Journal of Computer Science

Original Research Paper

Investigations on Orthogonal-Frequency Division Multiplexed-Mode-Division Multiplexed MM Wave-on-Free Space Optics Transmission using Laguerre-Gaussian Modal Beams

[1,2]Anita Suman and [2]Ajay Kumar

[1]Research Scholar, IK Gujral Punjab Technical University, Kapurthala, India
[2]Department of ECE, Sardar Beant Singh State University, Gurdaspur, India

Article history
Received: 30-09-2021
Revised: 27-10-2021
Accepted: 01-11-2021

Corresponding Author:
Anita Suman
Research Scholar, IK Gujral Punjab Technical University, Kapurthala, India
Emai: suman_a1@yahoo.com

Abstract: We report the simulation-modelling and evaluation of an integrated Orthogonal-Frequency Division Multiplexed (OFDM)-Mode-Division Multiplexed (MDM) Radio-on-Free Space Optics (Ro-FSO) scheme carrying 2-independent 40 GHz millimetre waves (mm Wave) at 20 Gbps per channel for 5th generation wireless applications. The reported Ro-FSO scheme transports 2-independent 20 Gbps 4-Quadrature-Amplitude Modulated (4-QAM) signals, each carrying 40 GHz mm Wave signal over 2-distinct Laguerre-Gaussian (LG) modal beams and their performance evaluation is carried out for varying levels of clear and foggy weather. Also, we have taken into consideration the effect of increasing size of optical beam signal on the reported scheme performance. The reported results elucidate favourable transportation of both mm Wave signals along 40 km range for clear sky and 1.5 km for heavy-foggy weather.

Keywords: mm Wave, MDM, Ro-FSO, Foggy Weather, Divergence

Introduction

Millimetre waves (mmWave) ranging from 24 GHz - 100 GHz frequency results in many performance merits and are considered as a crucial part of future 5th Generation (5G) wireless services (Pham *et al*., 2015). It provides the mobile service providers with an important competitive merit to address the huge demand for high information rate transmission and to extend 5G services to industrial, enterprise and fixed wireless applications (Singh *et al*., 2021a; Borges *et al*., 2021). The transportation of mmWave signals over wireless channel is challenging due to large amount of path loss and blockage sensitivity (Majumdar and Ricklin, 2010). Free Space Optics (FSO) transmission is a relatively novel concept in contrast to Radio Frequency (RF) wireless links and employs optical light beam signals as the data carriers to transport information from sender to destination, both of which are in Line-Of-Sight (LOS) configuration (Majumdar, 2014; Rosker and Wallace, 2017). Since abundantly available optical frequency signals which do not have any licensing restrictions are deployed in FSO systems, it is a very cost-efficient technology with capability to transmit huge channel bandwidth data at high rates of transmission. Further, it is robust to interference from electromagnetic signals and RF beams and provides reliable and secure transportation of data signals due to LOS transmission and deployment of very narrow-sized laser beam signals (Seeds *et al*., 2015; Pottoo *et al*., 2020; Ramirez-Iniguez *et al*., 2008). Furthermore, the components and equipment deployed for FSO transmission have small footprint and low power requirements. FSO systems can be easily and quickly installed at roof-top stations in the case of terrestrial building-to-building links and have the ability of redeployment (Willebrand and Ghuman, 2001; Kaushal and Kaddoum, 2016). These merits of FSO transmission systems makes it a front-runner technology for future large-bandwidth wireless networks. The transmission of mmWave over FSO systems, also referred to as Radio-on-Free Space Optics (Ro-FSO) transmission is regarded as a crucial and significant technological solution for practical implementation of 5G services in both rural and urban areas (Singh and Malhotra, 2019a; Singh *et al*., 2021b; Singh and Malhotra, 2020a; Singh and Malhotra, 2019b; Singh and Malhotra, 2020b). Apart from secure transmission of mmWave over free-space medium, Ro-FSO system provide additional low-latency networks and high availability. But the performance of Ro-FSO transmission is adversely affected by environmental weather conditions, which absorb and scatter the power of optical laser beam carrying data and may lead to link failure.

Different weather conditions like fog, storm, haze, rainfall, etc. result in suspension of different-sized particles in the atmosphere which interfere with propagation of optical beam through free-space medium. Fog is the most transmission performance degrading weather conditions since the size of fog particle is almost same as the size of optical signal and thus resulting in high attenuation of signal due to scattering and absorption.

Literature Survey

Orthogonal-Frequency Division Multiplexing (OFDM) is a form of multi-carrier digital information modulation technique which divides a high information rate data signal into large number of very-low speed signals and each signal is transmitted over a distinct orthogonal sub-carrier signal. The orthogonality of sub-carriers achieved using Inverse Fast Fourier Transformation (IFFT) at the transmitter module results in interference-free transmission and demodulation of each sub-carrier data signal. The integration of OFDM signals with FSO transmission can provide large technological merits including better spectral efficiency, inter-channel interference and inter-symbol interference immunity, higher information rate transmission, etc. (Singh and Malhotra, 2020c; Boobalan *et al*., 2021). The transmission evaluation of OFDM-FSO systems have been proposed and reported in many recent works.

Sharma (2014) reported an OFDM-FSO transmission scheme where coherent detection is employed for better receiver sensitivity. The authors reported performance comparison of optical single-sideband signals and optical dual-sideband signals and evaluated the systems' performance under clear sky atmospheric conditions. A faithful transmission along 3 km range is reported with favourable Signal-to-Noise Ratio (SNR) at the demodulator. Patel *et al.* (2014) reported an OFDM-FSO transmission scheme with coherent detection and reported performance comparison of 2 Gbps and 5 Gbps information transmission rates of the link. The maximum range for clear atmospheric conditions is reported as 17 km at 2 Gbps and 14 km at 5 Gbps information rate. Nistazakis *et al.* (2016) reported the derivation of mathematical expression for calculating the outage probability of a multi-hop terrestrial OFDM-Ro-FSO transmission scheme under the influence of atmospheric turbulent conditions and pointing errors. The authors analytically reported that as the number of relay nodes increases in the multi-hop system, the outage probability performance of the OFDM-Ro-FSO transmission improves.

