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RESEARCH ARTICLE

Investigation and performance analysis of LG-SDM-FSO transmission system using 2 µm laser beam under atmospheric turbulences

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Abstract The deployment of free-space optical (FSO) communication links is simple, fast and economical than optical fiber networks. However, it presents weakness in front of low visibility and its performance is deteriorated by atmospheric turbulence due to different weather conditions. In this paper, we have investigated an effective FSO system by integrating space division multiplexing (SDM) that can be used to enhance the information-carrying capabilities of FSO links. In addition, we have used a laser beam operating at 2 µm wavelength as an optical link in the proposed SDM-FSO system, which relates the telecom performance and the FSO link state, in terms of turbulence. In this system, information channels are transmitted concurrently over distinct Laguerre–Gaussian modes (LG) of the laser beam, where each mode is used to carrying independent 10 Gbps data stream. The availability of the LG-SDM-FSO system in dependence on weather conditions and on FSO link parameters, such as transmitted optical power, geometric loss, beam divergence, receiver aperture diameter, and link range, is discussed. The performance of our system is evaluated based on eye diagram, Q Factor and BER measurements.

Keywords Free space optics (FSO) · Space division multiplexing (SDM) · Laguerre–Gaussian modes (LG) · 2 µm wavelength region · Atmospheric turbulence

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Introduction

The need to transmit huge amounts of information in safe and fast ways without the risk of getting lost has prompted scientists and researchers to work with the FSO system exploiting the free space as a means of fast and secure communication. The technique of FSO is almost the same as the theory of optical fiber transmission. The difference is that FSO is a powerful technology capable of transmitting information at very high speeds from one point in the atmosphere to another using a single beam of light. This technology has many benefits including high-speed data rates, large capacity and long transmission distance, free from electromagnetic interference problems, and cost effective infrastructure [1–6]. In addition, to the fact that the safety factor of this technology is very strong compared to wireless transmission, this technology has made a huge difference from using cables to using air [7]. Since previous years, FSO systems have been used in various applications such as aerospace, terrestrial applications as a solution to extend and connect networks, and military field [8, 9]. Despite many characteristics, however, there are many problems facing this technology, atmospheric conditions are one of the challenges in FSO communications, which can lead to signal loss and distorts it. Attenuation is mainly the result of atmospheric conditions such as fog, rain, snow and turbulence due to fluctuations in the refraction index, which can cause significant attenuation and distortion [10–12]. There are different solutions to these problems, in particular with the choice of an appropriate wavelength. The systems currently in use operate at wavelengths in the visible and near infrared, located in atmospheric transmission windows.

2 µm wavelength region has recently attracted huge attention for several applications such as spectroscopy, gas detection, laser ablation, light detection and ranging

(LIDAR) for remote sensing, plastic and glass processing, as well as in the medical field [13]. Furthermore, it has become a promising candidate to be the next FSO communication window [14], yet the area remains unexploited. On the other hand, the evolution of optical telecommunication networks requires the search for systems offering a high bandwidth and access to multiple resources. Many researchers have been interested in spatial multiplexing by the principle of SDM, which opens up a new dimension for optical transmission since space is a dimension that has not been exploited. This technology is based on transmission of individual data signals over multiple spatial paths of a single optical fiber [15]. Among the available spatial multiplexes, we mention: Mode Division Multiplexing (MDM) over Multi-Mode Fiber (MMF) and Few-Mode Fiber (FMF) [16]. From this point on, MDM could be a promising approach to increase the aggregate bandwidth if reliable transmission over long distances can be achieved. MDM has been proposed for FSO systems based on the use of different modes that are transmitted over multiple channels through a single optical channel [17–25]. It is worth mentioning that the Laguerre–Gaussian (LG), Hermit–Gaussian (HG) and Linearly Polarized (LP) are the most preferred modes used in optical communication [18–22].

This paper aims to design an effective LG-SDM-FSO system using a laser beam operating at 2 μm wavelength, to the author's best knowledge, was never reported in any work. Using simulations performed by the OptiSystem software, we report feasible N × 10 Gbps channels carrying independent data streams, in the proposed LG-SDM-FSO system with acceptable performance. This analysis is performed in terms of eye diagram, Q factor and BER. We consider geometric loss, and Rytov variance to model the effect of scintillation. A series of numerical simulations are analyzed for the different meteorological conditions such as very clear weather, light fog, moderate fog, and heavy fog. In addition, the variations of the different system parameters such as transmitted optical power, beam divergence, receiver aperture diameter, bit rate and number of modes.

The remainder of the paper is organized as follows: Sect. "LG- SDM- FSO system description" represents the design of the LG-SDM-FSO system. Section 3 represents simulation parameters and describes the results and discussions, followed by the conclusion in Sect. 4.

LG-SDM-FSO system description

The simulation configuration of the proposed hybrid LG-SDM-FSO system is shown in Fig. 1. In this system, optical transceivers communicate through the air to form direct point-to-point links. Firstly, the spatial transmitter, such as spatial vertical-cavity surface-emitting laser (spatial VCSEL), which emits the laser beam, is used to generate different sets of modes (LG, LP or HG) that operate over one wavelength (2 μm). In the proposed system (Fig. 1), different LG modes, generated by the spatial laser beam, are used to carry different channels with the SDM technique over 2 μm optical spatial carrier. It is worth noted that a laser beam with an ideal Gaussian intensity profile is the most frequently used model for the real laser-beam description. Since most FSO systems use large divergence beams (of the order of mrads) to allow easy alignment, the Gaussian beam that propagates along the z-axis can be characterized at the transmitter by the beam spot size to specifies the beam waist width, the radius of curvature to specifies the forming of the beam, and the beam divergence, which defines the spreading of the beam when propagating toward infinity. The transverse spatial profile of the LG mode in the source plane $z = 0$ is described by [26]:

