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Impact of Divergence Angle on FSO System Performance: A Study of SNR, BER, and Q Factor

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Abstract- Context: Free Space Optics (FSO) transmission is a promising alternative to conventional wired networks, offering high bandwidth, low latency, and enhanced security. However, FSO performance is highly sensitive to physical factors, particularly the divergence angle of the optical beam. **Objective:** This study aims to evaluate the impact of beam divergence on key FSO system performance metrics to guide optimal system design. **Method:** MATLAB-based simulations were conducted to model Signal-to-Noise Ratio (SNR), Bit Error Rate (BER), and Q factor under varying divergence angles. The sensitivity of system performance to beam alignment and signal strength was analyzed across different divergence configurations. **Results:** Results indicate that smaller divergence angles provide higher SNR and Q factor values and lower BER, ensuring superior communication quality but requiring precise alignment. Conversely, larger divergence angles tolerate misalignment more effectively but at the cost of reduced signal quality. **Conclusion:** These findings emphasize the critical role of optimizing beam divergence to balance alignment tolerance and signal integrity, thereby enhancing the efficiency and reliability of optical wireless communication systems.

Keywords- FSO, SNR, BER, Divergence angle, Q factor.

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1. Introduction

Free Space Optics communications systems are comprised of several advantageous features, including low latency, high bandwidth, and better security [1]. Despite such advantages, various challenges heavily impact the performance of these systems that result in weakened signal quality as well as compromised system reliability [2]. Atmospheric phenomena like smog, fog, snow, and rain cause absorption as well as scattering effects, leading to the deterioration of optical signals resulting in high Bit Error Rate (BER) as well as lower Signal-to-Noise Ratio (SNR). For instance, smog and fog can cause severe signal attenuation through light scattering of suspended particles, while rain contributes additional losses through scattering and absorption by raindrops. These environmental conditions can lead to rapid changes of received power, which impact the overall performance of FSO systems adversely [3].

Aside from that, turbulence of the atmosphere caused by temperature and wind speed variations creates scintillation effects that are responsible for compromising signal integrity. The turbulence induced scintillation can cause abrupt amplitude and phase fluctuations in the signal, rendering it hard to maintain a stable link for communication [4]. Other than atmospheric problems, non-atmospheric conditions such as misalignment between the transmitter and receiver, physical obstructions, and requirements for a line-of-sight (LOS) can also influence FSO system performance. Precise alignment is critical because minor misalignments can lead to enormous signal loss. Moreover, physical obstructions such as buildings or trees can block the optical path, resulting in link outages [5]. In order to combat these problems, several techniques have been proposed, including the use of adaptive optics, modulation formats, and error correction codes. These techniques aim to enhance the level of robustness of FSO systems against environmental and alignment-induced degradations [6].

In this paper, we study the performance of an FSO system by calculating and comparing some of the most significant performance metrics, the Signal-to-Noise Ratio, Bit Error Rate and Q factor to better understand the impact of atmospheric conditions and design the system accordingly. By comparing these metrics under various conditions, we aim to contribute to the knowledge of the design and deployment of high-performance reliable FSO communication systems even in harsh environments.

The remainder of this paper is organized as follows: Section 2 describes the Free Space Optics link model. Section 3 presents the criteria for analyzing the Signal-to-Noise Ratio in FSO systems and the mathematical expressions used in this work. Section 4 discusses the simulation results and performance evaluation based on key metrics. Finally, Section 5 concludes the paper.

1. FSO LINK

Free-space optics or fibreless or fiber-free photonics is a next-generation communication technology using modulated light pulses to transmit data in free space air or the atmosphere enabling high-speed and high-bandwidth communication [7]. Data in FSO systems are carried by a tightly focused, modulated laser beam to transmit information from an FSO transmitter to a receiver through an atmospheric link. The incoming signal is demodulated at the receiver, a procedure identical to that at the transmission end [8].

A principal requirement for FSO communication is an unobstructed line of sight (LOS) as shown in Figure 1. Here, the transmitter and receiver have a direct line between them. Any physical obstacle, buildings or trees along the signal path will break transmission and lower performance. FSO technology has an important role to play in 5G and beyond networks. It offers a reliable, high-speed option for connectivity in urban areas that can manage growing demand for bandwidth-intensive applications [9].