Reported the comparison of 128 and 512 sub-carriers in OFDM-FSO transmission scheme under the influence of moderate and strong turbulence. The authors reported 10 Gbps-30 km transmission with favourable SNR and an augmentation of 6 dB in the received SNR by using 512 sub-carriers in contrast to 128 sub-carriers. Zhang *et al.* (2018) reported the incorporation of OFDM-FSO transmission scheme for airborne communication system under the impact of exponentiated-Weilbull atmospheric turbulent model. The authors reported that as the laser power increases, the transmission performance under turbulent conditions improves. Ajewole *et al.* (2019) reported the comparative investigation of Binary Phase-Shift Keying (BPSK) modulation scheme and 64-level Quadrature-Amplitude Modulation (64-QAM) scheme in an OFDM-FSO transmission under varying gamma-gamma turbulence conditions. The authors reported that deteriorating turbulent conditions degrades the systems' performance and demonstrated that BPSK has a better transmission performance than 64-QAM. Gupta *et al.* (2019) reported transmission evaluation of a novel integrated low density parity code-trellis code modulation in an OFDM-FSO scheme and reported an improved performance of the system under weak turbulence conditions.

Hario *et al.* (2019) reported performance evaluation of OFDM-FSO scheme under tropical weather conditions in Indonesia and reported the use of 16-QAM signals. The authors reported faithful 10 Gbps-2 km transmission for sunny climate with favourable SNR at the demodulator. Darwesh and Kopeika (2020) reported the improvement in the detection mechanism of asymmetrical clipped optical-OFDM signals in a FSO scheme by employing deep learning techniques. Panda and Bhanja (2021) reported an improved performance evaluation of OFDM-FSO scheme by designing a modified OFDM receiver. In the previous works reported in (Sharma, 2014; Patel *et al*., 2014; Nistazakis *et al*., 2016; Attri *et al*., 2017; Zhang *et al*., 2018; Ajewole *et al*., 2019; Gupta *et al*., 2019; Hario *et al*., 2019; Darwesh and Kopeika, 2020; Panda and Bhanja, 2021) single-channel OFDM transmission has been discussed over free-space channel. Further enhancement of transmission capacity of FSO can be achieved by employing more OFDM channels transmission simultaneously which can be achieved using Wavelength-Division Multiplexed (WDM) transmission. But WDM technique is cost-inefficient and requires significant spectral bandwidth (Singh and Malhotra, 2021a; Shahid *et al*., 2020). An emerging data communication technique namely Mode-Division Multiplexing (MDM) transmits multiple information signals simultaneously by employing distinct spatial modal profiles of a single-frequency channel, thus providing higher spectral and cost effectiveness. This research article proposes OFDM-Ro-FSO transmission with MDM technique to realize a net transmission of 40 Gbps over single laser.

Proposed OFDM-MDM-Ro-FSO Architecture

Figure 1 explicates the architecture of OFDM-MDM-Ro-FSO transmission scheme where 2-independent 40 GHz mmWave signals are transmitted at 20 Gbps information rate using 2-distinct Laguerre-Gaussian (LG) modal channels. The spatial intensity patterns of LG modal channels employed in this research work (LG01 and LG03) produced using laser diode and multimode generator are explicated in Fig. 2.

Binary data signal at an information rate of 20 Gbps for each user at the transmitter is produced using Pseudo-Random-Bit-Sequence (PRBS) generator component. Binary data is mapped onto 4-QAM symbols where 2-bits are used per symbol. 4-QAM signal is OFDM modulated with 512-subcarriers, 1024-IFFT points and 32-prefix value. The OFDM electrical signal is modulated over 7.5 GHz carrier signal using Quadrature Modulation (QM) and further a 40 GHz mmWave signal is then mixed with this signal. Each OFDM signal is optically modulated using distinct LG modal profile by employing a MZM. Both the 4-QAM-OFDM-LG-modulated signals are combined using Multiplexer (MUX) and transported through free-space channel. The input power of laser diode in this study is 10 dBm with 5 MHz spectral-width of the laser. The beam width (divergence angle) is considered to be 0.25 mrad and the transmitter and receiver lens diameter are 10 cm and 20 cm respectively. A de-multiplexer (DEMUX) employed at the input stage of the receiver section splits LG01 and LG03 modal channels and directs them to individual demodulator units. A PIN-photodiode at each demodulator generates the electrical equivalent of optical signal and OFDM demodulator component performs Fast Fourier Transformation (FFT) algorithm. The original data bits are retrieved by using 4-QAM sequence decoder component. In Ro-FSO links, the optical power captured by the receiver lens after free-space channel is given by Singh *et al*. (2021b):

$$S_r = S_r \times \left[\frac{d_r^2}{\left(d_t + \theta z\right)^2} \right] \times 10^{-\sigma z/10} \tag{1}$$

where,

S_r = Power captured by receiver lens
S_t = Power of the laser diode
d_t = Transmitter lens diameter
d_r = Receiver lens diameter
θ = Beam width
σ = Atmospheric attenuation coefficient
Z = Range of FSO transmission