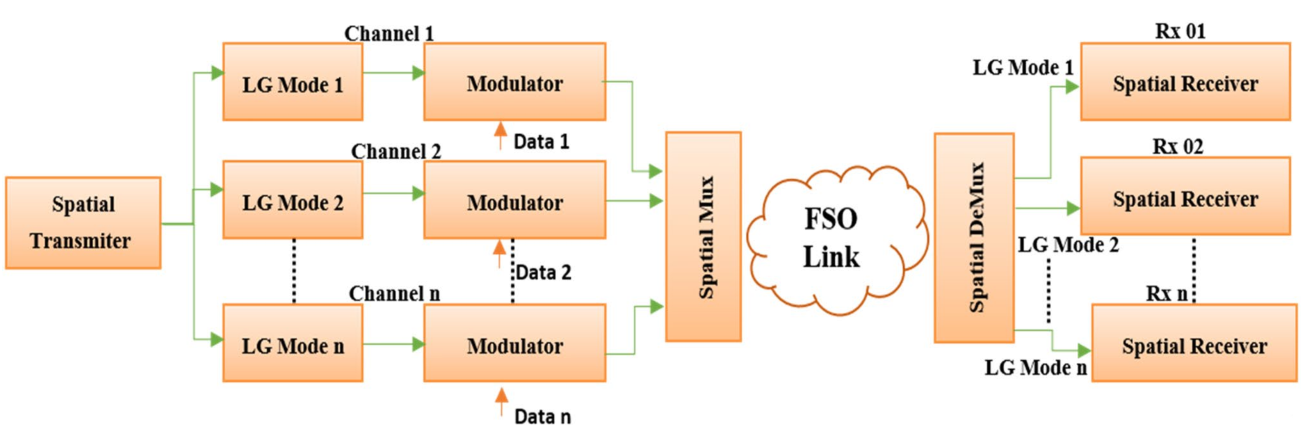

Fig. 1 Overall diagram of the proposed LG-SDM-FSO system

$$\psi_{n,m}(r,\varphi) = (\frac{2r^2}{\omega_0^2})^{|\frac{n}{2}|} L_m^n\left(\frac{2r^2}{\omega_0^2}\right)\exp\left(\frac{j\pi r^2}{\lambda R_0}\right)\begin{cases}\sin(|n|\varphi), n \geq 0\\ \cos(|n|\varphi), n > 0\end{cases} \tag{1}$$

where m and n describe the azimuthal and radial indexes, respectively. R_0 refers to the radius of curvature, ω_0 the spot size and L_m^n refers to Laguerre Polynomial.

On the transmission part, Channel 1 optical carrier is set to mode 1, channel 2 goes to mode 2, channel 3 goes to mode 3, etc., each with 10 Gbps non-return to zero (NRZ) modulated data. However, an optical modulator is used to provide a modulation format on the digital data. The results of optical modulators are combined, using SDM for sending across the FSO link. On the reception part, a spatial demultiplexer is used to separate the different LG modes (the channels), followed by spatial receivers. Each receiver consists of a mode selector, which selects the particular mode and a photodetector, PIN photodiode, to detect and convert the received signals from optical to electrical signals.

The received signal power for FSO parameter range depends on the propagation distance between the transmitter and the receiver. The attenuation of the laser beam power depends on two main parameters: atmospheric attenuation and geometrical loss. The first parameter describes the attenuation of the laser beam power in the atmosphere. The second parameter occurs due to spreading of the laser beam between the transmitter and the receiver. The received signal power for FSO parameter range can be defined by the following equation [27]:

$$P_{\text{recived}} = P_{\text{transmitted}}\frac{d_R^2}{\left(d_T + \theta L\right)^2}10^{\frac{-\alpha L}{10}} \tag{2}$$

where d_R represents receiver aperture diameter, d_T is a transmitter aperture diameter, θ is a beam divergence, L is the range and α is atmospheric attenuation.

When FSO signals are transmitted through the air, they are typically affected by many atmospheric conditions like fog, rain, and scintillation. The specific attenuation due to fog can be determined using the following equation:

$$\beta(\lambda)_{fog} = \left(\frac{3,91}{L}\right)\left(\frac{\lambda}{550}\right)^{-q} \tag{3}$$

where L (km) represents range of visibility, λ (nm) is the wavelength, and q is the distribution coefficient of scattering and it is determined by Kim and Kruse model [28, 29]. If the visibility range increases beyond 20 km, then the dependency of attenuation due to fog on wavelength reduces. Whereas, the attenuation due to the rain is independent of the wavelength.

Moreover, the major factor for the degradation of signal quality is scintillation. As the ground heats up from the sun, the air also heats up, this causes changes in the refractive index, which in turn alters the path that light takes in its propagation through air. This phenomenon induces attenuation of the power of the radiation affecting the performance of the links as well as their availability. If the size of the turbulent cells is smaller than the diameter of the laser beam, cause diffraction of the rays and distortions in the laser beam. The scintillation variance, given by the Rytov variance, for log-normal channel model, can be calculated with the following equation [30]:

$$\delta_{scin}^2 = 1.23.(K)^{\frac{7}{6}} C_n^2 L^{\frac{11}{6}} \tag{4}$$

where $K = \frac{2\pi}{\lambda}$ represents wave number, λ is wavelength (nm), C_n^2 is refractive index structure parameter $\text{m}^{-2/3}$, and L is link range (m).

The attenuation linked to scintillation is:

$$\gamma_{\text{scin}} = 2\delta_{\text{scin}} = 2\sqrt{(1.23.(K)^{\frac{7}{6}} C_n^2 L^{\frac{11}{6}}} \tag{5}$$

The other parameters decreasing FSO capacity is the geometric losses (A_{Geo}). For some FSO systems, the geometric loss does not change with time, which is a fixed value. Because the size of the emitted beam is much larger at the entrance of the receiver, part of the light is lost during transmission, which can be represented using the following equation [10]:

$$A_{\text{geo}} = \frac{S_L}{S_{\text{capture}}} = \frac{\frac{\pi}{4}(L.\theta)^2}{S_{\text{capture}}} \tag{6}$$

where S_L is spot size at the distance L, θ is the beam divergence,L is the distance between the transmitter and the receiver (the range), and S_{capture} is the capture area of the receiver.The proposed system is investigated and simulated using the parameters shown in Table 1.

Table 1 The parameters used in the simulation

Simulation parameter	Value
Range (L)	12 km
Wavelength (λ)	2 µm
Transmitter optical power ($P_{\text{transmitted}}$)	30 dBm
Bit rate per channel	10 Gbps
Spot size (ω_0)	15 µm
Transmitter aperture diameter (d_T)	20 cm
Beam divergence (θ)	0.25 mrad
Receiver aperture diameter (d_R)	20 cm
Spatial width of the photodetector (S_{capture})	30 µm
The scintillation model	Log-normal channel model

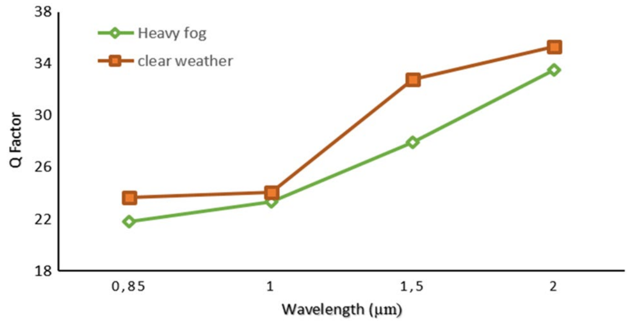

Fig. 2 Variation of the Q factor versus the wavelength under different weather conditions