FSO is well-suited to provide last-mile connectivity, thus connecting underserved and remote areas. It also becomes an attractive mobile backhaul option, enabling the transfer of data between cellular base stations and the core network [10].

Apart from telecommunication, FSO is helpful in disaster relief scenarios where it can restore communications infrastructure quickly. It is utilized for secure and effective Internet of Things (IoT) connection and has some use in military and defense due to its high capacity and secure transmission. FSO has utility in remote sensing and environmental monitoring where real-time data gathering can be observed across many field applications [11].

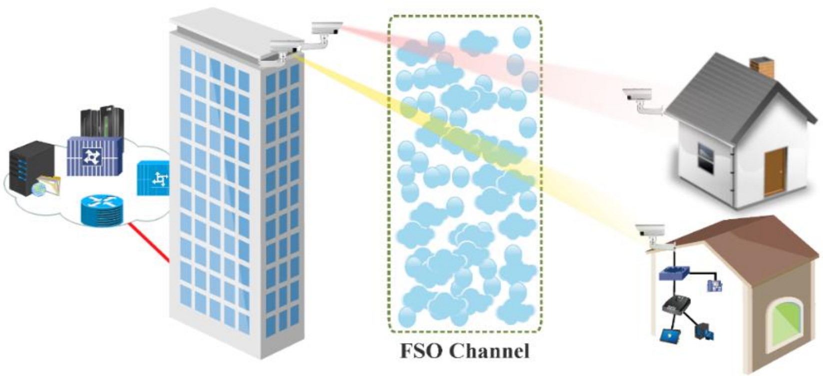

Figure 1. The LOS between transmitter and receiver in the FSO Link.

In addition, FSO is used in environmental monitoring and remote sensing to enable real-time collection in most field operations. Due to its multi-diversified applications and high-performance demands of modern communication systems, it is essential to comprehend and explore signal-to-noise ratio to enhance FSO system performance. The next section explores the most significant criteria in evaluating SNR in free-space optical systems.

2. Criteria for Analyzing SNR in Free Space Optical System

Signal-to-noise ratio is a fundamental metric in free-space optical systems, directly impacting the quality, reliability, and reach of data transmission. A higher SNR indicates a stronger signal relative to background noise, resulting in more accurate data reception and lower error rates.

In Figure 2, a block diagram of the FSO system is presented, illustrating the scenario where the optical axes of both the transmitter antenna (TA) and the receiver antenna (RA) are perfectly aligned. The distribution of optical radiation intensity, denoted as

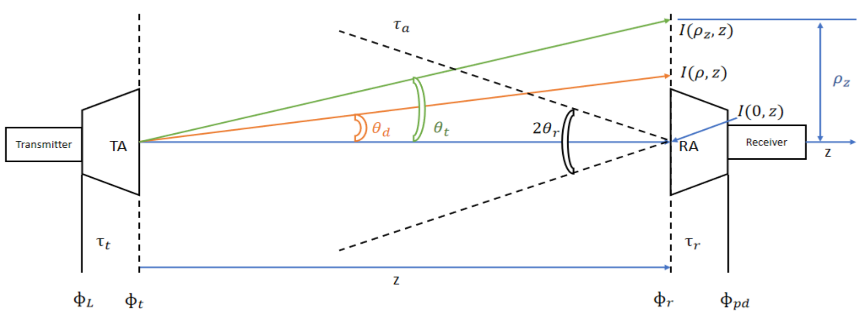

Figure 2. Structural diagram of the FSO link.

I (ρ,z), in the plane at z=const, is primarily influenced by the phase and amplitude distribution of the field at the transmitter antenna. For this specific analysis, a Gaussian amplitude distribution and an equiphasic condition are assumed. The diagram highlights key optical fluxes: Φ_L represents the flux transmitted by the laser, while Φ_t and Φ_r correspond to the flux passing through the apertures of the transmitter and receiver antennas, respectively, and Φ_{pd} denotes the flux at the entrance of the photodetector. Additionally, I(0,z) is the optical radiation intensity along the central axis of the antenna. The radius of the Gaussian laser beam, ρ_z, which exhibits azimuthal symmetry, is calculated using a mathematical expression, providing critical insights into the beam's propagation behavior [12].

