



Performance Evaluation of a 4 × 20-Gbps OFDM-Based FSO Link Incorporating Hybrid W-MDM Techniques

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Specialty section:

This article was submitted to
Optics and Photonics,
a section of the journal
Frontiers in Physics

Received: 24 July 2021

Accepted: 31 July 2021

Published: 20 September 2021

Citation:

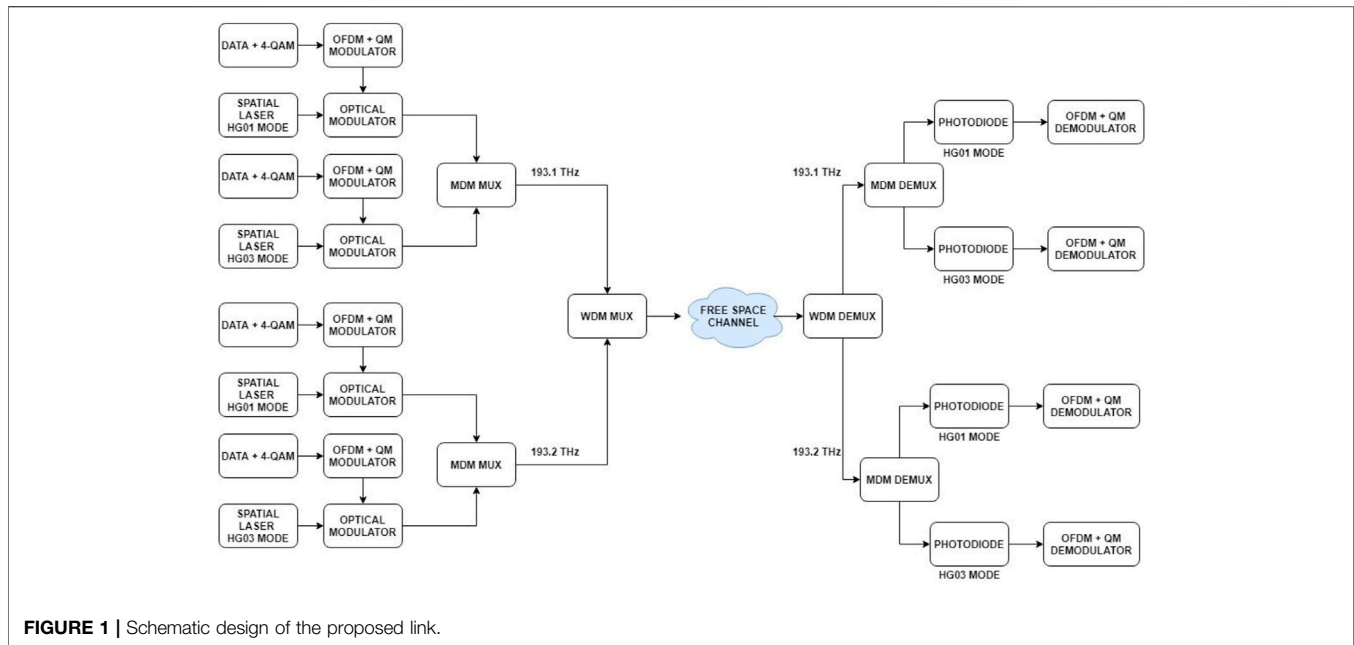
Singh M, Chebaane S, Ben Khalifa S,
Grover A, Dewra S and Angurula M
(2021) Performance Evaluation of a 4 ×
20-Gbps OFDM-Based FSO Link
Incorporating Hybrid W-
MDM Techniques.
Front. Phys. 9:746779.
doi: 10.3389/fphy.2021.746779

Free space optics (FSO) has been recognized as a crucial technique to meet the high-bandwidth requirements in future wireless information transmission links. It provides a feasible solution to the last-mile bottleneck problem due to its merits that include high-speed data transportation and secure and low-latency networks. Due to these merits, FSO is a reliable technology for future health-care and biomedical services like the transmission of biomedical sensor signals. But the main limiting factor in the data transmission employing FSO links is adverse atmospheric weather conditions. This research work reports the designing and simulative evaluation of the performance of a high-speed orthogonal frequency division multiplexing-based free space optics link by incorporating wavelength division multiplexing of two independent frequency channels (193.1 THz and 193.2 THz) along with mode division multiplexing of distinct spatial laser Hermite–Gaussian modes (HG01 and HG03). Four independent 20-Gbps quadrature amplitude-modulated data signals are transported simultaneously under different atmospheric weather conditions using the proposed link. Also, the link performance has been investigated for an increasing beam divergence angle.