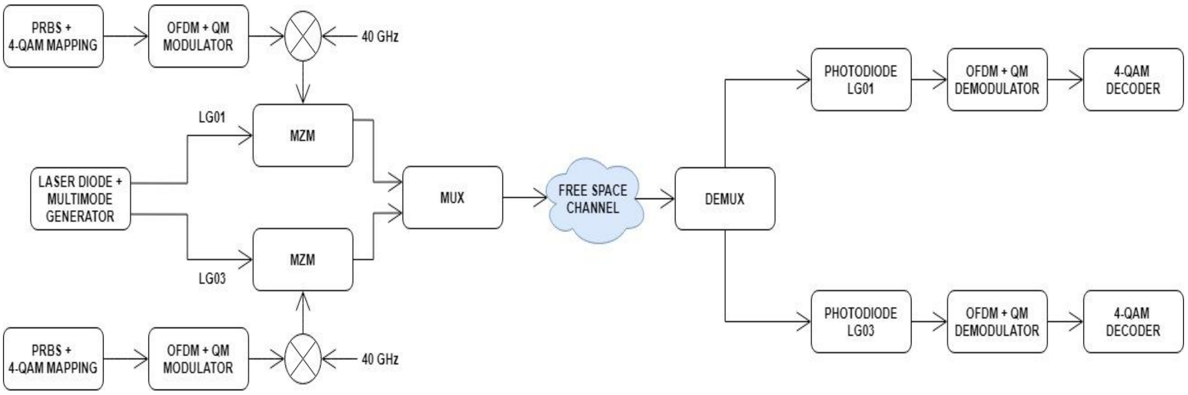


Fig. 1: MDM-OFDM-Ro-FSO architecture

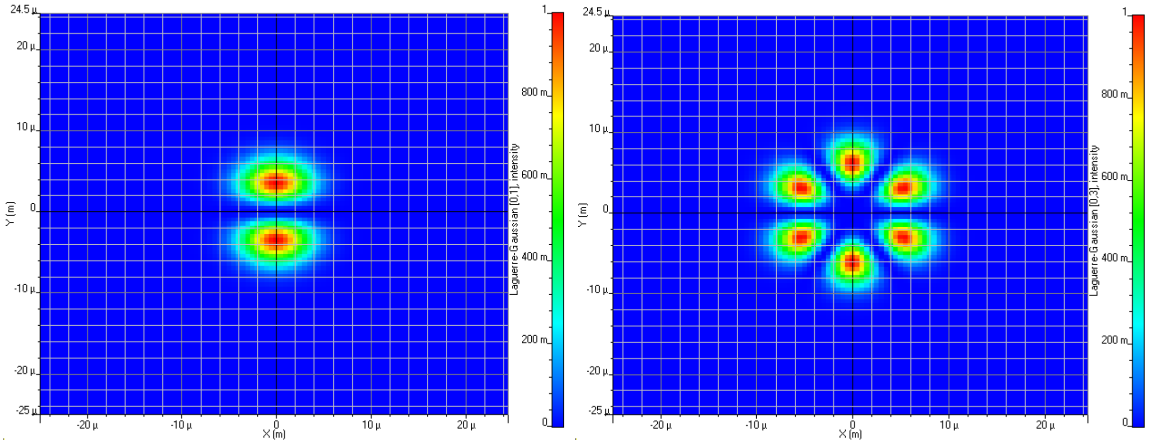


Fig. 2: Spatial intensity profiles of (a) LG01 modal channel (b) LG03 modal channel

Results

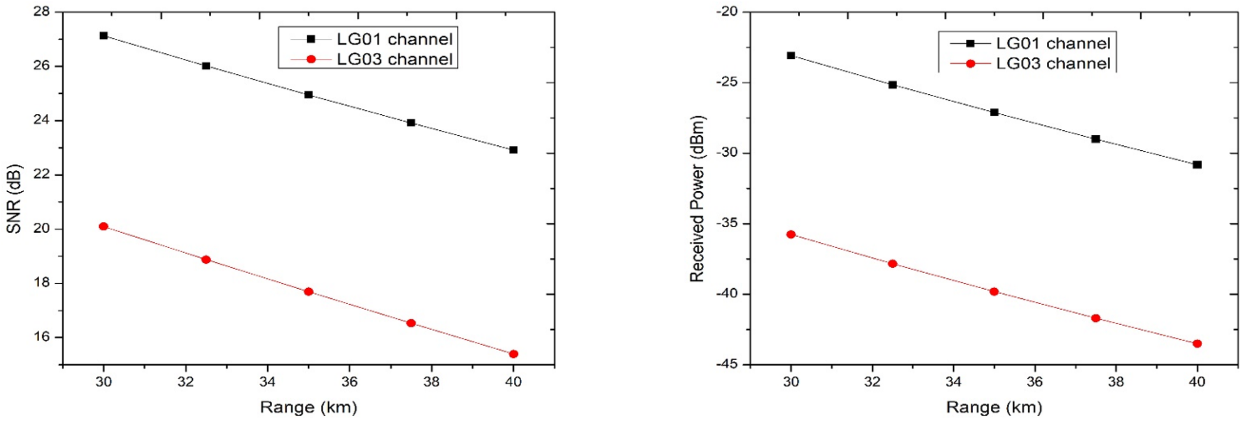
The simulation results are presented in this section Fig. 12. Figure 3 (a) and (b) explicates the transmission performance curves under clear sky weather in terms of SNR and received power at PIN-photodiode respectively. Figure 3 (a) reveals that SNR is 27.12, 24.94 and 22.91 dB for LG01 modal channel and 20.09, 17.69 and 15.39 dB for LG03 modal channel at 30, 35 and 40 km range respectively. Figure 3 (b) reveals that power is -23.07, -27.12 and -30.81 dBm for LG01 modal channel and -35.76, -39.81 and -43.50 dBm for LG03 modal channel at 30, 35 and 40 km range respectively. Figure 4 explicates the constellation plots of the LG modal channels at 40 km under clear sky conditions. We can see that the constellation plots are rotated which can be attributed to phase distortion of the received signal due to atmospheric disturbances. Clear constellation plots with significant SNR and power demonstrate favourable 40 km transmission for both 40 GHz mmWave signals at 20 Gbps information rate per channel.

Figure 5 explicates the transmission performance curves for increasing beam width (divergence) under clear sky weather at 30 km range. Figure 5 (a) reveals that SNR is 27.12, 18.27 and 13.12 dB for LG01 modal channel and 20.09, 9.97 and 3.78 dB for LG03 modal channel at 0.25, 0.625 and 1 mrad divergence angle respectively. Figure 3 (b) reveals that power is -23.07, -38.85 and -46.98 dBm for LG01 modal channel and -35.76, -51.53 and -59.61 dBm for LG03 modal channel at 0.25, 0.625 and 1 mrad divergence angle respectively. Figure 6 explicates the constellation plots for both channels with increasing beam width.

