.72 S_f^{(5.42\times10^{-5}\lambda)+5.49} \; in\ case\ of\ WSF \\ 1.38 S_f^{(1.02\times10^{-4}\lambda)+3.78} \; in\ case\ of\ DSF \end{cases} \quad (4)$$

Furthermore, climate-related changes in the air's refractive index structure, or C_n^2, Air intillation causes the strongest BER and varies from 10^{-17} $m^{-2/3}$ for weak turbulence (WT) to 10^{-13} $m^{-2/3}$ for strong turbulence (ST). It also affects the intensity of the optical received signal. Several models, such as gamma-gamma, K-distribution, and log-normal, are used to model the FSO channel when there is an air turbulence effect. The K-distribution model is used for ST weather, while the log-normal model is used for weather in WT and clear air (CA). This study considers the gamma-gamma (GG) distribution since it is a popular model that works with a number of turbulences, including WT, moderate turbulence (MT), and ST. The equation (5) defines the probability density function (PDF):

$$PDF(h_s) = \frac{2\,(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} h_s^{\frac{\alpha+\beta}{2}} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta h_s}\right); h_s > 0 \quad (5)$$

where α, β are defined in (6) and (7) as:

$$\alpha = \left\{ exp\left[\frac{0.49\sigma_r^2}{(1+0.65d^2+1.11\sigma_r^{\frac{12}{5}})^{\frac{7}{6}}}\right]^{-1} \right\}^{-1} \quad (6)$$

$$\beta = \left\{ exp\left[\frac{0.51\sigma_r^2(1+0.69\sigma_r^{12/5})^{-5/6}}{(1+0.9d^2+0.62\sigma_r^{12/5}}\right]^{-1} \right\}^{-1} \quad (7)$$

where α, β, h_s, $K_n(.)$, d, and σ_r^2 contains the number of eddies, whether large and small, the amount of weather-induced signal attenuation, this means that the Rytov variance is one of the dependent variables on C_n^2, the gamma function, and the normalized receiver collection lens. For WT, MT, and ST, the values of C_n^2 are 1×10^{-17} $m^{-2/3}$, 5×10^{-15} $m^{-2/3}$, and 1×10^{-13} $m^{-2/3}$, respectively. Rytov variance is used to categorize these turbulences into three types: WT, MT, and ST, σ_r^2, which depend on C_n^2 and is expressed in (8).

$$\sigma_R^2 = 1.23 C_n^2 K^{7/6} R_{FSO}^{11/6} \quad (8)$$

Furthermore, the Rytov variance provides an important difference amongst the various FSO links, as if less than $1\sigma_R^2$, then that means WT occurs, in contrast, MT happens if σ_R^2 is almost equal to 1, ST occurs if σ_R^2 is more than 1. The turbulence is saturated if σ_R^2 approaches infinity.

Phase induced intensity (PIIN) noise, the three types of noise that are present here are shot noise, thermal noise, and other noises. The PIIN noise is expressed in (9).

$$PIIN = \frac{(P_{RS})^2 B_e B_o (W+1)}{C} \quad (9)$$

where B_e is the electrical bandwidth in Hz and e is the electron charge in C. The equation (10) expressed the shot noise formula.

$$Shot\ noise = 2e\beta_e R < I > \quad (10)$$

Thermal noise is represented in (11) as:

$$Thermal\ Noise = \frac{4k_B T B_e}{R_L} \tag{11}$$

where T is the receiver's absolute temperature and R_L is its load resistance, and k_B is the Boltzmann constant. Next, the SNR is stated as in (12).

$$SNR = \frac{(I)^2}{Shot\ noise + PIIN\ noise + Thermal\ Noise} \tag{12}$$

The bit error rate (BER) is expressed in terms of Q-factor and SNR as in (13) and (14) respectively.

$$BER = \frac{1}{2} erfc\left(\frac{Q}{\sqrt{2}}\right) \tag{13}$$

$$BER = \frac{1}{2} erfc\left(\frac{\sqrt{SNR}}{2\sqrt{2}}\right) \tag{14}$$

Furthermore, the error complementary function is indicated by $erfc$.