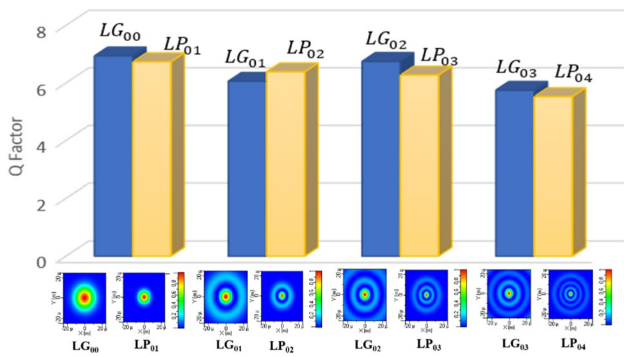

Fig. 3 Comparison between LG and LP modes for SDM-FSO in terms of Q factor

Results and discussion

In this part, we present the results obtained by the simulation of the proposed SDM-FSO system using beam laser operating at 2 µm wavelength. Before starting analysis, we have modeled the FSO link in order to determine its availability as a function of different wavelengths and atmospheric conditions. Firstly, we have investigated the FSO link performance of four different wavelengths (0.85 µm, 1 µm, 1.55 µm, and 2 µm), for a link range of one kilometer and transmitter optical power of 30 dBm. The results are done in two different metrological conditions; very clear weather and heavy fog, with attenuation values of 0, 15 and 19.77 dB, respectively [31].

Figure 2 shows the variation of *Q* factor as a function of wavelength for two atmospheric conditions (very clear weather and heavy fog). The results show that the 2 µm wavelength is the best option which has achieved the best quality in the different metrological conditions. The best *Q* factor of 35 and 34 is achieved for the wavelength of 2 µm in a clear weather and heavy fog, respectively (Fig. 2). Whereas, *Q* of 31 and 28 for 1.55 um, *Q* of *Q* of 24 and 23 for 1 um, and Q of 24 and 21 for 0.85 um, respectively. This comparison indicates the importance to choosing the wavelength for FSO links that can achieve the best quality, especially in poor atmospheric conditions (heavy fog). Moreover, the selection of the modes types in SDM is also an important issue. Therefore, the modes should be selected carefully to achieve the maximum range with best quality. Therefore, to investigate the performance of the proposed system according to different mode types, LG and LP modes are considered. The comparison between four LG modes (LG_{00}, LG_{01}, LG_{02} and LG_{03}) and four LP modes (LP_{01}, LP_{02}, LP_{03}, and LP_{04}) is shown in Fig. 3 for a maximum FSO link range of 12 Km and a geometric loss of 0.15 dB/Km. The results discussed in Fig. 3 show that LG modes present superior performance in terms of *Q* factor. *Q* factor

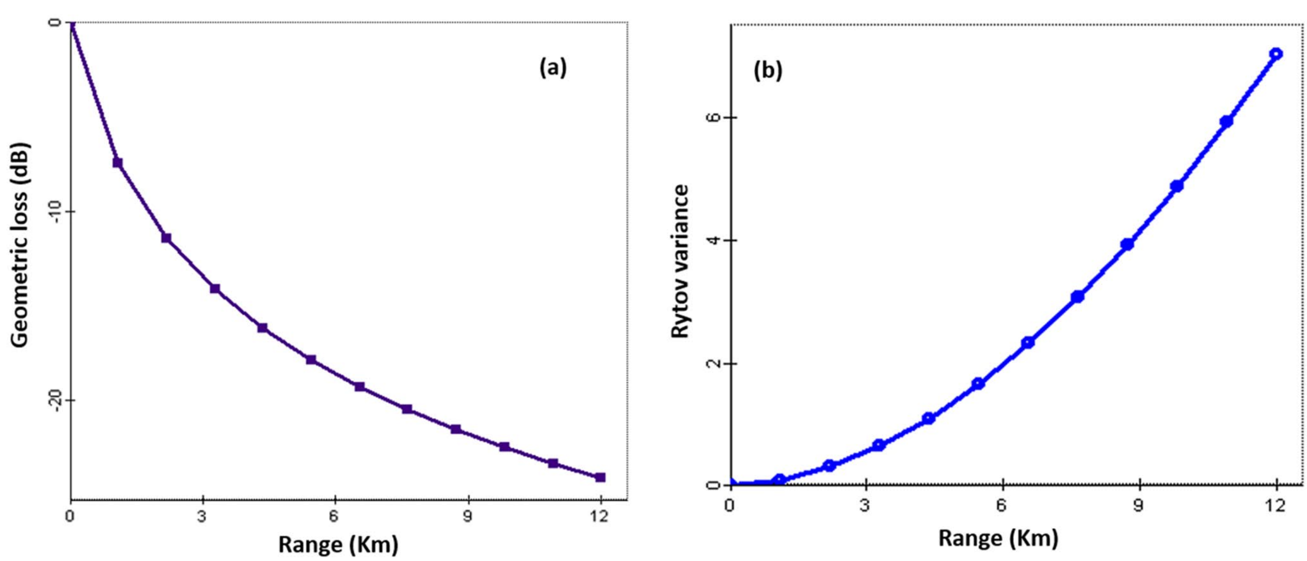

Fig. 4 The geometric losses **a** and the Rytov variance **b** as a function of link Range

more than 6 is achieved for almost LG modes. Hence, LG modes demonstrate more performance robust against FSO link effects. Only difference is that gives better results for LP_{02} mode. This comparison highlighted the importance of mode selection for SDM, which can achieve the best quality.

In the following section, we present the performance analysis of the proposed LG-SDM-FSO system, with four LG modes (LG_{00}, LG_{01}, LG_{02} and LG_{03}), under the impact of geometric losses and for various weather conditions, namely clear, light fog, moderate fog and heavy fog, and under the effect of scintillation. The availability calculation in the present work is based on the atmospheric attenuation and on the power budget analysis of FSO. Figure 4a and b represents the variations of the Rytov variance for the scintillation and the geometric losses, respectively, with increasing FSO link range. The effect of scintillation depends on the refractive index structure parameter C_n^2, which is given as a parameter to the FSO channel and the signal is attenuated according to the value of C_n^2. For our system, C_n^2 is taken to 10^{-13} $m^{-2/3}$, which corresponds to strong turbulence. Power loss caused by turbulence is modeled using the Rytov scintillation theory calculated according to Eq. 5. Power loss due to geometric losses is calculated using Eq. 6.