$$I(\rho_z, z) = \frac{I(0,z)}{e^2} \tag{1}$$

$$\rho_z(z) = \sqrt{\rho_0^2 + \left(\theta_{t,exp} z\right)^2} \tag{2}$$

With

$$\theta_{t,exp} = K_\theta \theta_{t,teor} \quad \text{and} \quad \rho_0 = \frac{K_\theta \lambda_0}{\pi \theta_{t,exp}} \tag{3}$$

where λ_0 is the central wavelength of the light source, $K_\theta \geq 10$ is the coefficient indicating the random fluctuations of the field phase in A_t(phase and amplitude distribution of the field in the emitting aperture ($A = \pi R_t^2$) and R_t(is the aperture radius of the transmitting antenna $R_t \geq 2\rho_0$

The radius ρ_z determines the divergence angle $\theta_t$of the optical beam in the far-field region (where z>z_c, with z_c representing the transition point from the near-field, or cone region, which approximately corresponds to the Fraunhofer zone). The relationship between the divergence and the beam radius is given by

$$-tang\theta_t = \rho_z/z \tag{4}$$

Additionally, $\tau_t$and τ_r denote the losses incurred in the transmitting and receiving antennas, respectively, while τ_a represents atmospheric transparency. The angular width of the directivity pattern of the receiving antenna (RA) is expressed as $2\theta_r$.

Under the assumption of a Gaussian radial intensity distribution for the optical radiation in the plane z=const (where the receiving aperture is located), it is further presumed that the radius of the receiving antenna R_r is significantly smaller than the radius of the laser beam ($R_r \ll \rho_z$). This condition ensures that the majority of the beam's power is intercepted by the receiver, a critical factor for efficient signal reception in Free Space Optics systems [13]

The received optical flux ϕ_r at a radial displacement ρ from the center of the receiving antenna RA relative to the optical beam's axis can be approximated by multiplying the optical intensity at the center of the RA by the area $A_r$of the receiving antenna. This estimation assumes that the intensity distribution remains nearly constant across the aperture of the receiving antenna, allowing for the simplification of the total received optical flux as a product of the central intensity and the antenna's surface area [14]

$$\phi_r = I(\rho, z) A_r \tag{5}$$

$$\rho = \theta[rad]z \tag{6}$$

$$A_r = \pi R_r^2 \tag{7}$$

The Gaussian amplitude distribution at the transmitting antenna results in a corresponding Gaussian intensity profile in the far-field region, where the receiving antenna is located. This distribution causes the beam's intensity to decrease symmetrically with radial distance, which is crucial for accurately predicting the performance and alignment of Free Space Optical systems, especially over long distances where beam divergence and intensity loss are significant.

$$I(\rho, z) = I(0, z) exp\left(-2\frac{\rho^2}{\rho_z^2(z)}\right) \tag{8}$$

At $\rho = \rho_{max}$ follows $I = I_{min}$

$$I_{min} = I(0,z) = exp\left(-2\frac{\rho_{max}^2}{\rho_z^2(z)}\right) \quad (9)$$

The optical radiation intensity along the axis of the laser beam is influenced by both the transmitter's characteristics and the atmospheric communication channel, highlighting the combined impact of equipment design and environmental factors on the performance of optical communication systems [15]

$$I(0,z) = \frac{2\tau_t\tau_a(\lambda_0,S_M,z)\phi_L}{\pi\rho_z^2(z)} \quad (10)$$

The transparency of the atmosphere is directly linked to the meteorological visual range S_M and the wavelength of the transmitter, emphasizing how atmospheric conditions and the specific wavelength used in transmission affect signal clarity and strength in optical communication systems

$$\tau_a(\lambda_0,S_M,z) = exp\left[-\frac{3{,}92}{S_M[km]}\left(\frac{\lambda[\mu m]}{0{,}55}\right)^{-q}\right] \quad (11)$$

When $S_M \leq 10\ km\ and\ \ q = 0{,}585\sqrt[3]{S_M[km]}$

From (9) and (10)

$$\rho_{max} = \frac{1}{\sqrt{2}}\rho_z\sqrt{\ln\frac{2\tau_t\tau_a\phi_L}{\pi\rho_z^2 I_{min}}} \quad (12)$$

This relationship enables the determination of the maximum value of ρ_{max} as a function of ρ_z. The specific value of ρ_z that results in the maximum ρ_{max} is:

$$\rho_z = \rho_{z,opt} = \sqrt{\frac{2\tau_t\tau_a\phi_L}{\pi e I_{min}}} \quad (13)$$