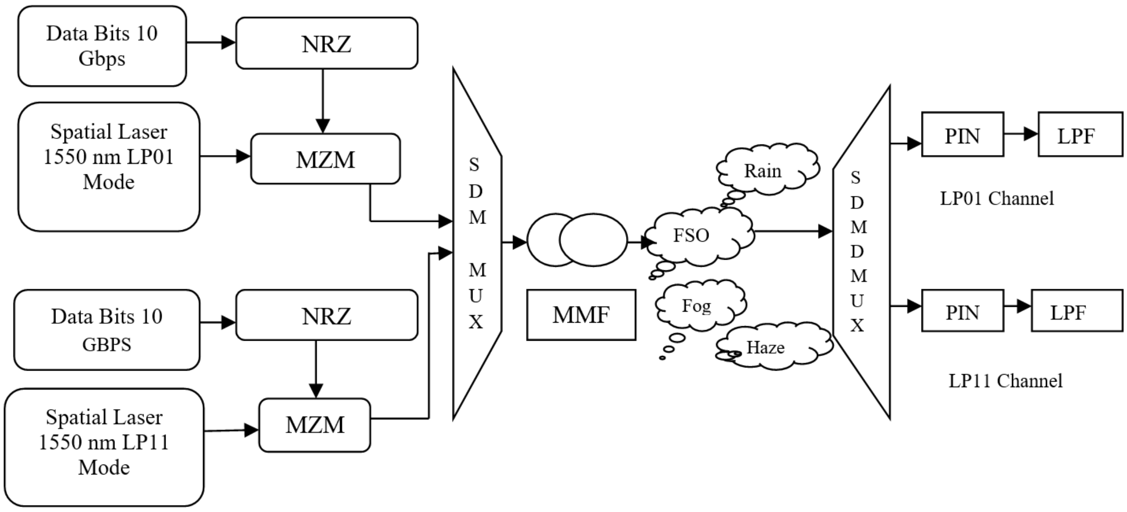


Figure 1. Block diagram of high-speed space division multiplexing based integrated fiber transmission system transmission system

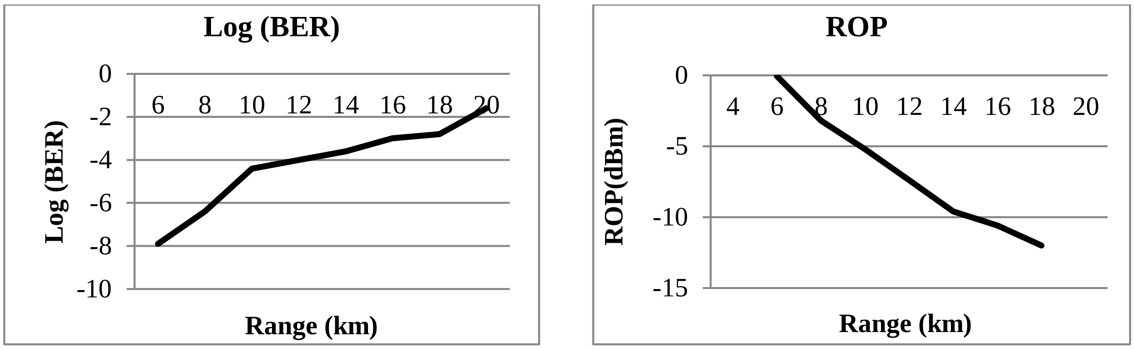
3. RESULTS AND DISCUSSION

In this work, high speed space division multiplexing based integrated fiber/FSO transmission system and its impact on atmospheric conditions is demonstrated. Four weather conditions are categorized based on the results. The Figure 2 shows the system results under clear sky conditions. The CA condition results are demonstrated for log (BER) and ROP in Figure 2 (a) and 2(b) respectively.