Figure 7 explicates the transmission performance curves under light-foggy weather. Figure 7 (a) reveals that SNR is 26.83, 24.30 and 21.72 dB for LG01 modal channel and 19.78, 16.97 and 14.03 dB for LG03 modal channel at 2700, 2900 and 3100 m range respectively. Figure 7 (b) reveals that power is -23.61, -28.30 and -32.90 dBm for LG01 modal channel and -36.30, -40.99 and -45.60 dBm for LG03 modal channel at 2700, 2900 and 3100 m range respectively. Figure 8 explicates the constellation plots of the LG modal channels at 3100 m under light-foggy conditions. Clear constellation plots with significant SNR and power demonstrate favourable 3100 m transmission for both 40 GHz mmWave signals at 20 Gbps information rate per channel.

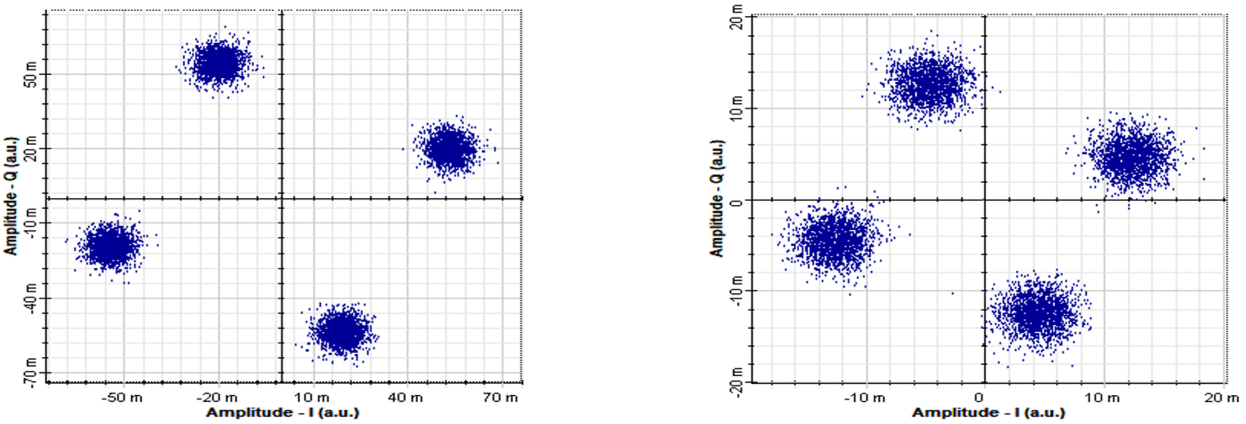
Figure 9 explicates the transmission performance curves under medium-foggy weather. Figure 9 (a) reveals that SNR is 29.48, 25.19 and 20.78 dB for LG01 modal channel and 22.64, 17.97 and 12.94 dB for LG03 modal channel at 1600, 1800 and 2000 m range respectively. Figure 9 (b) reveals that power is -18.60, -26.66 and -34.57 dBm for LG01 modal channel and -31.29, -39.34 and -47.25 dBm for LG03 modal channel at 1600, 1800 and 2000 m range respectively. Figure 10 explicates the constellation plots of the LG modal channels at 2000 m under medium-foggy conditions. Clear constellation plots with significant SNR and power demonstrate favourable 2000 m transmission for both 40 GHz mmWave signals at 20 Gbps information rate per channel.

Figure 11 explicates the transmission performance curves under heavy-foggy weather. Figure 10 (a) reveals that SNR is 27.81, 24.91 and 21.96 dB for LG01 modal channel and 20.84, 17.66 and 14.30 dB for LG03 modal channel at 1300, 1400 and 1500 m range respectively. Figure 10 (b) reveals that power is -21.78, -27.17 and -32.51 dBm for LG01 modal channel and -34.47, -39.86 and -45.19 dBm for LG03 modal channel at 1300, 1400 and 1500 m range respectively. Figure 11 explicates the constellation plots of the LG modal channels at 1500 m under medium-foggy conditions. Clear constellation plots with significant SNR and power demonstrate favourable 1500 m transmission for both 40 GHz mmWave signals at 20 Gbps information rate per channel.



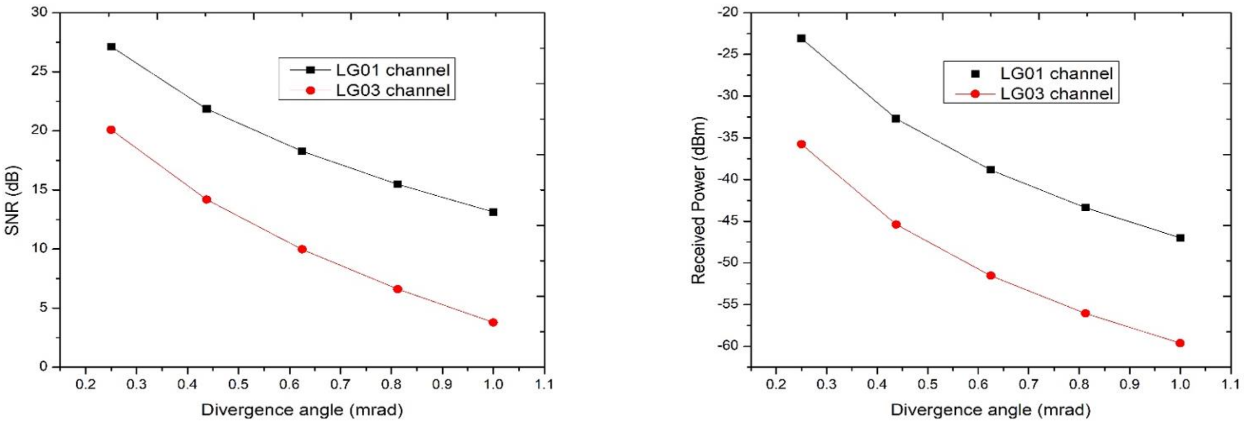
(a) (b)

