**Hybrid Mode-Dense Wavelength Division Multiplexing of Spiral-Phased LG Modes over Free Space Optics based on Electrical DFE Equalization**

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**Abstract -** Exponential growth in data traffic has brought demanding requirements for advanced communication systems supporting ultra-high data rates. Free space optics (FSO), with its high bandwidth, has emerged as a strong contender. Previous work on FSO investigated various multiplexing strategies using spatial modes. This work presents a mode-dense wavelength division multiplexing (M-DWDM) system over FSO links, employing spiral-phased Laguerre-Gaussian modes. This is further enhanced by electrical decision feedback equalization to handle inter-symbol interference and support reliable performance under turbulent weather conditions. The proposed approach is based on the diversity LG modes and the capacity benefits of M-DWDM to achieve high data rates with strong channel separation. Simulation results verify the effectiveness of the system in achieving enhanced BER, enlarged channel capacity, and robustness against atmospheric degradations. This research contributes to the development of high-speed, scalable, and reliable optical communication systems, addressing increasing bandwidth demand in modern networks.

# INTRODUCTION

The persistent growth of global data traffic has compelled the development of cutting-edge communication systems capable of supporting ultra-high data rates. Among such technologies, free space optics (FSO) has emerged as a promising solution, offering bandwidth gains . These advantages position FSO as a key enabler of high-capacity communication systems. Nevertheless, atmospheric turbulence causes significant challenges in FSO systems [1, 2]. To address these challenges, researchers have proposed various approaches for extending the capacity and robustness of FSO communications systems. Multiplexing and multiple access strategies such based on wavelength [3, 4], orthogonal frequencies [5, 6], orthogonal codes [7-9], nonorthogonal codes [10-12] have significantly enhanced FSO system capacity and signal integrity. Recently, spatial modes have been leveraged for multiplexing data streams in FSO systems through the design of photonic crystal fibers and metasurfaces [13-17]. Spatial modes have been used in conjunction with wavelength [18-20] and codes [21-23] for addressing capacity issues. Despite these advancements, challenges such as ISI and crosstalk between channels over extended distances remain critical issues.

# RELATED WORK

To alleviate ISI and enhance signal integrity in FSO multiplexing systems, decision feedback equalizers (DFE) have been employed. By dynamically altering the transmitted signals based on real-time channel conditions and using previously detected symbols, DFE effectively cancels ISI without amplifying noise. Using DFE, a data rate of 7.5 Gbps was attained in an MDM-FSO system, achieving low bit error rates and high throughput under various weather regimes [20], [24]. Furthermore, recent research in 2024 has shown that integrating DFE with hybrid MWDM systems utilizing LG modes alleviates mode coupling and ISI, thereby enhancing channel diversity and system capacity [25, 26]. These developments highlight DFE’s critical role in addressing the growing demand for high-speed, reliable FSO communication.

The integration of advanced hybrid multiplexing techniques and equalization strategies, alongside photonic device innovations, has opened new avenues for the realization of robust and high-capacity FSO systems. While the benefits of FSO communication are evident, overcoming environmental challenges such as turbulence and signal distortion remains imperative [27]. This work focuses on a hybrid multiplexing approach incorporating mode-dense WDM and spiral-phased LG modes for FSO, further enhanced by electrical DFE equalization, to address these challenges and unlock the full potential of FSO communication systems. This work is motivated by several studies demonstrating multiplexing and equalization techniques, as follows. [28] investigates the performance of MDM in FSO systems under various weather conditions ranging from intense haze to clear sky. Results achieved are as high as 30 Gbit/s using three channels over 6 km. [29] proposes a hybrid WDMA-FSO system capable of transmitting 140 Gbit/s across 14 channels, with a range of 9.65 km in clear skies and heavy rain. The inclusion of an electrical filter enhances system performance, but the limited exploration of extreme weather scenarios such as fog and snow leaves room for improvement. Additionally, while the system achieves impressive distance and capacity, its reliance on electrical filtering raises concerns about scalability and cost in large-scale deployments. In [30], coarse and dense WDM are combined to tackle the attenuation created by moderate and heavy rain, resulting in 140 Gbit/s over 14 channels for 2.6 and 1.6 km, respectively. In the hybrid system, scalability and data rates have been well-weighted. However, the work may be extended to a deeper analysis of the system performance for longer transmission distances and including adaptive channel spacing considering future demands for high-capacity networks. The focus on rain attenuation also limits its applicability in haze or fog conditions. In [31], an 8-channel MDM-FSO system is designed, demonstrating a 40 Gbps data rate over 3 km in clear weather.