With clear weather, this transmission system has achieved a very low attenuation of 0.138 dB/km, which is an extremely less value when the sky is clear. Shorter FSO lines operate better than longer ones, with low log (BER) and good received signal quality. This system has a log (BER) of -7.9 and a maximum FSO range of 6 km. From Figure 2(b) it is observed that range has effect on ROP. The shorter ranges have high ROP compared to longer ranges. At 6 km FSO range, the ROP is -0.02 dB and -12 dB when the distance between transmitter and receiver is 18 km. The Figure 3 shows the FSO model performance versus FSO propagation range under snowy conditions. The Figure 3(a) and 3(b) shows log (BER) under dry and wet snow (WS) and 3 (c) and 3(d) shows ROP under dry and WS weather conditions.

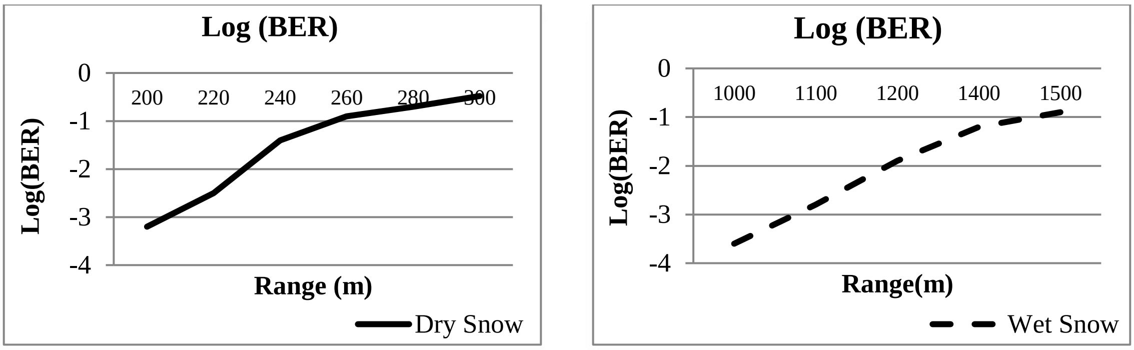
Attenuation is caused due to the snow fall and it differs based on the type of snowfall weather it is dry or wet. The attenuation caused due to WS is 13.78 dB/km. This FSO system propagates maximum propagation range of 1000 m under WS with -0.13 dBm and under dry snow (DS) it propagates 220 m with 0.51 dBm and the log (BER) of -3.2 for DS and -3.6 for WS. The Table 1 shows the FSO range and ROP at snow conditions.

The system's performance is evaluated under Turbulence conditions such as MT, ST, and WT. The Figure 4 displays the log (BER) under turbulence conditions. Figure 4 demonstrates that the performance decreases as the distance range increases and the turbulence gets stronger. This FSO model propagates 860 m with log (BER) of -2.2 under weak turbulence. For the same range, the log (BER) for MT and ST are 0.5 and -2.1 respectively.

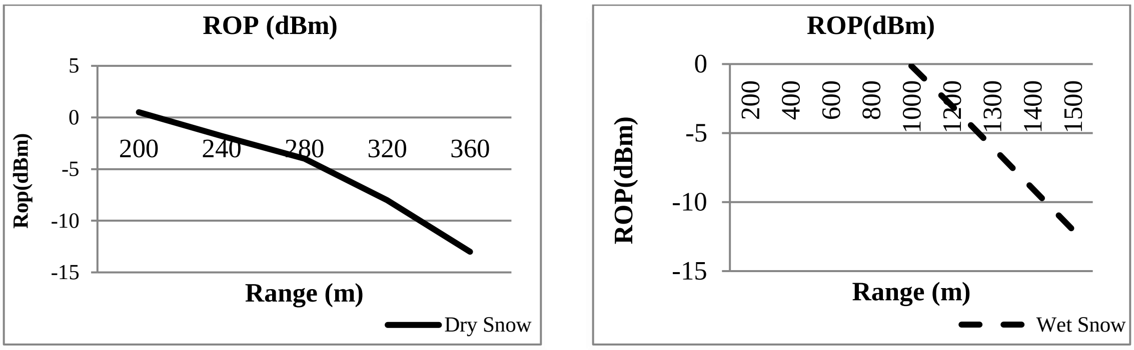


(a) (b)

Figure 2. The results under clear air for 2 (a) Log (BER) and 2(b) ROP (dBm)