Fig. 3: Performance curves for clear sky in terms of (a) SNR (b) Power



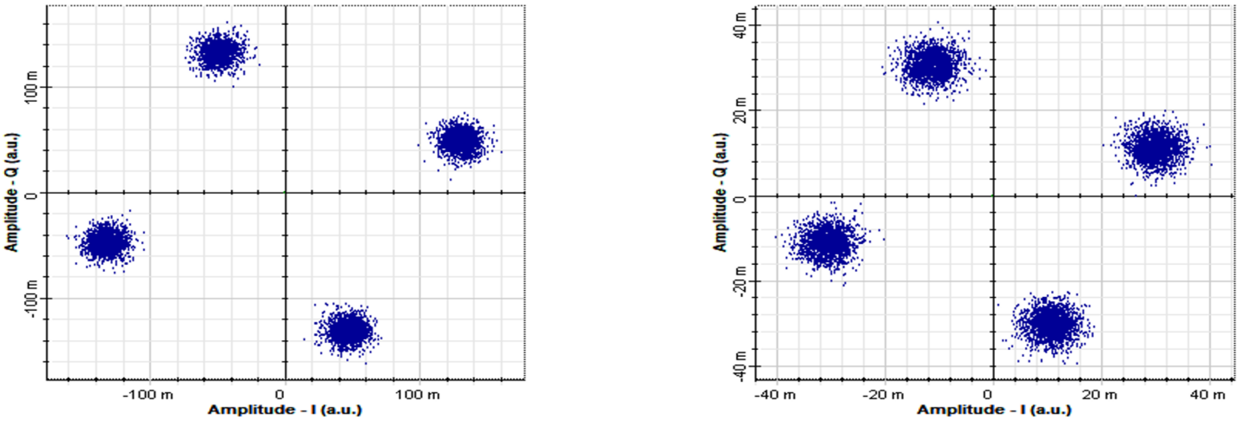
(a) (b)

Fig. 4: Constellation plots at 40 km for (a) LG01 modal channel (b) LG03 modal channel

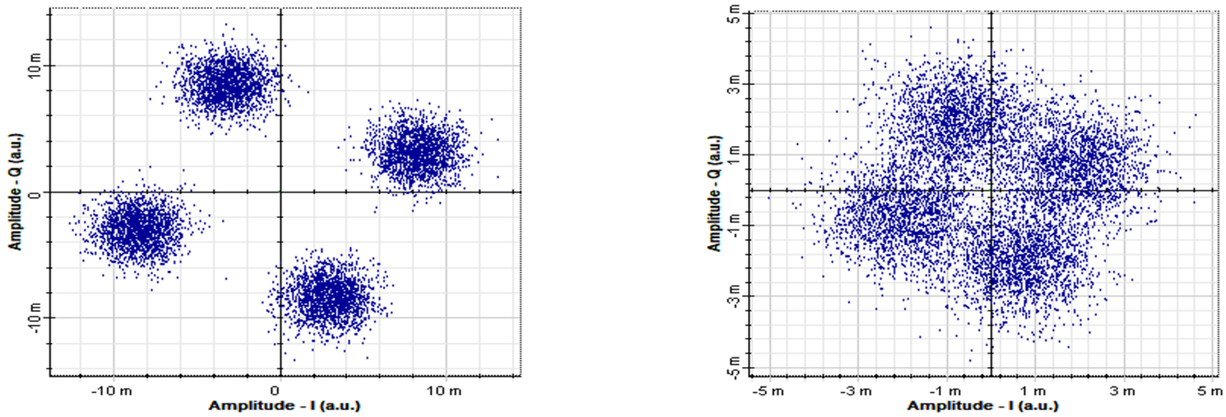


(a) (b)

Fig. 5: Performance curves for divergence angle in terms of (a) SNR (b) Power



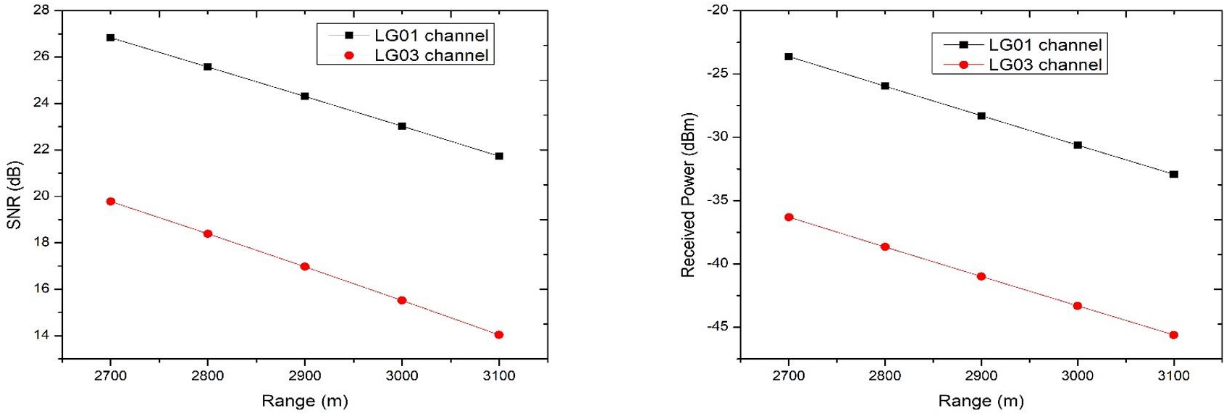
(a) (b)



(c)

(d)

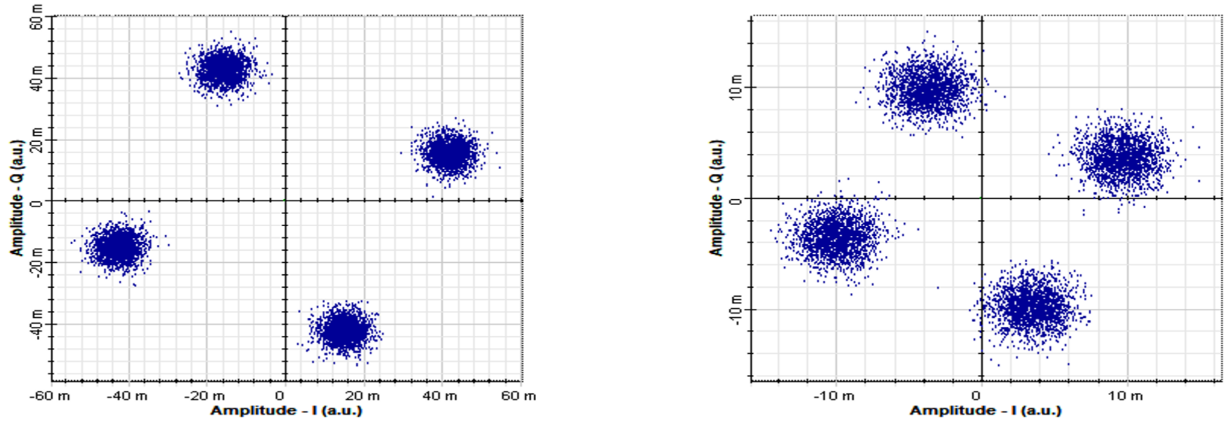
Fig. 6: Constellation plots at 0.25 mrad divergence angle for (a) LG01 modal channel (b) LG03 modal channel; at 1 mrad divergence angle for (c) LG01 modal channel (d) LG03 modal