The use of OptiSystem simulations and LG modes highlights the potential of MDM for improving service quality. However, the study does not address mode coupling or interference challenges, which are critical for maintaining signal integrity in real-world applications. Expanding the analysis to include adaptive modulation techniques could further enhance the system's performance under varying weather conditions. [32] proposes a hybrid MDM-FSO- Fiber to the Home (FTTH) system that achieves 100 Gbit/s over 10 channels for 3.2 km in clear weather. The addition of LG modes increases channel diversity but is limited under heavy rain with a range of 650 m. Although the system benefits from FTTH integration, the cost-effectiveness needs further analysis. [33] explores a 12-channel SDM-FSO-FTTH system with a data rate of 120 Gbit/s over 8.5 km in clear weather and heavy haze. The use of linear equalization addresses turbulence and mode dispersion effectively. [34] demonstrates the adoption of the Hermite-Gaussian (HG) mode in a 10-channel SDM-FSO system to realize a transmission rate up to 100 Gbit/s over distances of 12 km in conditions under clear weather. A Gaussian filter successfully mitigates most of the turbulence, but this study lacks a detailed comparison between HG and Laguerre–Gaussian (LG) modes under the same test conditions. However, the interest in HG modes in hybrid systems that incorporate the use of adaptive optics is yet to be pursued. In [20], the decision feedback equalization is introduced in the FSO system, which, with WDM and MDM, reaches a capacity of only 24 Gbps for 2.6 km. While the study remarkably reduces inter-symbol interference (ISI), this is at the cost of its capacity and range compared to other systems considered herein.

# SYSTEM DESCRIPTION

Inspired the above recent work on MDM, WDM and equalization, the proposed system combines mode division and dense wavelength division multiplexing to establish a FSO mode-wavelength division multiplexing (M-DWDM) system with 10 channels utilizing spiral-phased Laguerre-Gaussian (LG) modes, as illustrated in Figure 1. The transmitter and the receiver are modeled in according to Kadhim et al. [35], designed using RSoft OptSim software to simulate the FSO M-DWDM system under clear weather conditions. The FSO channel distance at 5 km; transmitter and receiver apertures of 20 cm; beam divergence = 1 µrad; and an optical transmitter power of 0 dBm [33, 34]. These parameters ensure optimal performance in a clean atmospheric environment.

The transmitter consists of 10 independent data streams, at a data rate of 31 Gbps each. Each data stream is modulated onto a spiral-phased Laguerre-Gaussian (LG) modes by a vertical-cavity surface-emitting lasers (VCSELs). Spiral-phased LG modes are generated through vortex lenses, enabling spatial multiplexing. This approach ensures orthogonality between channels, reducing crosstalk and enhancing spectral efficiency. Channels 1 to 5 are configured at a wavelength of 1550 nm, on LG 00, LG 01, LG 02, LG 10 and LG 11 modes respectively. Channels 1 to 6 are configured at a wavelength of 1550.20 nm, on LG 00, LG 01, LG 02, LG 10 and LG 11 modes respectively. The modulated signals are multiplexed using an optical M-DWDM , combining both spatial and wavelength domains for simultaneous transmission over the FSO channel. Figure 2 depict the phase profiles of the spiral-phased Laguerre-Gaussian modes on 1550 nm. LG modes demonstrate orthogonality and distinct spatial profiles. These characteristics are critical for efficient MDM, as they reduce inter-channel crosstalk, allowing the system to transmit multiple data streams simultaneously over a single optical link. This also highlights the possibility of M-DWDM for increasing data capacity in FSO communication systems. The distinguishable spatial patterns across channels confirm that LG modes are generated effectively and aligned properly. The minor variation in wavelength, 1550.20 nm, further confirms that the system is robust enough to allow more channels with minimal effect on mode profiles. These results confirm that spiral-phased LG modes are suitable for high-capacity optical communication systems, especially when assisted by WDM techniques.