(a) (b)



(c) (d)

Figure 3. FSO model performance under snowy versus FSO propagation range (a) Log (BER) of DS, (b) Log (BER) of WS, (c) ROP of DS, and (d) ROP of WS

Table 1. shows the proposed FSO's FSO range and matching ROP for snow conditions at BER -3

Snow condition	FSO range (m)	ROP (dBm)
WS	1000	-0.13
DS	220	0.51

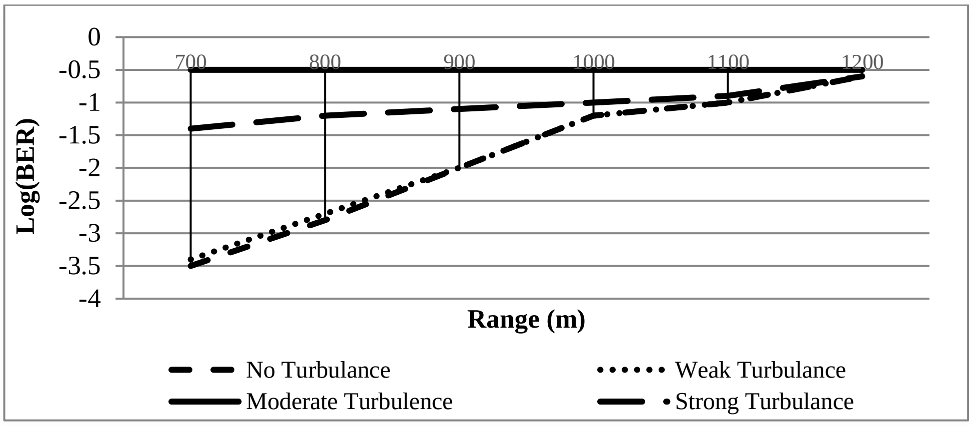


Figure 4. Presented FSO model under turbulence

4. CONCLUSION

High speed space division multiplexing based integrated fiber/FSO transmission system and its impact on atmospheric conditions is presented in this work. This paper presents and investigates the high-speed LP modes-based SDM transmission in the FSO communication link under various atmospheric conditions, including turbulence and snow. In a 10.5 km MMF link, two 10 Gbps signals are transported over two different LP modes (LP01 and LP11), with the FSO transmission ranges being impacted by the external atmospheric weather. When it is exposed to these conditions, ROP and log (BER) are used to express the performance. This FSO can go up to 6 km in CS conditions. The minimum range is 220 meters in DS. Considering the effects of various turbulence types, under WT conditions, up to 860 meters can be propagated by the suggested FSO model. Compared to earlier models, this model has achieved better performance under various weather conditions. Thus, this method can be used in metropolitan areas and cities where connecting fiber cable is costly and challenging. In future, hybrid multiplexing techniques will be implemented to further improve the FSO performance under various weather conditions.

REFERENCES

[1] V. K. Mani and V. Kumar, "Free-space optical channel performance under atmospheric losses using orthogonal frequency division multiplexing," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 25, no. 3, pp. 1571–1579, Mar. 2022, doi: 10.11591/ijeecs.v25.i3.pp1571-1579.

[2] M. M. A. Eid and A. N. Z. Rashed, "Hybrid NRZ/RZ line coding scheme based hybrid FSO/FO dual channel communication systems," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 22, no. 2, pp. 866–873, May 2021, doi: 10.11591/ijeecs.v22.i2.pp866-873.

[3] F. El-Nahal, T. Xu, D. AlQahtani, and M. Leeson, "A bidirectional wavelength division multiplexed (WDM) free space optical communication (FSO) system for deployment in data center networks (DCNs)," *Sensors*, vol. 22, no. 24, pp. 1–13, Dec. 2022, doi: 10.3390/s22249703.

[4] V. Mai and H. Kim, "Beam steering and divergence control using variable focus liquid lenses for WDM FSO communications," *IEEE Photonics Technology Letters*, vol. 34, no. 22, pp. 1226–1229, Nov. 2022, doi: 10.1109/LPT.2022.3210024.