Furthermore, desired output is achieved at the receiver, which is visualized and inspected using BER analyzer. The block 'BER analyzer' allows us to evaluate the BER and the Q factor and still allows us to visualize the eye diagram. The performance of the proposed system is analyzed in terms of eye diagram, Q factor and BER, with respect to transmission distance over various atmospheric turbulence. Firstly, we have evaluated the proposed system in a clear weather conditions (with attenuation values of 0.15 dB/km) at a distance of 12 km. Figures 5 and 6 illustrate, respectively, the eye diagram of the four LG modes (four channel), and the variation of the Q factor and the BER as a function of the link range. Figure 5 shows good results presented by the good openings of the eye diagrams, which also indicates the better signal reception. The major degradation of the proposed system is due to the effect of scintillation, since the value of the geometric loss used in this simulation is 0.15 dB/km. In addition, Fig. 6a and b shows that the Q factor and BER values, of the four modes, are varied in the same manner and their performance becomes equivalent. They reached values of 7 and 10^{-10} for Q factor and BER, respectively, at link range of 12 km. From these results, it is observed that all the modes (channels) are reliably transported up to a FSO range of 12 km with acceptable quality. Beyond that, the signal performance degrades and the message signal cannot be intercepted without errors.

Further, we have analyzed the effect of different parameters on the performance of the proposed LG-SDM-FSO system as, atmospheric attenuation, transmitted optical power, laser beam divergence, receiver aperture diameter, transmission Bit rate and number of modes (number of channels).

a. **Effect of atmospheric attenuation**

Figure 7 illustrates the variation of the Q factor as a function of link range with different values of atmospheric attenuation for different metrological conditions: very clear weather (0.15 dB/km), light rain (2.61 dB/km), light fog (6.80 dB/km) and heavy fog (19.77 dB/km) [31]. From these results, we noted that the increase in atmospheric attenuation causes a loss of power at the receiver, which leads to a strong decrease in the value of the Q factor and thus decrease in the system performance. We noted also that the Q factor of the four modes (four channel) is varied in the same manner and their performance becomes equivalent for different weather conditions. The Q value of the four modes is reached a value of 7 at a distance of 12 km and in the case of very clear weather. The same value of Q is reached at a distance of 5 km in the case of light rain, at a distance of 3 km in the case of light fog, and at a distance of 1 km in the case of heavy fog.

b. **Effect of transmitted optical power**

Figure 8a and b shows the variation of the *Q* factor values of the four modes (four channels), as a function of the transmitted optical power. From these results, it is very clear that the increase in transmitted optical power enhances the performance of the proposed system. Here, it is seen that LG_{00} mode performs better for low transmitted optical power, preceding LG_{01} mode, LG_{02} mode, and LG_{03} mode. The Q value of 7 is achieved at a transmitted power of 30 dBm, in the case of LG_{00} mode. followed by LG_{01} and LG_{02} mode, with Q value of 6.8 and 6.5, respectively. This difference in the *Q* value indicates the better reception of the optical signal from LG_{00}, LG_{01} and LG_{02} mode than LG_{03} mode. Thus, the highest received power is obtained for LG_{00} mode, and lowest one for LG_{03} mode. High power guarantees reliable recovery of the transmitted information at the spatial receiver.

c. **Effect of laser beam divergence**

The divergence of a laser beam is a very important parameter in an FSO link, and its variation has remarkable impacts on the system performance. Figure 9 illustrates the system performance in terms of *Q* factor for the four modes (four channels) with a beam divergence angle increasing from 0 to 2 mrad. The results show that increasing the beam

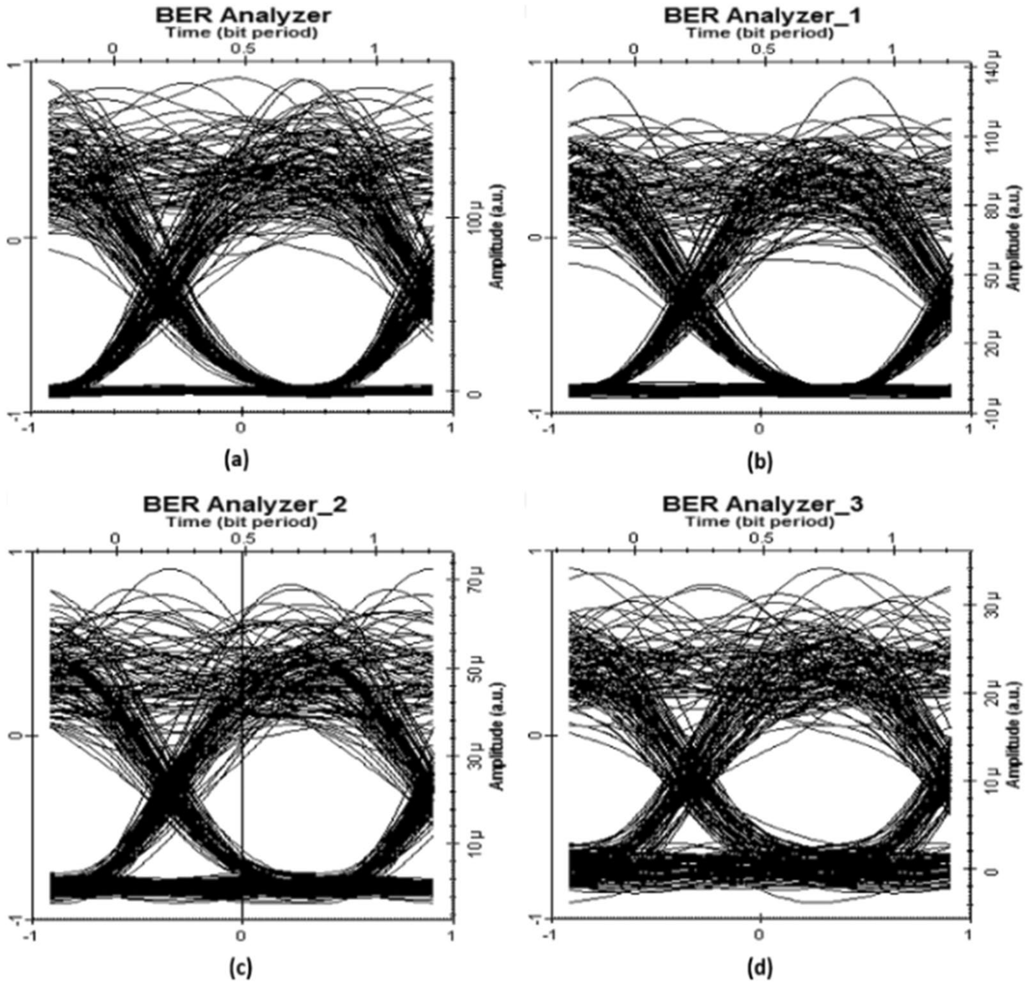

Fig. 5 The eye diagrams of the four modes (four channels): LG_{00} **a**, LG_{01} **b**, LG_{02} **c**, and LG_{03} **d**