The LG modes on both 1550 nm and 1550.20 nm are propagated through a clear FSO channel. The aperture size of 20 cm with beam divergence of 1 µrad will efficiently collect and propagate the light through the link of 5 km. This optimized configuration enables the successful delivery of high-data-rate signals with minimal degradation, making it suitable for high-performance applications

A diagram of a system

Description automatically generated

**FIGURE 1.** System Diagram of Hybrid Mode-Dense Wavelength Division Multiplexing (M-DWDM) scheme

At the receiver end, the received signals are separated first into their respective spatial and wavelength channels accordingly using an optical M-DWDM demultiplexer. That ensures the exact separation of modes since each channel corresponds to a distinct LG mode. These optical signals then undergo conversion to the electrical domain for further processing. Electrical decision feedback equalization (DFE) is applied on each M-DWDM channel to mitigate ISI caused by residual channel effects and atmospheric disturbances. The DFE consists of a feedforward filter (FFF) with 15 taps and a feedback filter (FBF) with 9 taps, dynamically adapting to channel variations in real time. The DFE output signal is represented as:

(1)

whereby *y*(*n*) is the electrically equalized output signal, *x*(*n* −) is the input signal, is the feed-forward tap coefficients (= 0, 1…M−1), is the feedback tap coefficients ( = 1, 2…N), and *y*(*n* − ) are previously detected symbols. The minimum mean square error (MMSE) criterion is employed to optimize the tap wi and bj for precise equalization, ensuring effective ISI mitigation. By integrating spiral-phased Laguerre-Gaussian (LG) modes with the M-DWDM scheme and applying electrical DFE, the system achieves robust performance and high data rates (31 Gbps per channel) over 5 km-FSO links. The BER analysis confirms the stability under clear atmospheric conditions, while the architecture provides a scalable and efficient solution for high-capacity optical networks.

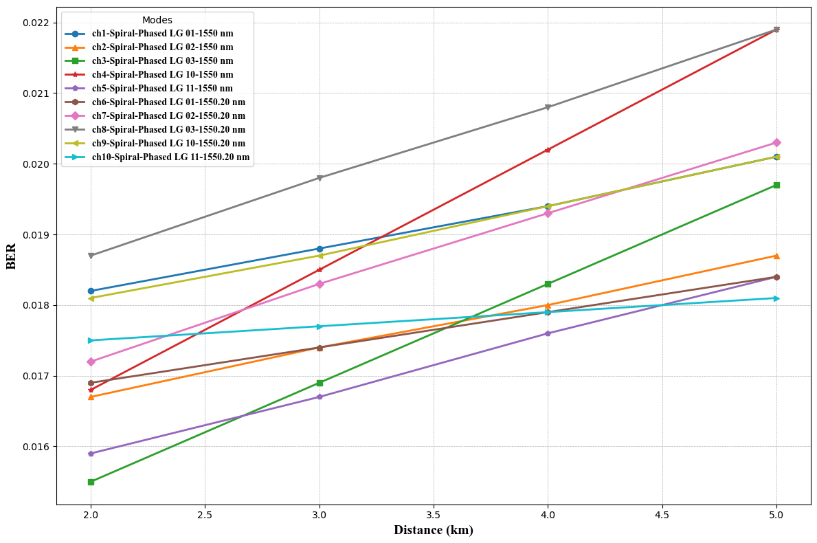
A diagram of a spectrum

Description automatically generated with medium confidence

**FIGURE 2.** Spatial visualizer results of spiral-phased Laguerre-Gaussian (LG) modes for 5 first channels based on 1550 nm