When I_{min} is determined by the condition [16]:

$$I_{min} = \frac{\phi_{pd}|SNR=const}{\pi\tau_r R_r^2} \quad (14)$$

And the optical beam through the input aperture of the receiver corresponding to the upper level of the optical code impulse is:

$$\phi_{pd}(\theta,z) = \pi\tau_r R_r^2 I(\theta,z) \quad (15)$$

Here, R_r denotes the aperture radius of the receiver telescope, while τ_r represents the transmission coefficient of the optical receiver system. The aforementioned equation holds true under the condition that $\rho_z(z) \gg R_r$[17]

$$\phi_B = \pi^2\tau_r L_{\lambda,B}(\lambda_0)R_r^2\theta_{r,exp}^2\Delta\lambda_F \quad (16)$$

The background optical flux ϕ_B is influenced by the spectral brightness of the background radiation $L_{\lambda,B}$ as well as the parameters of the receiver [16], which include the aperture radius R_r, the transmission coefficient τ_r, and the angular width of the receiving antenna θ_r. With $\Delta\lambda_F$ is denoted the transmission wavelength of the interference filter before the photodetector.

Using the previously derived expressions, the value of SNR can be calculated accurately [18]:

$$SNR = \frac{R_I(\lambda_0)\phi_{pd}(\theta,z)}{\sqrt{C_I\left\{\frac{2K_B T.A}{R_{Fb}} + eR_I(\lambda_0)[\phi_{pd}(\theta,z)+\phi_B]\right\}}} \quad (17)$$

When

$$R_I(\lambda_0) = 8{,}06.10^5 \eta(\lambda_0)\lambda_0 \quad (18)$$

The parameter $\eta(\lambda_0)$represents the quantum efficiency of the photodetector material. C_I denotes the information throughput of the digital communication system. The Boltzmann constant k_B , is given as $1.38.10^{-23}$J/K, while T signifies the absolute temperature. The constant A refers to a characteristic of the receiver, and R_{Fb} indicates the resistance value in the feedback loop of the preamplifier.

Additionally, e=$1.602.10^{-19}$C represents the charge of an electron.

To calculate the BER and the Q factor, the two-performance metrics, the following equations are used [19].

$$Q = \sqrt{\left(\frac{SNR}{2}\right)} \quad (19)$$

$$BER = 0.5 * erfc\left(\frac{Q}{\sqrt{2}}\right) \quad (20)$$

3. Simulation and results

This section presents the MATLAB simulation results, beginning with the calculation of SNR, BER, and Q factor to evaluate the performance of the FSO system. The SNR can be calculated using the following values provided in the table:

Table 1. Parameters to calculate SNR [20].

Parameter	Symbol	Value
Transmission and receiver coefficient	τ_t=τ_r	0.85
Phase Fluctuation Coefficient	K_θ	10
Central wavelength	λ_0	850 nm
Information Throughput	C_I	100 Mbps
Aperture radius	R_r	5.5 cm
Angular Width	θ_r	5 mrad
Quantum efficiency	$\eta(\lambda_0)$	0.7
Transmission wavelength	$\Delta\lambda_F$	10 nm
Feedback Resistor Value	R_{Fb}	1kΩ
Receiver Constant	A	5
power in optical bit pulse	ϕ_L	10 mW
Meteorological visual range	S_M	10 km
Background radiation	$L_{\lambda,B}$	$10^{-2}W/m^2$. sr.Å
Temperature	T	300 K
Boltzmann constant	k_B	$1.38.10^{-23}$J/K
Electron Charge	E	$1.602.10^{-19}$C

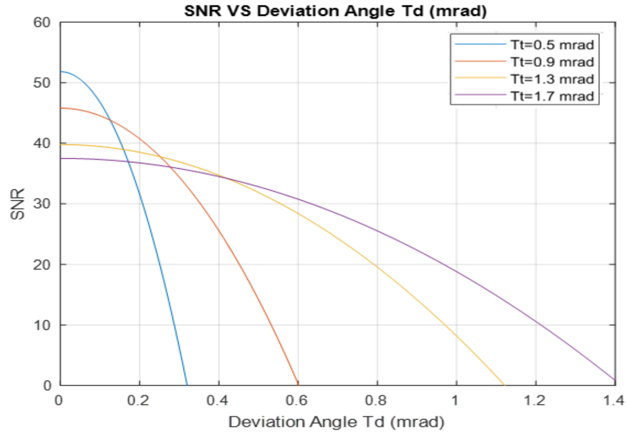

Figure 3. Variation of Signal-to-Noise Ratio with Angular Deviation $\theta_d$of the Transmitter Beam at Different Optical Radiation Divergence Angles θ_t.