[5] H. Saidi and N. Hamdi, "End-to-end performance of DF multihop hybrid RF/FSO system using MPPM coding and MIMO technique under dependent GG turbulence channels," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 19, no. 2, pp. 811–818, Aug. 2020, doi: 10.11591/ijeecs.v19.i2.pp811-818.

[6] A. M. Dehnaw *et al.*, "Integrated sensor-optics communication system using bidirectional fiber and FSO channels and hybrid deep learning techniques," *Sensors*, vol. 23, no. 20, pp. 8434, Oct. 2023, doi: 10.3390/s23208434.

[7] M. Kamal *et al.*, "Free space optics transmission performance enhancement for sustaining 5G high capacity data services," *Micromachines*, vol. 13, no. 8, pp. 1248, Aug. 2022, doi: 10.3390/mi13081248.

[8] S. El-Mottaleb, M. Singh, A. Chehri, H. Ahmed, M. Zeghid, and A. Khan, "Capacity enhancement for free space optics transmission system using orbital angular momentum optical code division multiple access in 5G and beyond networks," *Energies*, vol. 15, no. 19, pp. 1–19, Sep. 2022, doi: 10.3390/en15197100.

[9] 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, doi: 10.1109/JPHOT.2021.3113650.

[10] F. T. Mahmood, A. H. Ali, and A. H. Ali Haeder, "Weathers effect on the free space optics communication system," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 31, no. 1, pp. 222–228, 2023, doi: 10.11591/ijeecs.v31.i1.pp 222-228.

[11] M. Singh, J. Kříž, M. M. Kamruzzaman, V. Dhasarathan, A. Sharma, and S. A. Abd El-Mottaleb, "Design of a high-speed OFDM-SAC-OCDMA-based FSO system using EDW codes for supporting 5G data services and smart city applications," *Frontiers in Physics*, vol. 10, pp. 1–11, 2022, doi: 10.3389/fphy.2022.934848.

[12] S. Sinha and C. Kumar, "Evaluation of a high-speed hybrid OAM-OFDM-MDM multiplexed coherent FSO system under desert conditions," *Optica Applicata*, vol. 53, no. 3, pp. 431–445, 2023, doi: 10.37190/oa230308.