# RESULTS AND DISCUSSION

The postulated FSO M-DWDM with electrical DFE will be evaluated under weather conditions characterized as clear, while the main metric of performance will be the BER. In this direction, system performance is compared before and after the application of Electrical DFE, highlighting the contribution of equalization in suppressing ISI and enhancing signal integrity. The overall BER trends across distance without electrical DFE are shown in Figure 3. As the transmission distance increases from 2 km to 5 km, BER consistently rises across all modes due to signal degradation caused by atmospheric turbulence and free-space attenuation, which become more pronounced at longer distances. Performance Comparison Between Wavelengths, the two wavelengths, 1550 nm and 1550.20 nm, show distinct BER patterns. Modes operating at 1550 nm generally achieve slightly lower BER values, indicating better atmospheric compatibility. Lower-order modes, such as LG 01 and LG 02, outperform higher-order modes like LG 10 and LG 11. Their simpler spatial structures make them less vulnerable to turbulence-induced distortions, enhancing their robustness for longer-distance transmissions. Impact of Electrical Equalization, higher-order modes (e.g., LG 10 and LG 11) experience a steeper increase in BER as distance growth. Their complex spatial profiles are more susceptible to phase and amplitude distortions caused by atmospheric conditions. Without DFE equalization, these distortions remain unmitigated, leading to suboptimal performance, especially beyond 4 km, where BER values escalate significantly.



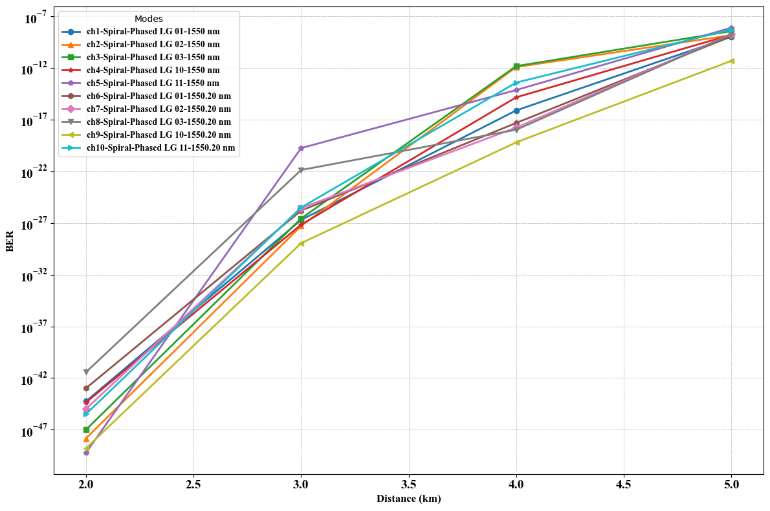
**FIGURE 3.** BER results of spiral-phased LG modes without electrical DFE equalization

Mode-specific observations and implications emphasize the need for careful mode and wavelength selection to minimize BER in FSO systems. Lower-order modes at 1550 nm are preferable for achieving better performance without equalization. However, for higher-order modes or extended transmission distances, integrating advanced equalization techniques like DFE is crucial to maintaining signal integrity and enhancing reliability. Future research should focus on hybrid approaches combining mode selection, wavelength tuning, and equalization to optimize system performance.

Figure 4 shows the BER performance for spiral-phased Laguerre-Gaussian LG modes with electrical equalization across distances ranging from 2 km to 5 km. As expected, the BER increases with distance for all modes and wavelengths due to the cumulative effects of signal attenuation and atmospheric turbulence. However, the inclusion of electrical equalization significantly improves BER performance compared to scenarios without equalization, especially for longer distances.