Keywords: FSO, WDM, MDM, HG modes, atmospheric weather conditions, beam divergence, biomedical services

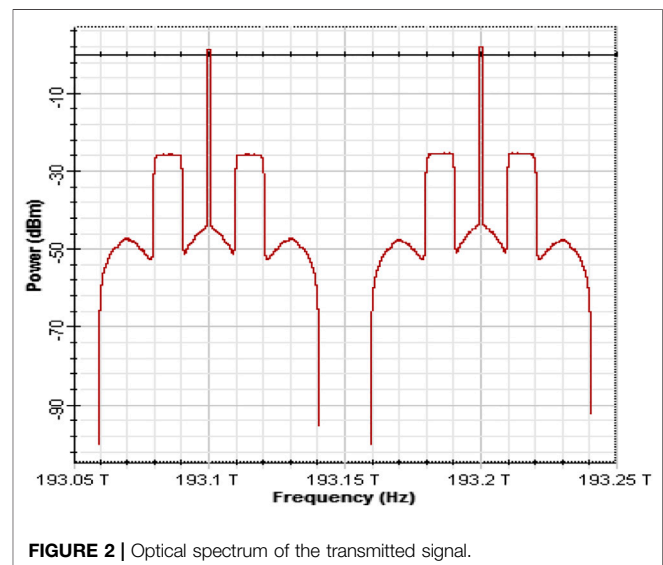
INTRODUCTION

Recent years have seen a significant increase in network traffic due to growth in the use of multimedia applications consuming high channel bandwidth like video conferencing, fast Internet, and live streaming. This has challenged the limited and congested radio frequency (RF) spectrum-based conventional wireless transmission systems [1]. Free space optics (FSO) is considered a promising solution to meet the high capacity and large transmission rate demand of the users. Optically modulated carrier signals are used to carry data signals over the free space medium between tightly aligned transmitter and receiver units. FSO technology has numerous merits, such as quick and easy installation, high channel bandwidth, immunity to electromagnetic interference, a high-speed

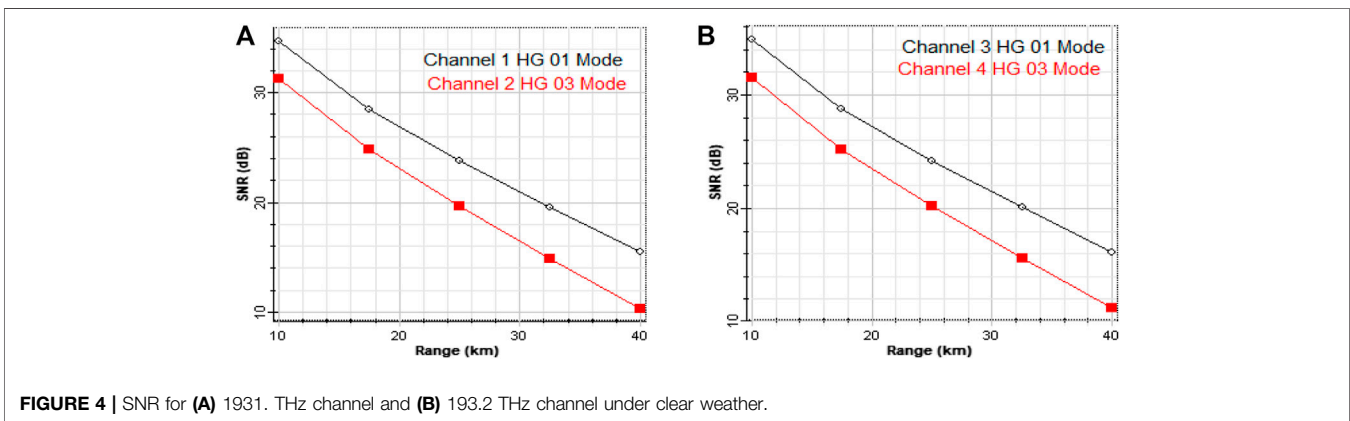
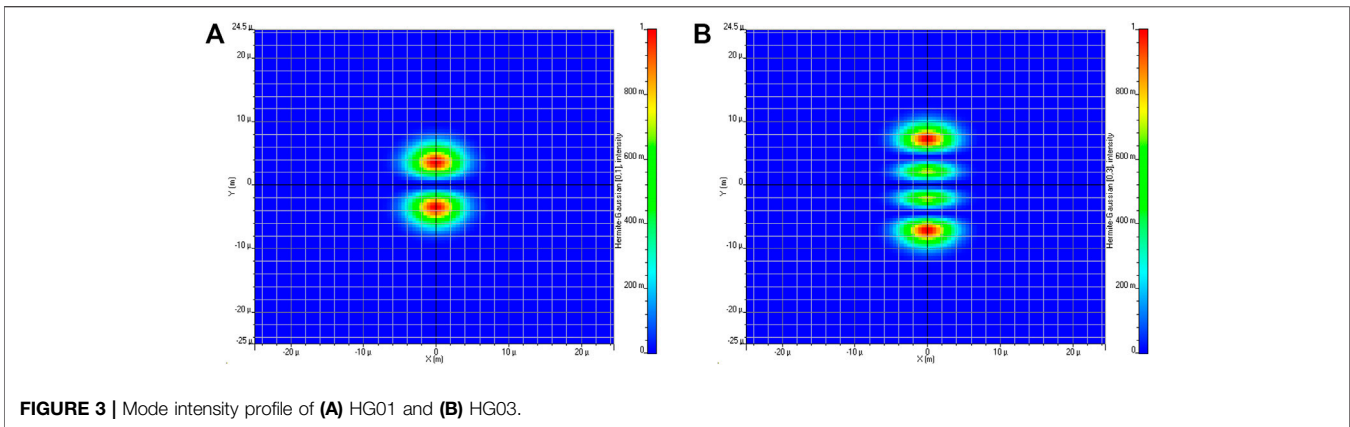