[13] S. A. Abd El-Mottaleb, M. Singh, H. Y. Ahmed, M. Zeghid, and K. S. Nisar, "Performance analysis of a spectral-efficient high-speed hybrid PDM-MDM enabled integrated MMF-FSO transmission," *IEEE Photonics Journal*, vol. 15, no. 4, pp. 1–12, Aug. 2023, doi: 10.1109/JPHOT.2023.3292550.
[14] Y. Dong, C. Zheng, P. Lin, and T. Wang, "Free space optical communication system based on the combination of WDM and polarization multiplexing," in *2021 13th International Conference on Advanced Infocomm Technology (ICAIT)*, IEEE, Oct. 2021, pp. 114–117. doi: 10.1109/ICAIT52638.2021.9702040.
[15] C.-H. Yeh, W.-P. Lin, S.-Y. Jiang, S.-E. Hsieh, C.-H. Hsu, and C.-W. Chow, "Integrated fiber-FSO WDM access system with fiber fault protection," *Electronics*, vol. 11, no. 13, pp. 1–11, Jul. 2022, doi: 10.3390/electronics11132101.
[16] S. A. Abd El-Mottaleb, M. Singh, S. Alshathri, W. El-Shafai, and M. H. Aly, "Enhancing security and capacity in FSO transmission for next-generation networks using OFDM/OCDMA-based ICSM codes," *Frontiers in Physics*, vol. 11, pp. 1–12, Aug. 2023, doi: 10.3389/fphy.2023.1231025.
[17] X. Weng and L. T. Vuong, "Fractal, diffraction-encoded space-division multiplexing for FSO with misalignment-robust, roaming transceivers," *Scientific Reports*, vol. 12, no. 1, pp. 1–9, Feb. 2022, doi: 10.1038/s41598-022-06660-3.
[18] F. A. Barbosa and F. M. Ferreira, "On a scalable path for multimode SDM transmission," *Journal of Lightwave Technology*, vol. 42, no. 1, pp. 219–228, Jan. 2024, doi: 10.1109/JLT.2023.3308777.
[19] X.-H. Huang *et al.*, "WDM free-space optical communication system of high-speed hybrid signals," *IEEE Photonics Journal*, vol. 10, no. 6, pp. 1–7, Dec. 2018, doi: 10.1109/JPHOT.2018.2881701.
[20] 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, 2024, doi: 10.11591/ijeecs.v33.i1.pp159-166.
[21] M. T. Rahman, M. Rahman, M. M. Hossain, and M. S. H. Chowdhury, "Integration of optical and free space optics network architecture for high-speed communication in adverse weather using suitable optical bands," *International Journal of Electrical and Electronics Research*, vol. 11, no. 2, pp. 328–333, May 2023, doi: 10.37391/ijeer.110212.
[22] J. Zhang, F. Li, J. Li, and Z. Li, "228 Gb/s vector-mode-division-multiplexing signal transmission in free-space based on optical frequency comb," in *2017 16th International Conference on Optical Communications and Networks (ICOCN)*, IEEE, Aug. 2017, pp. 1–3. doi: 10.1109/ICOCN.2017.8121482.
[23] Y. Zhang *et al.*, "20 Gbps free-space optical chaotic communication based on orbital angular momentum multiplexing," in *2023 Asia Communications and Photonics Conference/2023 International Photonics and Optoelectronics Meetings (ACP/POEM)*, IEEE, Nov. 2023, pp. 1–4. doi: 10.1109/ACP/POEM59049.2023.10369467.
[24] K. Zou *et al.*, "High-capacity free-space optical communications using wavelength- and mode-division-multiplexing in the mid-infrared region," *Nature Communications*, vol. 13, no. 1, pp. 1-10, Dec. 2022, doi: 10.1038/s41467-022-35327-w.
[25] T. Siegel and S.-P. Chen, "Investigations of free space optical communications under real-world atmospheric conditions," *Wireless Personal Communications*, vol. 116, no. 1, pp. 475–490, Jan. 2021, doi: 10.1007/s11277-020-07724-1.
[26] F. Nashwan *et al.*, "Design and analysis of dense wavelength division multiplexing free space optical (DWDM FSO) system with multiple input multiple output (MIMO)," in *2022 2nd International Conference on Emerging Smart Technologies and Applications (eSmarTA)*, IEEE, Oct. 2022, pp. 1–8. doi: 10.1109/eSmarTA56775.2022.9935482.
[27] M. Singh *et al.*, "Performance investigation of a high data rate mode division multiplexed-free space optics link under harsh weather conditions," *Frontiers in Physics*, vol. 9, Aug. 2021, pp.1-9. doi: 10.3389/fphy.2021.743545.
[28] A. Almogahed, A. Amphawan, F. Mohammed, and A. Alawadhi, "Performance improvement of mode division multiplexing free space optical communication system through various atmospheric conditions with a decision feedback equalizer," *Cogent Engineering*, vol. 9, no. 1, Dec. 2022, doi: 10.1080/23311916.2022.2034268.

BIOGRAPHIES OF AUTHORS

Kakarla Phaneendra Kumar received the B.Tech. degree in electronics and communication engineering from J.N.T. University in 2004 and master of technology degree in digital electronics and communication systems from J.N.T. University in 2006. Presently, pursuing PhD in the department of electronics and communication engineering, Sri Venkateswara University College of Engineering, Tirupati. He can be contacted at email: phanieceobvp@gmail.com.

T. Sreenivasulu Reddy received the B.Tech. degree in electronics and communication engineering from Sri Venkateswara University in 1990 and master of engineering degree in digital electronics from Karnataka University in 1996, and the PhD degree from Sri Venkateswara University, Tirupati, India, in 2012. He joined the department of electrical and electronics engineering, College of Engineering, S.V. University, Tirupati, India, as an associate professor in 2007. Presently, working as a professor in the Department of Electronics and Communication Engineering. He is a fellow of IETE and a member of ISTE. He can be contacted at email: mettu86@yahoo.co.in.