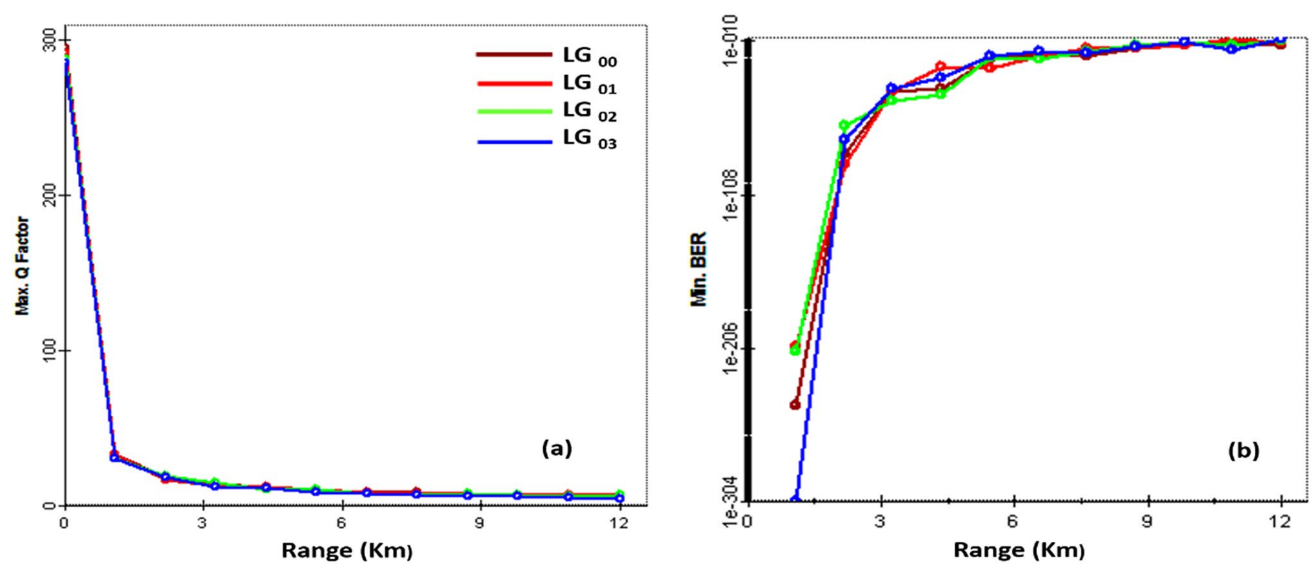

Fig. 6 Variation of the Q factor **a** and BER **b** of the four modes (channels) as a function of the link range

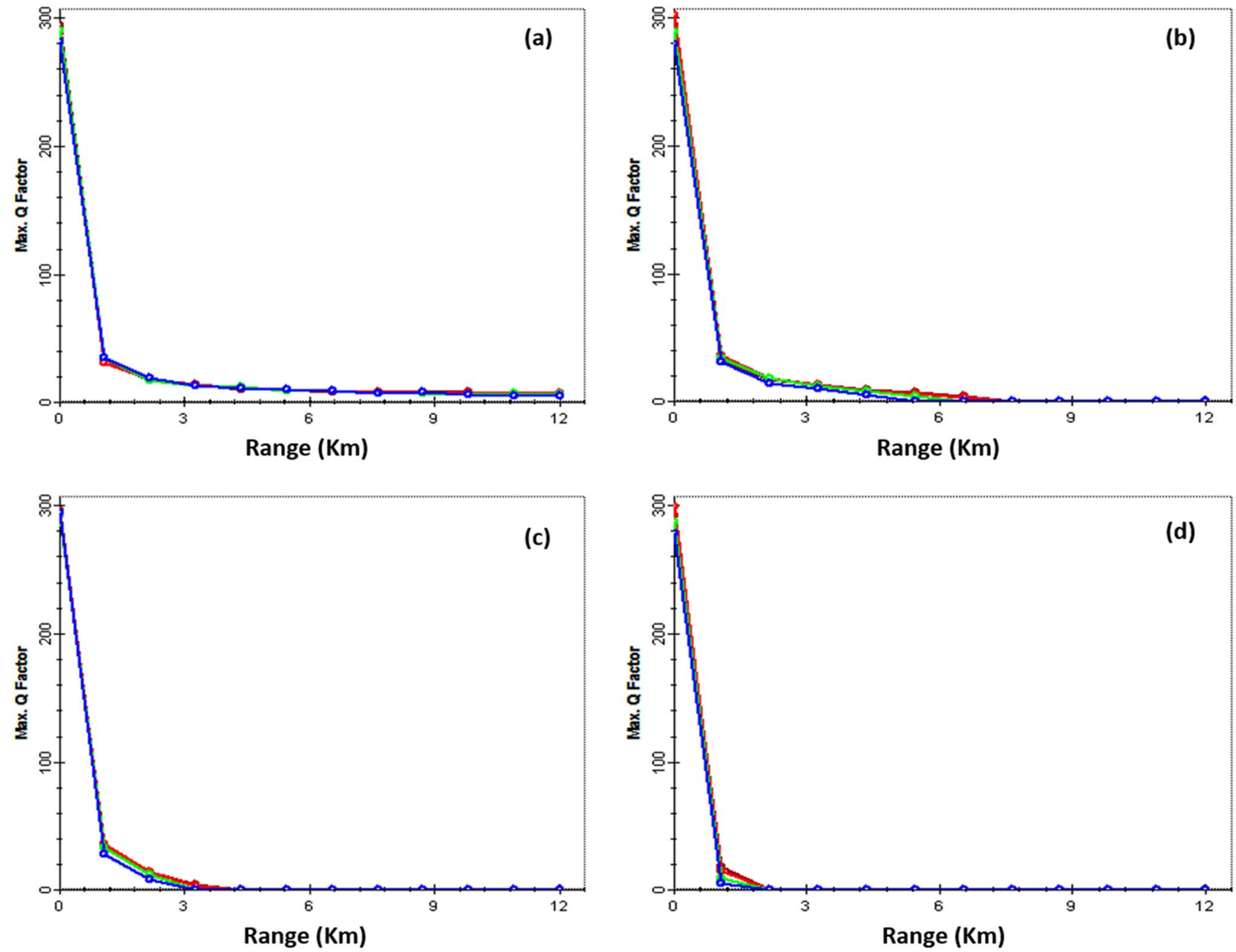

Fig. 7 The variation of the Q factors of the four modes as a function of link range for different weather conditions; very clear weather **a**, light rain **b**, light fog **c** and heavy fog **d**

divergence degrades the quality of the received signal, which should be expected, because increasing the beam divergence leads optical signal power loss to the environment. Since the spatial receiver has a limited field of view, only a portion of the laser beam power is detected by the receiver. From the comparison of the performance of the different modes according to the increase in the beam divergence, it can be seen that LG_{00} mode performs better for high beam divergence, which is the most robust against the atmospheric effects with Q factor of 6 at beam divergence of 0.5 mrad. Whereas LG_{03} mode appears the most affected by atmospheric effects, it can be achieved the same performance only at beam divergence of 0.25 mrad. From Fig. 9, it is also observed that all the modes show results up to laser beam divergence value of 0.25 mrad. No results are obtained beyond 1.25 mrad.