(a)

(b)

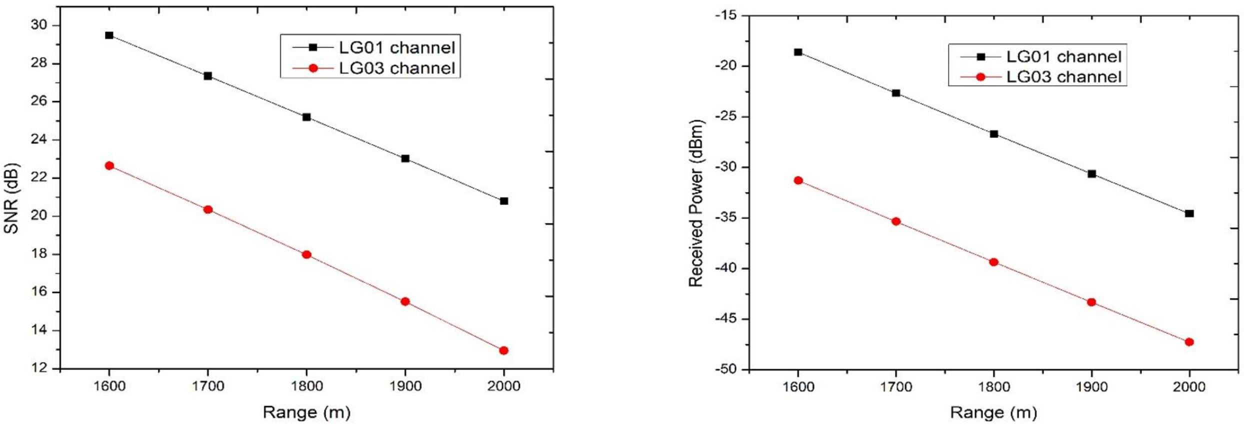
Fig. 7: Performance curves for light-foggy weather in terms of (a) SNR (b) Power



(a)

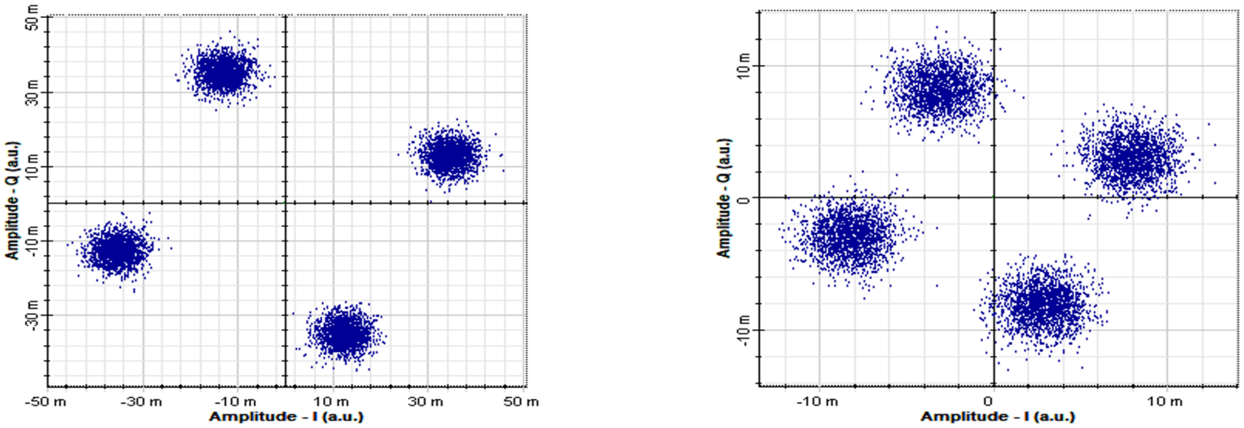
(b)

Fig. 8: Constellation plots at 3100 m for (a) LG01 modal channel (b) LG03 modal channel



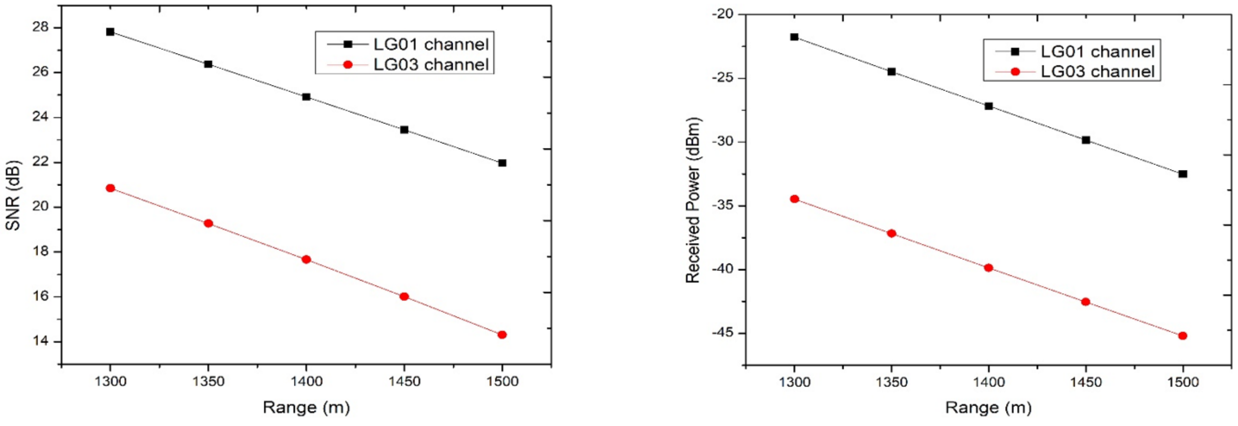
(a) (b)