The graph illustrates the variation of the signal-to-noise ratio (SNR) with the deviation angle θ_d of the transmitting beam from its principal direction, comparing the behavior for different beam divergence angles θ_t. For narrow beams (θ_t= 0.5 mrad), SNR is high at the beginning but drops off quickly even for small deviations. This indicates that narrow beams are extremely sensitive to misalignment small angular deviations cause a drastic decrease in signal strength. The steep drops off indicates the need for precise alignment for narrow beams. In contrast, beams with a larger divergence angle (θ_t= 1.7 mrad) show a more gradual drop in SNR for increasing θ_d. These wider beams are less prone to misalignment and can tolerate greater angular deviations before experiencing appreciable signal loss. They have a lower initial SNR, however, as the signal is dispersed over a wider area, reducing intensity at any given point.

Overall, the graph depicts a fundamental trade-off in optical communications: smaller beams have higher peak SNR but demand precise alignment, while larger beams tolerate misalignment but have a lower peak SNR. The optimum choice depends on the alignment precision of the system and the application.

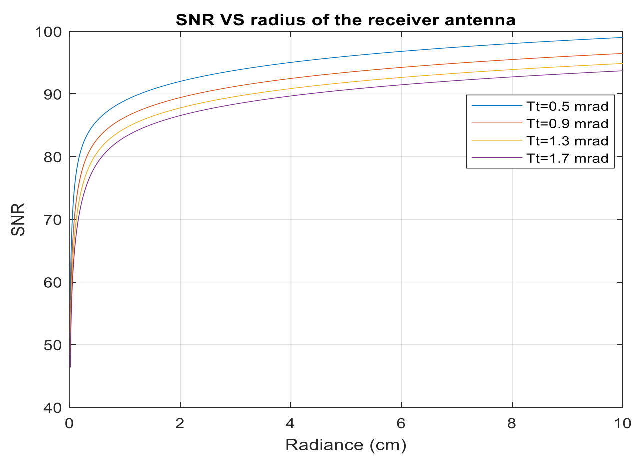

Figure 4. Variation of Signal-to-Noise Ratio with radius of the receiver antenna $R_r$at Different Optical Radiation Divergence Angles θ_t.

The plot shows how SNR varies with the receiver antenna radius (in cm) for different beam divergence angles (θ_t= 0.5, 0.9, 1.3, and 1.7 mrad) in an optical communication system. SNR improves noticeably as the antenna radius increases, but the rate of improvement gradually decreases to reach a saturation for all divergence angles. Beams of smaller divergence angles, 0.5 mrad have constantly higher SNR values irrespective of antenna size compared to broader beams. This means that thinner beams preserve signal quality better. Overall, the results indicate that using beams of smaller divergence angles is preferable in order to achieve good signal quality even with large receiver antennas.

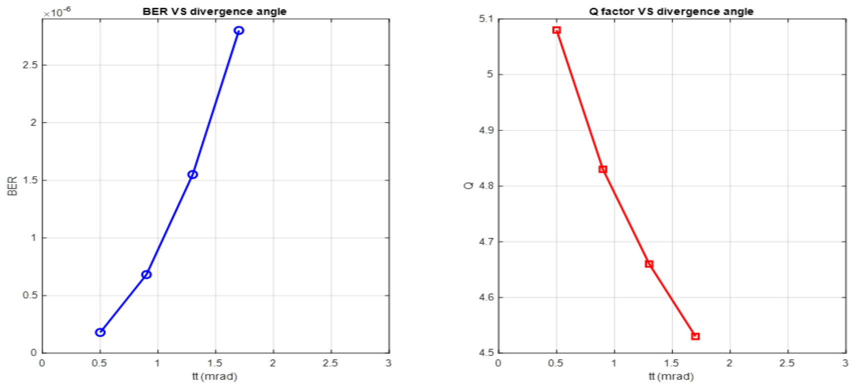

Figure 5. Effect of Divergence Angle tt on BER and Q Factor in an FSO System.