network, secure data transmission, and license-free spectrum availability [2–5]. Orthogonal frequency division multiplexing (OFDM) is a subset of multi-carrier modulation techniques using which a high-bit rate signal is transported over several low-speed subcarriers, which are spaced closely in the frequency domain and are orthogonal to each other, thus eliminating the inter-carrier interference [6, 7]. By incorporating OFDM technology with FSO links, highly reliable long-reach data transmission links can be realized. Here, the authors in references [8–10] report the design and performance investigation of the OFDM-based FSO terrestrial link under the effect of different atmospheric conditions. To increase the data-carrying capacity of the link, wavelength division multiplexing (WDM) can be used which transmits multiple information signals at the same time over the same medium using different wavelengths [11–14].

Mode division multiplexing (MDM) is an important and evolving transmission technique that capitalizes on different spatial modes of a single laser beam to transport independent data signals over the same channel. The authors in references [15–17] report optical signal-processing techniques to generate and de-multiplex different laser modes. The application of a spatial light modulator to multiplex and de-multiplex optical spatial laser beams has been reported in references [18, 19]. Y. Jung et al. proposed the application of dual-fused optical fiber for MDM transmission applications in reference [20]. A. Amphawan et al. report the application of a photonic crystal fiber with a single core to generate different linear polarized (LP) modes. In recent years, the incorporation of MDM in optical fiber links has been extensively investigated to realize high-speed transmission [21]. A. Juarez et al. reported an MDM system capable of realizing high-speed data transmission in multi-mode fiber (MMF) links using linear polarized (LP) modes [22]. The authors reported feasible transportation of 120-Gbps data with 3 GHz-km bandwidth-length product over an MMF link of 50 km length



using a multi-mode erbium-doped fiber amplifier (EDFA) at the receiver unit. T. Kodama et al. reported a novel hybrid all-optical MDM code division multiplexed system to realize future generation optical access networks [23]. The authors experimentally reported feasible transmission of 2 LP modes \times 4 phase-shift-keyed optical codes \times 10-Gbps on-off-keyed data streams over a 42 km fiber length using a single-mode and a multi-mode fiber without the application of dispersion compensation. T. Masunda et al. proposed hybrid MDM and WDM architecture to realize high-speed MMF interconnects [24]. Six independent vertical-cavity surface-emitting laser diodes are used, where each wavelength generates three distinct Laguerre–Gaussian (LG) modes to realize 18 parallel channel transmissions. The authors report feasible 60 Gbps transmission



over a 2.5-km MMF link by using a novel tap configuration in a feed-forward equalizer to mitigate the effects of inter-mode coupling.