In terms of comparison between wavelengths, modes operating at 1550 nm generally achieve better BER values than their counterparts at 1550.20 nm. This is attributed to the optimized transmission characteristics of the 1550 nm wavelength, which has minimal dispersion and higher atmospheric transparency. This advantage is most noticeable at greater distances, where the BER gap between the two wavelengths widens slightly, indicating the superiority of   
1550 nm for long-distance free-space optical communication. Electrical equalization proves effective in reducing BER for all modes, mitigating the effects of inter-symbol interference and turbulence-induced distortions. The equalization benefits are particularly evident for higher-order modes (e.g., LG 10 and LG 11), which would otherwise exhibit significantly higher BER values due to their complex spatial profiles. This improvement underscores the importance of equalization in enhancing the reliability of free-space optical systems.

Based on comparison of mode-specific observations, lower-order modes, such as LG 01 and LG 02, consistently outperform higher-order modes like LG 10 and LG 11 across all distances. Their simpler spatial structures make them less susceptible to atmospheric perturbations. These results highlight the practicality of using lower-order modes for robust long-distance communication, while the inclusion of electrical equalization makes higher-order modes viable for shorter to moderate distances. This finding supports a hybrid approach where mode selection and equalization techniques are tailored to specific communication requirements.



**FIGURE 4**. BER results of spiral-phased LG modes with electrical DFE equalization

The incorporation of M-DWDM significantly increases the system capacity through the simultaneous combination of closely spaced wavelength channels with multiple spatial modes, including spiral-phased LG modes. The method allows for the simultaneous carrying of various data streams through an individual FSO link, increasing the spectral efficiency and the capacity for higher data rates, i.e., 31 Gbps per channel in the presented system. With the use of both wavelength and spatial multiplexing, M-DWDM makes it possible to have scalable, high-capacity free-space optical systems to accommodate the increasing demands of contemporary communication networks. In order to maintain signal integrity at such high rates of data, DFE is used on all M-DWDM channels to cancel ISI resulting from channel distortion and residual dispersion. The DFE configuration includes a 15-tap feedforward filter and 9-tap feedback filter, optimized with the aid of the MMSE criterion to adapt dynamically to channel variations. With the cancellation of ISI through the use of past symbol decisions, the distortion of the signal is reduced and the system's BER is improved, guaranteeing the reliability of data transfer even in harsh operational scenarios.

# CONCLUSION

By means of hybrid M-DWDM, this work achieves 31 Gbps over a 5 km-FSO link with 10 spiral-phased Laguerre-Gaussian modes. Integrating electrical DFE significantly improves the system performance, overcomes ISI, and enhances the BER. The results confirm that the system could provide high data rates, robust channel separation, and scalability; it is one of the promising approaches to address future demands on modern high-speed optical communication networks.