Fig. 9: Performance curves for medium-foggy weather in terms of (a) SNR (b) Power



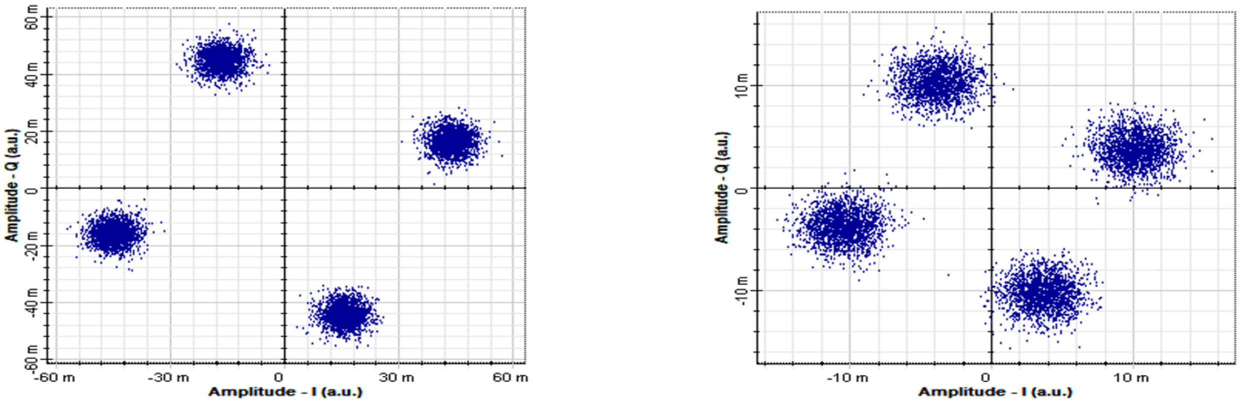
(a) (b)

Fig. 10: Constellation plots at 2000 m for (a) LG01 modal channel (b) LG03 modal channel



(a) (b)

Fig. 11: Performance curves for heavy-foggy weather in terms of (a) SNR (b) Power



(a) (b)

Fig. 12: Constellation plots at 1500 m for (a) LG01 modal channel (b) LG03 modal channel

Conclusion

We have developed a 4-QAM-OFDM-MDM-Ro-FSO transmission scheme which transmits 2-independent 40 GHz mmWave signals, each at 20 Gbps information rate using distinct LG modal beams over free-space over varying weather conditions. LG01 modal beam demonstrates higher robustness and better transmission performance than as compared to LG03 modal beam. Also, we have investigated the transmission performance of the proposed scheme with increasing beam width and the results reported that as the beam width increases, the transmission performance deteriorates. The results demonstrate transmission of both 40 GHz mmWave signals at 20 Gbps information rate per channel along 40 km for clear weather and 3100, 2000 and 1500 m for light-foggy, medium-foggy and heavy-foggy weather respectively with favourable performance.

Acknowledgement

The authors are thankful to IK Gujral Punjab Technical University, Kapurthala for providing necessary technical assistance and software to accomplish this work.

Author Contributions

Anita Suman: Simulative investigation and manuscript dafting.

Ajay Kumar: Project supervision and final draft preparation.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

References

Ajewole, B. D., Odeyemi, K. O., Owolawi, P. A., & Srivastava, V. M. (2019). Performance of OFDM-FSO Communication System with Different Modulation Schemes over Gamma-Gamma Turbulence Channel. J. Commun., 14(6), 490-497. doi.org/10.12720/jcm.14.6.490-497

Attri, S., Narula, C., & Kumar, S. (2017). Performance analysis of FSO Link using CO-OFDM under the effect of atmospheric turbulence. In Proceeding of International Conference on Intelligent Communication, Control and Devices (pp. 167-172). Springer, Singapore. doi.org/10.1007/978-981-10-1708-7_18

Borges, R. M., de Souza Lopes, C. H., Lima, E. S., de Oliveira, M. A., Cunha, M. S. B., Alexandre, L. C., ... & Sodré Junior, A. C. (2021). Integrating Optical and Wireless Techniques towards Novel Fronthaul and Access Architectures in a 5G NR Framework. Applied Sciences, 11(11), 5048. doi.org/10.3390/app11115048

Darwesh, L., & Kopeika, N. (2020). Improved Performance in the Detection of ACO-OFDM Modulated Signals Using Deep Learning Modules. Applied Sciences, 10(23), 8380. doi.org/10.3390/app10238380

Gupta, R., Kamal, T. S., & Singh, P. (2019). Performance of OFDM: FSO communication system with hybrid channel codes during weak turbulence. Journal of Computer Networks and Communications, 2019. doi.org/10.1155/2019/1306491

Hario, F., Maulana, E., Pramono, S. H., Sari, S. N., & Al Junaedi, A. M. (2019, October). Design of OFDM-FSO communication system on high data rate for tropical climate region. In 2019 International Conference on Advanced Technologies for Communications (ATC) (pp. 74-78). IEEE. doi.org/10.1109/ATC.2019.8924543

Kaushal, H., & Kaddoum, G. (2016). Optical communication in space: Challenges and mitigation techniques. IEEE communications surveys & tutorials, 19(1), 57-96.