R. Murad et al. reported a high-capacity MDM system using hybrid modes for high-capacity optical interconnects in data centers [25]. The authors reported feasible transportation of 44-Gbps data using two helical-phased ring modes over a 1,550.12-nm channel and two radially offset Hermite–Gaussian (HG) modes over a 1,551.72-nm channel along an MMF of 1,500 m range with an acceptable bit error rate of the system. E. Hamed et al. reported the performance comparison of three different types of optical fibers, that is, a step-index few-mode fiber (FMF), graded-index FMF, and transversal index-FMF in a spectral-efficient MDM system [26]. Three distinct LP modes, where each mode carries 10-Gbps quadrature amplitude-modulated (QAM) data signals are transmitted over all the three optical fiber types. The authors reported that transversal index-FMF performs the best and demonstrated a feasible 500 km transmission of 30-Gbps QAM data with good performance. Z. Feng et al. reported an ultra-high channel capacity optical access network based on hybridization of MDM and WDM technologies with advanced modulation formats [27]. The incorporation of the 200-Gbps polarization division multiplexed (PDM)-16-level-QAM-OFDM data signal has been proposed in the system.

The authors reported feasible data transmission of 4 wavelength channels \times 6 spatial modes \times 200 Gbps QAM data signals along a 37-km MMF with seven cores with acceptable performance.

The application of the orbital angular momentum (OAM) dimension of the optical signal to carry different independent information channels for realizing high-speed optical networks has been reported by many research groups in the last few years. The design of a hollow-core optical fiber capable of transporting 16 distinct OAM modes to realize high-capacity long-range MDM transmission has been reported by C. Brunet et al. in reference [28]. X. Zhang et al. reported the fabrication of a circular photonic crystal fiber capable of supporting 14 distinct OAM modes with low confinement losses and low nonlinear coefficients [29]. Also, the authors reported the fabrication of a multi-mode EDFA based on the circular photonic crystal fiber capable of reliably amplifying all 14 modes with 20 dB gain. The designing of a novel photonic crystal fiber, capable of supporting 26 OAM modes with low confinement loss, low nonlinear coefficient, and high bandwidth for long-haul spectrum-efficient MDM transmission in future optical access networks, has been reported by M. Hassan et al. in reference [30]. K. Ingerslev et al. reported feasible

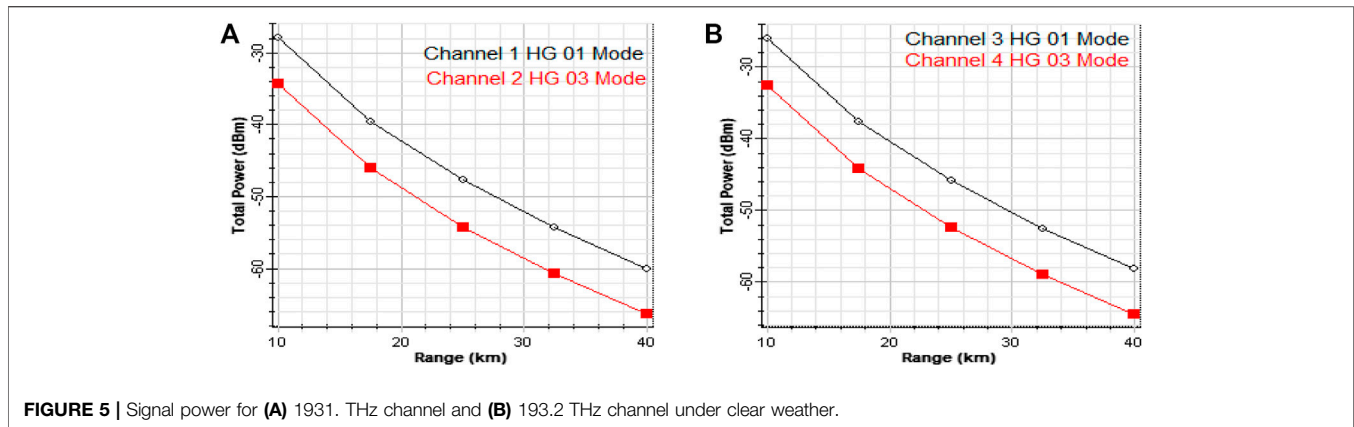


FIGURE 5 | Signal power for (A) 193.1 THz channel and (B) 193.2 THz channel under clear weather.