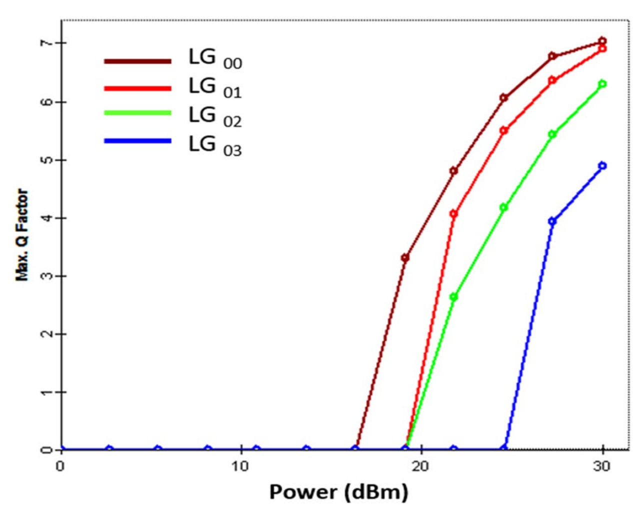

Fig. 8 Variation of the Q factor of the four modes as a function of the transmitted optical power

d. **Effect of receiver aperture diameter**

Figure 10 illustrates the variation of the Q factor of the four modes (four channels) as a function of the aperture diameter of an FSO receiver, increasing from 5 to 20 cm. It is observed that increasing the receiver aperture diameter enhances the performance of the proposed system, and thus, more optical signal power could be received. From the comparison of the performances of the different modes, when the receiver aperture diameter is 20 cm, it can be seen that LG_{00} and LG_{01} modes present the best performance with Q factor of 7, followed by LG_{02} mode with Q of 6. Whereas, Q of 5 is achieved in the case of LG_{03} mode, which presents the worst performance, as it is the most influenced by the presence of the secondary lobes.

e. **Effect of channel bit rate**

The performance of the proposed system has been also analyzed by varying the bit rate of the information carried by each mode (varying the bit rate per channel). Other parameters of the simulation are same as given in Table 1. Figure 11 shows the Q factor of the four modes (four channels) as a function of the link range for two different bit rate values: 10 Gbps and 20 Gbps. We noticed that the system performance declines as the data rate increases. The Q factor is an inversely proportional quantity related to the FSO link range and the data rate of each channel. The results indicate that the proposed system can successfully achieve a link range of 12 km at a bit rate per channel of 20 Gbps with a Q factor of 7. It is clear that at a shorter link range, for example, 1 km, the Q factor can reach a value of 35, which is sufficient. From Fig. 11, it is observed also that the four modes (four channels) are reliably transported up to an FSO range of 12 km regardless of the bit rate used.

f. **Effect of number of modes (number of channels)**

The objective of this part is to analyze the influence of the number of modes on the performance of the proposed system. We have increased the number of modes up to eight as follows: LG_{00}, LG_{01}, LG_{02}, LG_{03}, LG_{11}, LG_{12}, LG_{13}, and LG_{14}. Other parameters are same as given in Table 1. Figure 12a and b shows the variation of the Q factor and BER, respectively, of the eight modes (eight channels) as a function of the link range. From the results obtained, we noticed that the Q factor and BER values of the first four modes (LG_{00}, LG_{01}, LG_{02}, LG_{03}) are higher ($Q = 7$ and BER 10^{-10}) than those of the other four modes ($Q = 6$ and BER 10^{-9}), at a link range of 5 km. The difference in the value of Q and BER indicates the better reception of the signal from the first four modes. It can thus be concluded that the number of modes also limits the range of an FSO link. From Fig. 12, it is also observed that all the modes show results up to link range of 5 km. No results are obtained beyond 8 km.

Conclusion

FSO transmissions now offer the opportunity for high-speed communications in congested areas. A more detailed knowledge of the atmospheric channel under all conditions is therefore necessary in order to provide solutions to make this type of connection more reliable. The objective of this

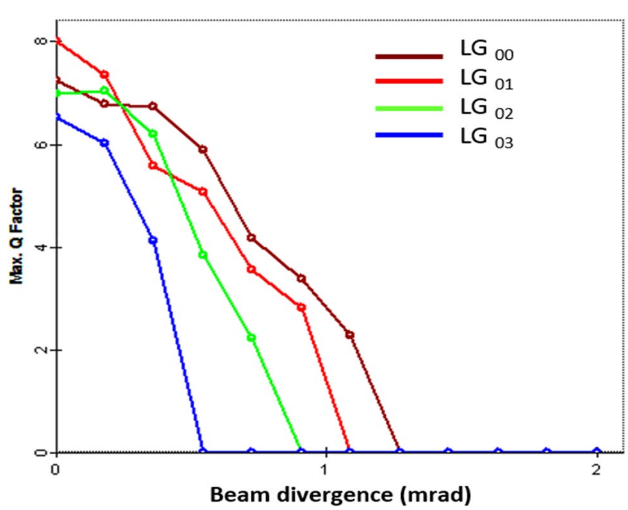

Fig. 9 Variation of Q factor of the four modes as a function of the laser beam divergence

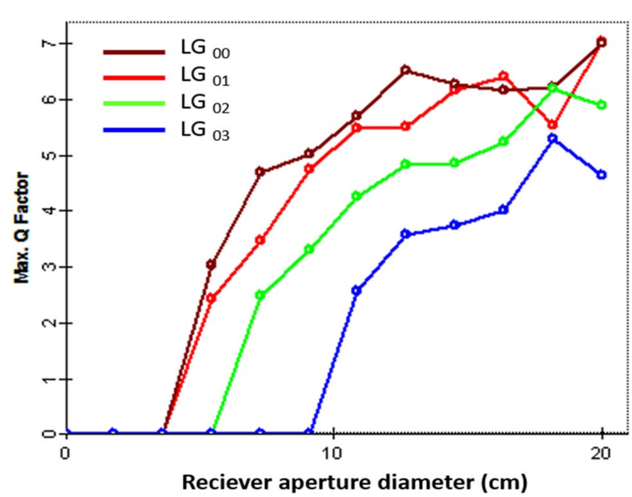

Fig. 10 Variation of Q factor of the four modes as a function of the receiver aperture diameter