The plots show how the divergence angle of the beam tt (in mrad) relates to two key performance metrics of a Free Space Optics communication system: Bit Error Rate and Quality factor. With decreasing divergence angle, the BER as well as Q factor also increases very much, thereby indicating increasing quality of communications. Smaller divergence angle gives a concentrated light beam, which reduces dispersion during propagation. The concentrated beam ensures that there is greater optical power delivered to the receiver, increasing detection of the signal and lowering errors, as suggested by a reduced BER. Simultaneously, a smaller angle elevates the Q factor, meaning the system's ability to isolate the signal from noise. Conversely, as the divergence angle increases, the beam becomes broader, resulting in greater dispersion and signal deterioration. This not only improves the BER but also lowers the Q factor, making the system noise-prone and less reliable to communicate with. These observations emphasize the importance of beam divergence optimization to achieve maximum signal integrity and have the best possible performance in FSO systems.

4. Conclusions

In this study, it has been evidently demonstrated how beam divergence angle significantly affects the overall performance of Free Space Optics systems. Simulation results indicate that beams with smaller sizes (θ_t = 0.5 mrad) generate greater initial values of SNR but are highly sensitive to angular misalignment and require precise alignment. On the other hand, wider beams (θ_t = 1.7 mrad) exhibit lower peak SNR but offer greater tolerance to misalignment, making them suitable for less controlled environments. With a growing receiver antenna radius, SNR improves for all divergence angles, yet smaller divergence beams consistently provide superior signal quality. Moreover, smaller divergence angles yield significantly enhanced BER and Q factor performance due to higher optical power concentration and minimal beam dispersion. These findings reveal a critical FSO design trade-off between beam alignment precision and system reliability. Therefore, reduction of the beam divergence angle is essential for maximizing signal integrity and communication dependability. Future work can extend this study by incorporating more sophisticated models of atmospheric turbulence, including real-world weather conditions such as fog, rain, and temperature gradients. Investigating adaptive beam divergence techniques, where beam width dynamically adjusts based on alignment and channel conditions, could further improve system robustness. Additionally, experimental validation of these simulation results in practical FSO deployments and integration with hybrid FSO/RF networks could provide deeper insights into achieving high-reliability optical wireless communications. Finally, exploring machine learning-based optimization strategies for beam alignment and divergence control could lead to smarter, more resilient FSO systems capable of operating under highly dynamic environments.

References

[1] Z. Zhu, M. Janasik, A. Fyffe, et al., “Compensation-free high-dimensional free-space optical communication using turbulence-resilient vector beams”, *Nature Communications*, vol. 12, p. 1666, 2021. https://doi.org/10.1038/s41467-021-21793-1

[2] Z. Zameer and K. A. Wahid, "Free space optics: Current applications and future challenges", *IEEE Access*, vol. 8, pp. 154243–154254, 2020. https://doi.org/10.1155/2015/945483

[3] H. Khalid, S. M. Sajid, H. E. Nistazakis, and M. Ijaz, "Survey on limitations, applications and challenges for machine learning aided hybrid FSO/RF systems under fog and smog influence", *J. Mod. Opt.*, vol. 71, no. 4–6, pp. 101–125, 2024. https://doi.org/10.1080/09500340.2024.2402428

[4] I. A. Alimi and P. P. Monteiro, "Revolutionizing free-space optics: A survey of enabling technologies, challenges, trends, and prospects of beyond 5G free-space optical (FSO) communication systems"; *Sensors*, vol. 24, no. 24, p. 8036, 2024. https://doi.org/10.3390/s24248036

[5] E. Vasani and V. Shah, "Spectrum slicing-based performance analysis of free space optical communication under atmospheric turbulence", *J. Inst. Eng. India Ser. B*, vol. 104, pp. 319–326, 2023. https://doi.org/10.1007/s40031-022-00832-5

[6] X. Sun, C. H. Kang, M. Kong, O. Alkhazragi, Y. Guo, M. Ouhssain, Y. Weng, B. H. Jones, T. K. Ng, and B. S. Ooi, "A review on practical considerations and solutions in underwater wireless optical communication", *J. Lightwave Technol.*, vol. 38, pp. 421–431, 2020. https://doi.org/10.1109/JLT.2019.2960131