transportation of 12 OAM modes, where each mode carries 10 Gbaud quadrature phase-shift-keyed (QPSK) signals over a 1.2-km MMF link with good performance [31]. Further, the authors have demonstrated ultrahigh capacity reliable transmission by using 60 independent wavelength channels with a channel spacing of 25 GHz. A. Tatarczak et al. reported an experimental demonstration of feasible transportation of three distinct OAM modes, where each mode transported a 10-Gbps on-off-keyed signal over a 400-m MMF link for short-reach links and high-capacity data centers [32]. F. Al-Zahrani et al. reported the development and analysis of a ring-core photonic crystal fiber with high refractive index separation, capable of supporting 76 OAM modes and six LP modes for large-speed high-range optical communication networks [33]. The free space transmission of OAM modes showing a spectral efficiency of 95.7 bit/sec/Hz with a net information rate of 100.8 Tbps and a 1.1 km MMF transmission of OAM modes to realize a 1.6 Tbps optical fiber network has been discussed by J. Wang et al. in reference [34].

The application of OAM modes to realize high-speed FSO links has also been reported by different research groups [35–39]. The designing and evaluation of a low-density parity check coded FSO link incorporating high-capacity transmission under strong turbulence conditions using OAM multiplexing has been discussed by Z. Qu. et al. in reference [35]. The use of OAM multiplexing for deep space applications and multi-gigabit near-Earth optical networks has been reported by I. Djordjevic in reference [36]. Z. Qu. et al. reported a multi-gigabit capacity FSO link incorporating hybrid OAM multiplexing and WDM techniques [37]. Further, the link performance under strong turbulent conditions has been improved by deploying adaptive optics and channel coding techniques. L. Li et al. reported an OAM-multiplexed FSO communication system, where 80-Gbps information is transmitted between two ground terminals separated at 100 m *via* an unmanned aerial vehicle (UAV) using two independent 40-Gbps QPSK-modulated OAM beams [38]. Z. Zhao et al. reported an ultrahigh capacity FSO communication system over strong atmospheric turbulence conditions by incorporating hybridization of OAM multiplexing, polarization multiplexing, and frequency multiplexing [39]. The research works in references [40–44]

report the simulative analysis of MDM-based high-capacity radio over fiber (RoF) links.

The main motivation here is to model an FSO link capable of securely transmitting biosensor data in health-care facilities under different atmospheric conditions at high bit rates. We discuss the simulation designing and evaluation of the OFDM-FSO link with high-speed data transmission capabilities using WDM and MDM techniques under different atmospheric conditions. The link design is reported in *Link Design of Wavelength-Mode Division Multiplexing-Orthogonal Frequency Division Multiplexing-Based Free Space Optics Link* Section, and the simulative evaluation results are discussed in *Numerical Results* Section. *Conclusion* Section concludes this research work.

LINK DESIGN OF WAVELENGTH-MODE DIVISION MULTIPLEXING-ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING-BASED FREE SPACE OPTICS LINK

Figure 1 presents the schematic design of the proposed FSO link. OptisystemTM simulation software v.15 has been used for designing and evaluating the FSO link.

Four 20-Gbps OFDM-encoded data signals are transported over the FSO channel under different weather conditions. Two channels (1 and 2) are transmitted at 193.1-THz frequency over HG01 and HG03 modes, and another two channels (3 and 4) are transmitted at 193.2 THz frequency over HG01 and HG03 modes. A WDM multiplexer is used to combine the two frequencies at the transmitter side. **Figure 2** presents the optical spectrum of the transmitted signal.