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# REFERENCES

1. J. Long *et al.*, "Digital Frequency-Domain MIMO Equalizer Enabling Six-LP-Mode Strong-Coupling IM/DD MDM Optical Transmission System," *Sensors,* vol. 25, no. 8, p. 2562 (2025)
2. E. Haraguchi *et al.*, "Free space optical communication based on a multi-wavelength optical phased array using Fresnel reflection," *Applied Physics Express,* vol. 18, no. 1, p. 012004 (2025)
3. D. AlQahtani and F. El-Nahal, "Coherent WDM-PON and free space optical (FSO) system for front-haul in next-generation cellular networks," *Optik,* vol. 323, p. 172212 (2025)
4. F. K. Shakir, M. A. A. Ali, and S. K. Rahi, "Enhancement of free-space optical communication in fog conditions with wavelength division multiplexing technique," *Journal of Optics,*  (2025)
5. A. Amphawan, S. Chaudhary, and V. Chan, "Optical millimeter wave mode division multiplexing of LG and HG modes for OFDM Ro-FSO system," *Optics Communications,* vol. 431, pp. 245-254 (2019)
6. A. M. Ramly, A. Amphawan, T. J. Xuan, and N. T. Kian, "Analysis of OAM Modes and OFDM Modulation for Outdoor Conditions," *International Journal of Technology,* vol. 14, no. 6, (2023)
7. W. Sahraoui *et al.*, "Design and Development of Fibonacci Code for SAC-OCDMA System," in *IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO)*, 2022: IEEE, pp. 462-466
8. A. Ghazi, S. Aljunid, S. Z. S. Idrus, A. Fareed, C. Rashidi, and A. Al-dawoodi, "Comparison of Laguerre-Gaussian and Hermite–Gaussian Modes for Optical-CDMA over Multi-Mode Fiber," in *IOP conference series: materials science and engineering*, 2020, vol. 767, no. 1: IOP Publishing, p. 012011
9. W. Sahraoui, A. Amphawan, M. B. Jasser, and T.-K. Neo, "Performance Analysis of New 2D Spatial OCDMA Encoding based on HG Modes in Multicore Fiber," *International Journal on Advanced Science, Engineering and Information Technology,* vol. 13, no. 6, pp. 2164-2170 (2023)
10. Y.-T. Li, T.-W. Geng, and S.-J. Gao, "On the signal combinations for a uniquely decodable coded MIMO-FSO communication system," *Optics & Laser Technology,* vol. 172, p. 110533 (2024)
11. A. Gupta, D. Dhawan, N. Gupta, and H. Kaushal, "Investigation of Outage Performance in NOMA-based Dual-hop FSO Communication," *Wireless Personal Communications,*  (2025)
12. M. Ghanem, A. Amphawan, A. M. Ramly, N. I. S. A. Blya, and T.-K. Neo, "Sparse Code Multiple Access with Hermite-Gaussian Modes for Enhanced Security in Free Space Optical Communications," presented at the 4th International Conference on Computer, Information Technology and Intelligent Computing (CITIC 2024), Cyberjaya, Selangor, (2024)
13. T. Masunda, A. Amphawan, S. Alshwani, and A. Aldawoodi, "Modal Properties of a Varied High Indexed Large Core 4-Mode Photonic Crystal Fiber," presented at the 2018 IEEE 7th International Conference on Photonics (ICP), Langkawi, (9-11 April 2018, 2018)
14. A. Ghazi *et al.*, "Spiral-phased laguerre-gaussian modes generation in swdm over few mode fiber based on electrical equalization," in *Journal of Physics: Conference Series*, 2020, vol. 1529, no. 2: IOP Publishing, p. 022012
15. S. Chaudhary and A. Amphawan, "Selective excitation of LG 00, LG 01, and LG 02 modes by a solid core PCF based mode selector in MDM-Ro-FSO transmission systems," *Laser Physics,* vol. 28, no. 7, p. 075106 (2018)
16. A. Amphawan, A. Anwar, S. K. Ong, J. Sutanto, T. K. Neo, and K. Anwar, "Free-Space Optical Space Division Multiplexing for Smart Healthcare," in *2022 8th Annual International Conference on Network and Information Systems for Computers (ICNISC)*, 16-19 Sept. 2022 2022, pp. 527-532
17. S. NHuda *et al.*, "Generation orbital angular momentum modes using metasurfaces," in *AIP Conference Proceedings*, 2023, vol. 2579, no. 1: AIP Publishing,
18. A. Amphawan, S. Chaudhary, Z. Ghassemlooy, and T.-K. Neo, "2× 2-channel mode-wavelength division multiplexing in Ro-FSO system with PCF mode group demultiplexers and equalizers," *Optics Communications,* vol. 467, p. 125539 (2020)