Majumdar, A. K. (2014). Advanced free space optics (FSO): A systems approach (Vol. 186). Springer. ISBN-10: 9781493909186

Majumdar, A. K., & Ricklin, J. C. (Eds.). (2010). Free-space laser communications: principles and advances (Vol. 2). Springer Science & Business Media. ISBN-10: 9780387286778

Nistazakis, H. E., Ninos, M. P., Tsigopoulos, A. D., Zervos, D. A., & Tombras, G. S. (2016). Performance study of terrestrial multi-hop OFDM FSO communication systems with pointing errors over turbulence channels. Journal of Modern Optics, 63(14), 1403-1413. doi.org/10.1080/09500340.2016.1149626

Panda, C., & Bhanja, U. (2021). Performance improvement of hybrid OFDM-FSO system using modified OFDM receiver. International Journal of Systems, Control and Communications, 12(3), 227-242. https://www.inderscienceonline.com/doi/abs/10.1504/IJSCC.2021.116756

Patel, P., Mishra, V., & Singh, V. (2014, December). Performance analysis of CO-OFDM FSO system under different weather conditions. In 2014 2nd International Conference on Emerging Technology Trends in Electronics, Communication and Networking (pp. 1-5). IEEE. doi.org/10.1109/ET2ECN.2014.7044972

Pham, A. T., Trinh, P. V., Mai, V. V., Dang, N. T., & Truong, C. T. (2015, June). Hybrid free-space optics/millimeter-wave architecture for 5G cellular backhaul networks. In 2015 Opto-Electronics and Communications Conference (OECC) (pp. 1-3). IEEE. doi.org/10.1109/OECC.2015.7340269

Pottoo, S. N., Goyal, R., & Gupta, A. (2020). Development of 32-GBaud DP-QPSK free space optical transceiver using homodyne detection and advanced digital signal processing for future optical networks. Optical and Quantum Electronics, 52(11), 1-17. doi.org/10.1007/s11082-020-02623-y

Ramirez-Iniguez, R., Idrus, S. M., & Sun, Z. (2008). Optical wireless communications: IR for wireless connectivity. CRC press. ISBN-10: 9781420013443

Rosker, M. J., & Wallace, H. B. (2007, June). Imaging through the atmosphere at terahertz frequencies. In 2007 IEEE/MTT-S International Microwave Symposium (pp. 773-776). IEEE. https://ieeexplore.ieee.org/abstract/document/4263933/

Seeds, A. J., Shams, H., Fice, M. J., & Renaud, C. C. (2015). Terahertz photonics for wireless communications. Journal of Lightwave Technology, 33(3), 579-587. https://www.osapublishing.org/abstract.cfm?uri=jlt-33-3-579

Shahid, T., Khalid, F., Qamar, F., Shahzad, A., Shahzadi, R., Ali, M., & Qamar, N. (2020, November). Performance Analysis of WDM Based FSO Communication with Advance Modulation Formats. In 2020 IEEE 23rd International Multitopic Conference (INMIC) (pp. 1-6). IEEE. doi.org/10.1109/INMIC50486.2020.9318129

Sharma, V. (2014). High speed CO-OFDM-FSO transmission system. Optik, 125(6), 1761-1763. doi.org/10.1016/j.ijleo.2013.10.010

Singh, K., Singh, M., Malhotra, J., & Grover, A. (2021). Long-reach cost-effective 100 Gbit/s CO-OFDM-MDM-based inter-satellite optical wireless communication (IsOWC) system. Optoelectronics and Advanced Materials-Rapid Communications, 15(May-June 2021), 245-253. https://oam-rc.inoe.ro/articles/long-reach-cost-effective-100-gbits-co-ofdm-mdm-based-inter-satellite-optical-wireless-communication-isowc-system/

Singh, M., & Malhotra, J. (2019a). 2× 10 Gbit/s–10 GHz radio over free space optics transmission system incorporating mode division multiplexing of Hermite Gaussian modes. Journal of Optical Communications. doi.org/10.1515/joc-2019-0047

Singh, M., & Malhotra, J. (2019b). Enhanced performance of 40Gbit/s-80GHz OFDM based radio over FSO transmission link incorporating mode division multiplexing under strong atmospheric turbulence. Optoelectronics and Advanced Materials-Rapid Communications, 13(July-August 2019), 437-447.

Singh, M., & Malhotra, J. (2020a). Modeling and performance analysis of 400 Gbps CO-OFDM based inter-satellite optical wireless communication (IsOWC) system incorporating polarization division multiplexing with enhanced detection. Wireless Personal Communications, 111(1), 495-511. https://link.springer.com/article/10.1007/s11277-019-06870-5

Singh, M., & Malhotra, J. (2020b). Performance comparison of different modulation schemes in high-speed MDM based radio over FSO transmission link under the effect of atmospheric turbulence using aperture averaging. Wireless Personal Communications, 111(2), 825-842. https://link.springer.com/article/10.1007/s11277-019-068fta86-x

Singh, M., & Malhotra, J. (2020c). 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. Optoelectronics and Advanced Materials-Rapid Communications, 14(May-June 2020), 233-243.

Singh, M., & Malhotra, J. (2021). Performance investigation of a 3.84 Tb/s WDM-based FSO transmission system incorporating 3-D orthogonal modulation scheme. Photonic Network Communications, 41(2), 177-188. doi.org/10.1007/s11107-021-00927-x

Singh, M., Pottoo, S. N., Dewra, S., Grover, A., Manikandan, A., & Sheetal, A. (2021a). Performance Investigation of a High Data Rate Mode Division Multiplexed-Free Space Optics Link Under Harsh Weather Conditions. Frontiers in Physics, 451. doi.org/10.3389/fphy.2021.743545

Singh, M., Pottoo, S. N., Malhotra, J., Grover, A., & Aly, M. H. (2021b). Millimeter-wave hybrid OFDM-MDM radio over free space optical transceiver for 5G services in desert environment. Alexandria Engineering Journal, 60(5), 4275-4285. doi.org/10.1016/j.aej.2021.03.029

Boobalan, S., Prakash, S. A., Angurala, M., Malhotra, J., & Singh, M. (2021). Performance Enhancement of 3× 20 Gbit/s MDM-Based OFDM-FSO System. Wireless Personal Communications, 1-29. doi.org/10.1007/s11277-021-09044-4

Willebrand, H. A., & Ghuman, B. S. (2001). Fiber optics without fiber. IEEE spectrum, 38(8), 40-45. https://ieeexplore.ieee.org/abstract/document/938713/

Zhang, Y., Wang, X., & Zhao, S. H. (2018, December). Performance analysis of FSO-OFDM airborne communication system over exponentiated Weibull atmospheric turbulence. In Fiber Optic Sensing and Optical Communication (Vol. 10849, p. 108490R). International Society for Optics and Photonics. doi.org/10.1117/12.2505308