The HG modes can be mathematically described using the equation [45]:

$$\varphi_{r,s}(x, y) = H_m \left(\frac{\sqrt{2}x}{w_{0,x}} \right) \exp \left(-\frac{x^2}{w_{0,x}^2} \right) \exp \left(j \frac{\pi x^2}{\lambda R_{ox}} \right) \times H_n \left(\frac{\sqrt{2}y}{w_{0,y}} \right) \exp \left(-\frac{y^2}{w_{0,y}^2} \right) \exp \left(j \frac{\pi y^2}{\lambda R_{oy}} \right), \quad (1)$$

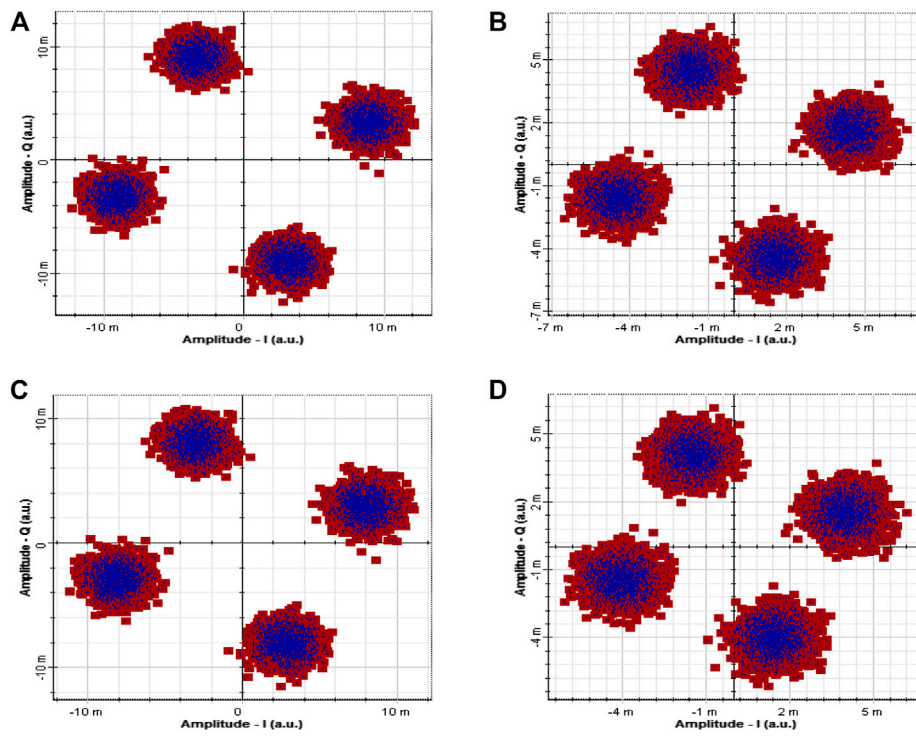


FIGURE 6 | Constellation plots after 32 km range for 193.1 THz channel (A) HG01 mode and (B) HG03 mode; for 193.2 THz channel (C) HG01 mode and (D) HG03 mode.