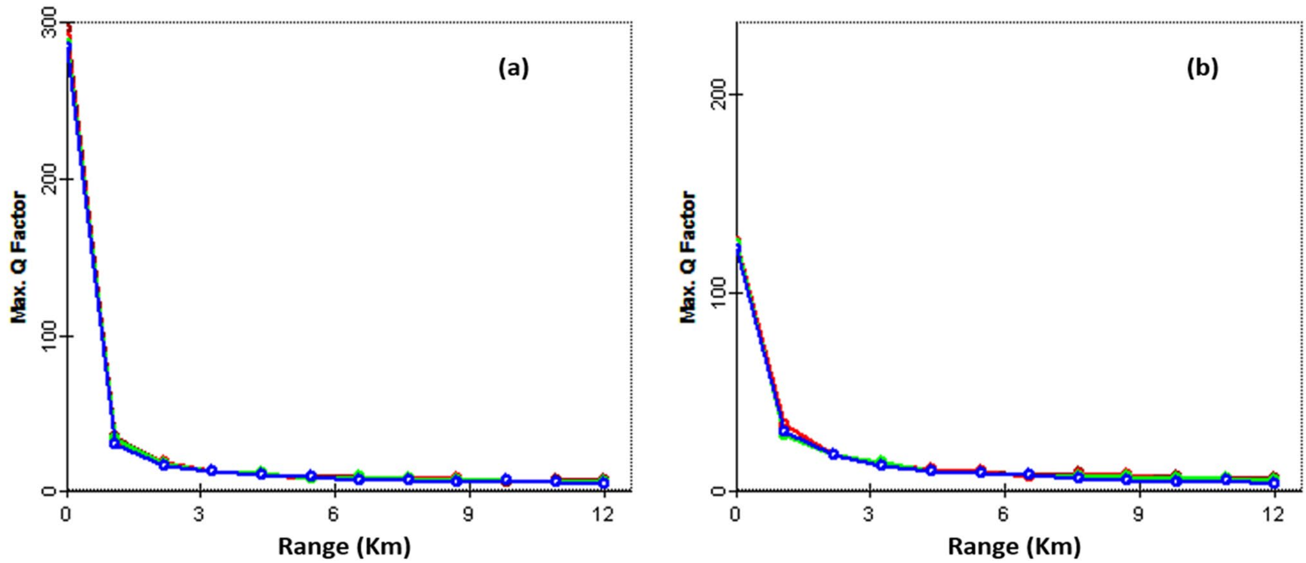

Fig. 11 Variation of Q factor of the four modes (four channels) as a function of link range for bit rate of 10 Gbps **a** and 20 Gbps **b**

paper is to evaluate the performance of an FSO system at $\lambda = 2$ µm using the SDM technique which represents one of the possible solutions for resource sharing in optical networks with maximum range. For this purpose, various numerical simulations are carried out to investigate the proposed LG-SDM-FSO system. Firstly, we have proved the choice of the wavelength and the type of modes used as 10 Gbps data carriers. The results showed that the 2 µm wavelength is the best option which has achieved the best quality in the different weather conditions. We have also demonstrated that the LG modes are the most preferred modes used in the proposed system. Next, we have studied the performance of our system in different atmospheric conditions. It is concluded from results from simulations that in a clear weather, the system successfully transmits a laser beam for a link range up to 12 km with good quality transmission. When the weather condition is changed, we have found that the range of an FSO link is reduced to 5 km, 3 km, and 1 km, with acceptable performance, under light fog, moderate fog, and heavy fog conditions, respectively. In addition, we have found that the maximum range in the proposed system increases as the transmitter

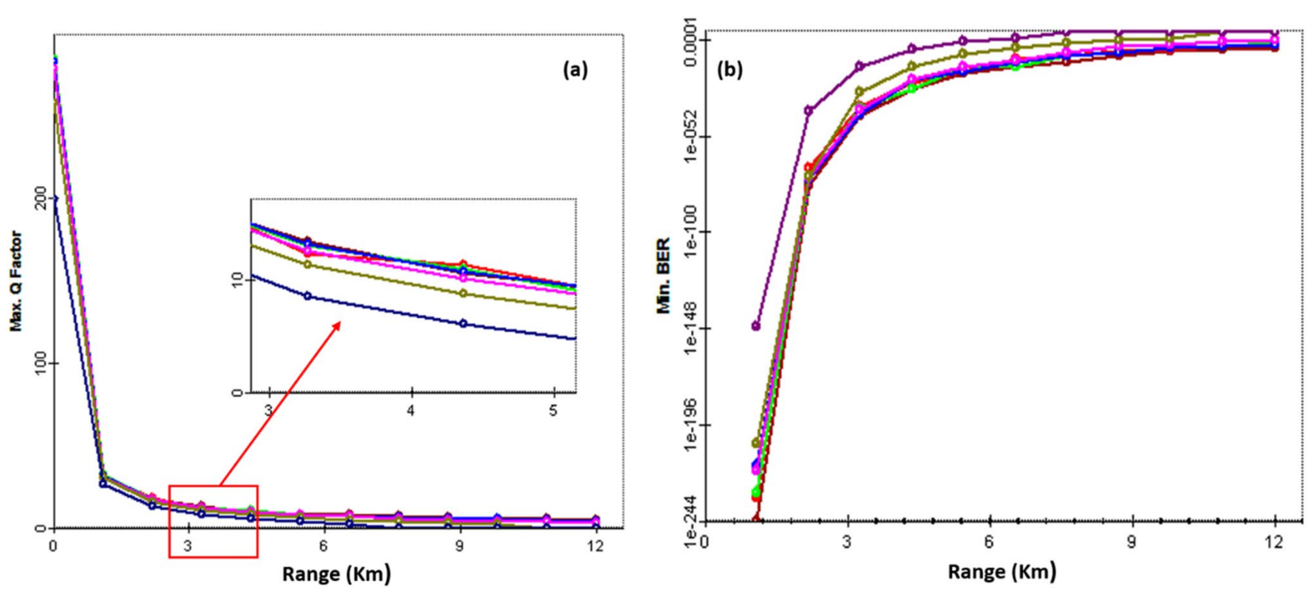

Fig. 12 Variation of Q factor **a** and BER **b** of the eight modes as a function of link range

optical power and the receiver aperture diameter increase. However, it decreases as increasing data bit rate, atmospheric attenuation, laser beam divergence and number of modes. This work can be expanded by including a higher number of modes and an orthogonal frequency division multiplexing (OFDM) of optical signal modulation at the transmitter to test the ability of different modes in achieve the maximum transmission capacity with maximum range. We are convinced that the proposed LG- SDM-FSO link is shown to be a notable option to provide the advantages of long distances and high transmission rate links under the impact of atmospheric turbulences for future optical wireless communications.