[7] A. Sufyan, K. B. Khan, O. A. Khashan, T. Mir, and U. Mir, "From 5G to beyond 5G: A comprehensive survey of wireless network evolution, challenges, and promising technologies", *Electronics*, vol. 12, no. 10, p. 2200, 2023. https://doi.org/10.3390/electronics12102200

[8] Q. V. Khanh, V. H. Nam, L. D. Manh, and G. Jeon, "Wireless communication technologies for IoT in 5G: Vision, applications, and challenges", *Wireless Commun. Mobile Comput.*, vol. 2022, Art. no. 3229294, 2022. https://doi.org/10.1155/2022/3229294

[9] T. Mazhar, M. A. Malik, I. Haq, I. Rozeela, I. Ullah, M. A. Khan, D. Adhikari, M. T. Ben Othman, and H. Hamam, "The role of ML, AI and 5G technology in smart energy and smart building management", *Electronics*, vol. 11, no. 23, p. 3960, 2022. https://doi.org/10.3390/electronics11233960

[10] A. Mukhopadhyay and M. Ruffini, "Design methodology for wireless backhaul/fronthaul using free space optics and fibers", *J. Lightwave Technol.*, vol. 41, pp. 17–30, 2023. https://doi.org/10.1109/JLT.2022.3210524

[11] P. Bhardwaj, V. Bansal, N. Biyani, S. Shukla, and S. M. Zafaruddin, "Performance of integrated IoT network with hybrid mmWave/FSO/THz backhaul link", *IEEE Internet Things J.*, vol. 11, no. 2, pp. 3639–3652, 2024. https://doi.org/10.1109/JIOT.2023.3297881

[12] F. Khalid and M. A. Ali, "Performance of free space optical communication link under foggy weather" *J. Commun.*, vol. 14, pp. 518–523, 2019. https://doi.org/10.5220/0011946200003612

[13] M. Meucci, M. Aresti, G. Cossu, L. Gilli, L. Oliviero, M. Bartolini, A. Pucci, E. Ciaramella, and J. Catani, "Comparative test of novel fluorescent optical antennas for LED- and laser-based optical wireless communications" *Adv. Opt. Mater.*, 2025. https://doi.org/10.1002/adom.202402367

[14] S. W. Sun and J. H. Noh, "End-to-End Performance Analysis of CCSDS O3K Optical Communication System Under Atmospheric Turbulence and Pointing Errors" *Aerospace*, vol. 12, no. 10, p. 869, 2025. https://doi.org/10.3390/aerospace12100869

[15] H. Wang, Y. Wang, X. Peng, L. Liu, Y. Cai, and F. Wang, "Real-time synthesis of twisted Gaussian Schell-model beams and their applications in suppressing the turbulence-induced scintillation and beam wander", *Opt. Lett.*, vol. 50, no. 13, pp. 4342–4345, 2025. https://doi.org/10.1364/OL.564963

[16] U. Younas, J. Muhammad, H. F. Ismael, T. A. Sulaiman, H. Emadifar, and K. K. Ahmed, "Diversity of solitary wave structures in Kerr media: Analyzing the complex paraxial wave equation in fiber optic communication systems", *Ain Shams Eng. J.*, 2025. https://doi.org/10.1016/j.asej.2025.103763

[17] G. Zhang, J. Wu, Y. Li, X. Wang, X. Yu, S. Gao, and L. Ma, "A review of variable-beam divergence angle FSO communication systems", *Photonics*, vol. 10, no. 7, p. 756, 2023. https://doi.org/10.3390/photonics10070756

[18] S. M. Hamzah and I. A. Murdas, "Enhancement of the performance of DWDM free space optics (FSO) communications systems under different weather conditions", *Int. J. Intell. Eng. Syst.*, vol. 13, no. 4, pp. 446–456, 2020. https://doi.org/10.22266/ijies2020.0831.39

[19] K. Kumar, M. S. Adhikari, I. Bhardwaj, S. Chawla, and M. Sindhwani, "Performance enhancement of Q factor and BER using Raman amplification in optical communication system", *J. Opt. Commun.*, 2025. https://doi.org/10.1515/joc-2025-0469

[20] H. Djellab, et al., "FSO system optimization for 6G applications: Using metaheuristic algorithms", *IEEE Access*, vol. 13, pp. 193508–193526, 2025. https://doi.org/10.1109/ACCESS.2025.3629005