19. A. Ghazi *et al.*, "Donut Modes in Space Wavelength Division Multiplexing: Multimode Optical Fiber Transmission based on Electrical Feedback Equalizer," in *Journal of Physics: Conference Series*, 2021, vol. 1755, no. 1: IOP Publishing, p. 012046
20. A. Amphawan, A. Ghazi, and A. Al-dawoodi, "Free-space optics mode-wavelength division multiplexing system using LG modes based on decision feedback equalization," in *EPJ Web of Conferences*, 2017, vol. 162: EDP Sciences, p. 01009
21. A. Ghazi *et al.*, "A Systematic review of Multi-Mode Fiber based on Dimensional Code in Optical-CDMA," in *Journal of Physics: Conference Series*, 2021, vol. 1860, no. 1: IOP Publishing, p. 012016
22. S. A. A. Ghazi *et al.*, "Comparison of MD & ZCC one dimension code for optical-CDMA over multi-mode fiber based on Laguerre-Gaussian modes," *Journal of Engineering Science and Technology,* vol. 16, no. 4, pp. 3588-3599 (2021)
23. A. Ghazi, S. Aljunid, S. Z. S. Idrus, A. Fareed, A. Al-dawoodi, and A. H. Mohsin, "Design of a hybrid WDMA-Optical-CDMA over multi-mode fiber transmission system based on LG modes for short haul-local area network," in *Journal of Physics: Conference Series*, 2021, vol. 1793, no. 1: IOP Publishing, p. 012016
24. A. Almogahed, A. Amphawan, and F. Mohammed, "Design of 7× 2.5 Gbps decision feedback equalization scheme for mode division multiplexing over free-space optics under diverse atmospheric turbulence," *Optical Engineering;,* vol. 61, no. 5, pp. 056102-056102 (2022)
25. A. Almogahed, A. Amphawan, and Y. Fazea, "Mitigation of atmospheric turbulences using mode division multiplexing based on decision feedback equalizer for free space optics," *Journal of optical communications,* vol. 41, no. 2, pp. 185-193 (2020)
26. B. Guan *et al.*, "Free-space coherent optical communication with orbital angular, momentum multiplexing/demultiplexing using a hybrid 3D photonic integrated circuit," *Optics express,* vol. 22, no. 1, pp. 145-156 (2013)
27. A. Fareed *et al.*, "Comparison of Laguerre-Gaussian, Hermite–Gaussian and linearly polarized modes in SDM over FMF with electrical nonlinear equalizer," in *AIP Conference Proceedings*, 2020, vol. 2203, no. 1: AIP Publishing,
28. M. K. Faeq *et al.*, "Design and Analysis of High-Speed FSO for Supporting Fifth Generation under various weather scenarios," *Texas Journal of Engineering and Technology,* vol. 8, pp. 133-139 (2022)
29. O. A. Mahmood, M. A. Hussein, A. Al-dawoodi, and H. Maraha, "Random weather phenomena in free-space optical-FTTx communication system," *Periodicals of Engineering and Natural Sciences (PEN),* vol. 8, no. 2, pp. 1060-1066 (2020)
30. A. Mohammed, "Hybrid coarse and dense wdm over fso link under the effect of moderate and heavy rain weather attenuations," *Journal of Engineering Science and Technology,* vol. 15, no. 5, pp. 3494-3501 (2020)
31. A. Al-dawoodi *et al.*, "Investigation of 8 x 5 Gb/s mode division multiplexing-FSO system under different weather condition," *Journal of Engineering Science and Technology,* vol. 14, no. 2, pp. 674-681 (2019)
32. A. Ghazi, S. Aljunid, A. Noori, S. Z. S. Idrus, C. Rashidi, and A. Al-Dawoodi, "Design & investigation of 10x10 gbit/s MDM over hybrid FSO link under different weather conditions and fiber to the home," *Bulletin of Electrical Engineering and Informatics,* vol. 8, no. 1, pp. 121-126 (2019
33. M. N. Ismael and A. M. Fakhrudeen, "SDM over hybrid FSO link under different weather conditions and FTTH based on electrical equalization," *International Journal of Civil Engineering and Technology (IJCIET),* vol. 10, no. 1, pp. 1396-1406 (2019)
34. S. Alshwani, A. M. Fakhrudeen, M. N. Ismael, A. Al-Dawoodi, and A. Ghazi, "Hermite-Gaussian mode in spatial division multiplexing over FSO system under different weather condition based on linear gaussian filter," *International Journal of Mechanical Engineering and Technology,* vol. 10, no. 1, pp. 1095-1105 (2019)
35. S. A. Kadhim, A. Shakir, A. N. Mohammad, and N. F. Mohammad, "System design and simulation using (OptiSystem 7.0) for performance characterization of the free space optical communication system," *International journal of innovative research in science, engineering and technology,* vol. 4, no. 6, pp. 4823-4831 (2015)