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Authors' contributions L. G supervised the project and conceived of the presented idea. I. H performed the analytic calculations and the numerical simulations. Both I. H and R. G contributed to the final version of the manuscript. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. L. Nadeem, M. Saadullah Qazi, A. Hassam, Performance of FSO links using CSRZ, RZ, and NRZ and effects of atmospheric turbulence. J. Opt. Commun. **39**, 191–197 (2018)
2. M. Grover, P. Singh, P. Kaur, 'Mitigation of scintillation effects in WDM FSO system using multibeam technique. J. Telecommun. Inform. Technolgy. **2**, 69–74 (2017)
3. A. Vanderka, L. Hajek, J. Latal, J. Vitasek, S. Hejduk, V. Vasinek, Testing resistance modulation formats for fso communication in turbulent environment, with used simulation Box. Proc. SPIE **9614**, 186–196 (2015)
4. J.G. Amora, M.V. Caya, W.Y. Chung (2017). Free space optical communication based outdoor wireless sensor node data acquisition using 532 nm laser. In: IEEE 9th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment and Management (HNICEM) (2017).
5. Dubey, A. and Sahu, S., 2020 Effect of atmospheric weather condition on the performance of FSO. 4th International Conference on Electronics, Communication and Aerospace Technology (ICECA) (2020).
6. Jiang, H., Yu, Z., Feng, X. and Gao, S., 2018 Demonstration of point-to-multipoint transmission for free-space optical communication networks. Asia Communications and Photonics Conference (2018).
7. J.E. Salamanca, D.A. López-Sarmiento, A.P. Gallego-Torres, A software pilot application to calculate the parameters involved in subsidiaries interconnection based on FSO technology. Facult. de Ingeniería. **26**(44), 147–156 (2017)
8. A. Prokes, Atmospheric effects on availability of free space optics systems. Opt. Eng. **48**(6), 066001 (2009)
9. S. Kumar, N. Sharma, Emerging military applications of free space optical communication technology. J. Phys. Conf. Ser. **2161**, 012011 (2022)
10. S. A. Zabidi, Wajdi Al Khateeb, Md. Rafiqul Islam and A.W. Naji. The effect of weather on free space optics communication (fso) under tropical weather conditions and a proposed setup for measurement. In: International Conference on Computer and Communication Engineering (ICCCE) (2010).
11. S.G. Sawhil, S. Agarwal, Y. Singhal, P. Bhardwaj, An overview of free space optical communication. Int. J. Eng. Trends Technol. (IJETT). **55**(3), 120–12 (2018)
12. L.J. Kumar, P. Krishnan, B. Shreya, M.S. Sudhakar, Performance enhancement of FSO communication system using machine learning for 5G/6G and IoT applications. Optik **252**, 168430 (2022)
13. K. Scholle, S. Lamrini, P. Koopmann, P. Fuhrberg, 2 µm laser sources and their possible applications. Front. Guided Wave Opt. Optoelectron. (2010). https://doi.org/10.5772/39538
14. T. Kishida, T. Sakaguti, K. Kumamoto, Z. Hong, Experiment of transmission performance of 2µm laser under turbulence. Broadband Access Commun. Technol. XV **11711**, 117110 (2021)
15. D.J. Richardson, J.M. Fini, L.E. Nelson, Space division multiplexing in optical fibres. Nat. Photo. **7**, 354–362 (2013)
16. B.J. Puttnam, G. Rademacher, R.S. Luís, Space-division multiplexing for optical fiber communications. Optica **8**(9), 1186–1203 (2021)
17. P. Liang, C. Zhang, J. Nebhen, S. Chaudhary, X. Tang, Cost-efficient hybrid WDM-MDM-Ro-FSO system for broadband services in hospitals. Front. Phys. **9**, 732236 (2021)
18. M. Singh, J. Malhotra, 4× 20Gbit/s-40GHzOFDM based Radio over FSO transmission link incorporating hybrid wavelength division multiplexing-mode division multiplexing of LG and HG modes with enhanced detection. Opt. Adv. Mater. Rapid Commun. **14**, 233–243 (2020)
19. M. Singh, J. Malhotra, 2× 10 Gbit/s–10 GHz radio over free space optics transmission system incorporating mode division multiplexing of Hermite Gaussian Modes. J. Opt. Commun. (2019). https://doi.org/10.1515/joc-2019-0047
20. M. Balasaraswathi, M. Singh, J. Malhotra, V. Dhasarathan, A high-speed radio-over-free-space optics link using wavelength division multiplexing-mode division multiplexing-multibeam technique. Comput. Electr. Eng. **87**, 106779 (2020)
21. M. Singh, S. Chebaane, S. Ben Khalifa, A. Grover, S. Dewra, M. Angurala, Performance evaluation of a 4×20-Gbps OFDM-based FSO link incorporating hybrid W-MDM techniques. Front. Phys. **9**, 746779 (2021)
22. M. Singh, S.N. Pottoo, M.H. Aly, Š Hubálovský, A. Grover, D. Adhikari, P. Yupapin, Mode division multiplexing free space optics system with 3D hybrid modulation under dust and fog. Alex. Eng. J. **62**, 113–127 (2023)
23. M. Singh, A. Atieh, M.H. Aly, S.A. Abd El-Mottaleb, 120 Gbps SAC-OCDMA-OAM-based FSO transmission system: Performance evaluation under different weather conditions. Alex. Eng. J. **61**(12), 10407–10418 (2022)
24. S.A.A. El-Mottaleb, M. Singh, A. Chehri, H.Y. Ahmed, M. Zeghid, A.N. Khan, Capacity enhancement for free space optics transmission system using orbital angular momentum optical code

division multiple access in 5G and beyond Networks. Energies **15**(19), 7100 (2022)
25. S. Sinha, C. Kumar, A. Armghan, M. Singh, M. Alsharari, K. Aliqab, Capacity enhancement analysis of an OAM-OFDM-SMM multiplexed free space communication system in atmospheric turbulence. Appl. Sci. **13**(6), 3897 (2023)
26. A. Ghatak, K. Thyagarajan, *An introduction to fiber optics* (Cambridge University Press, Cambridge, 1998)
27. D.R. Kolev, K. Wakamori, M. Matsumoto, Transmission analysis of OFDM-based services over line-of-sight indoor infrared laser wireless links. J. Lightwave Technol. **30**, 3727–3735 (2012)
28. I. Kim, B. Mcarthur, E. Korevaar, Optical wireless communication. Proc. SPIE **6303**, 1 (2006)
29. P.W. Kruse, L.D. McGlauchlin, R.B. McQuistan, *Elements of infrared technology: generation, transmission, and detection* (Wiley, Hoboken, New Jersey, 1962)
30. I.K. Son, S. Mao, A survey of free space optical networks. Dig. Commun. Netw. **3**, 67–77 (2017)
31. C.-H. Yeh, J.-R. Chen, W.-Y. You, C.-W. Chow, Hybrid WDM FSO fiber access network with rayleigh backscattering noise mitigation. IEEE Access **20**, 96449–96454 (2020)