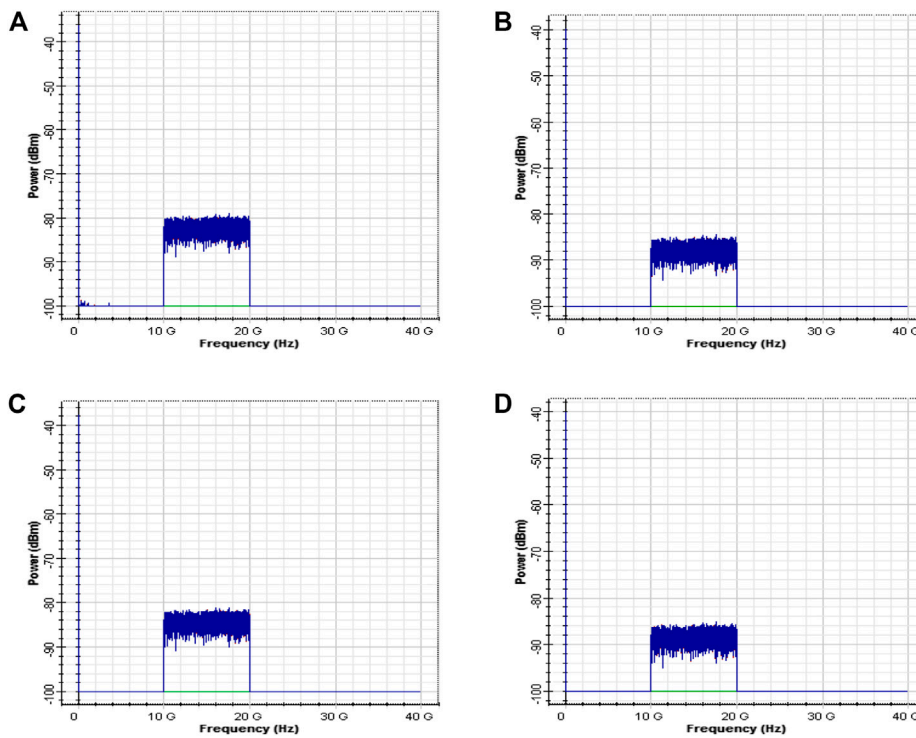
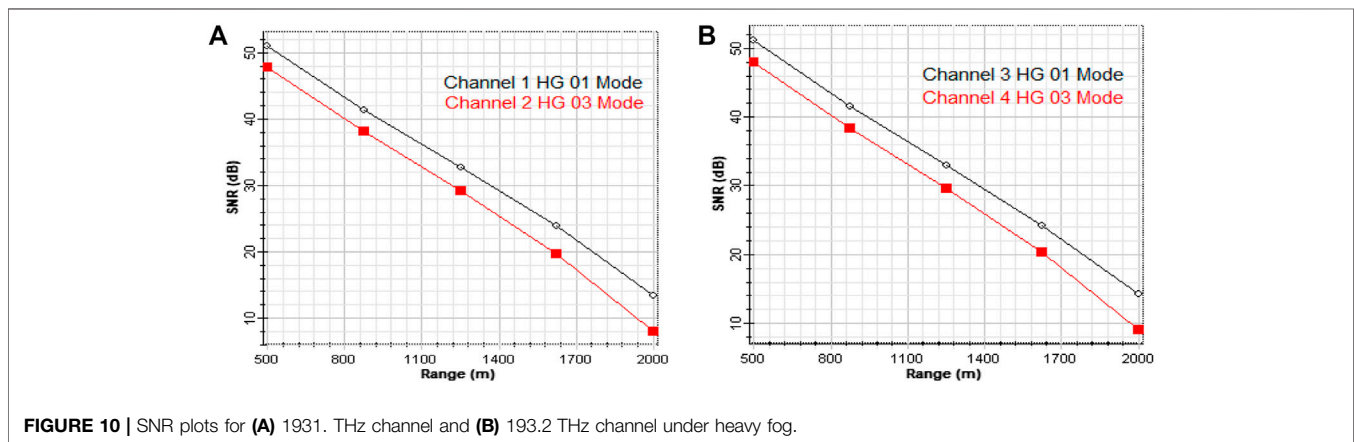
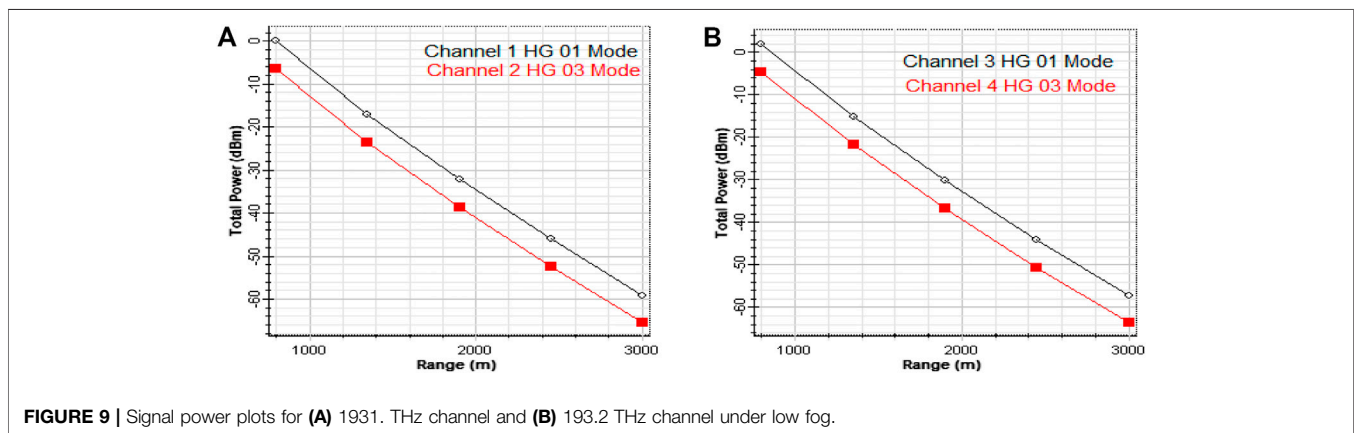
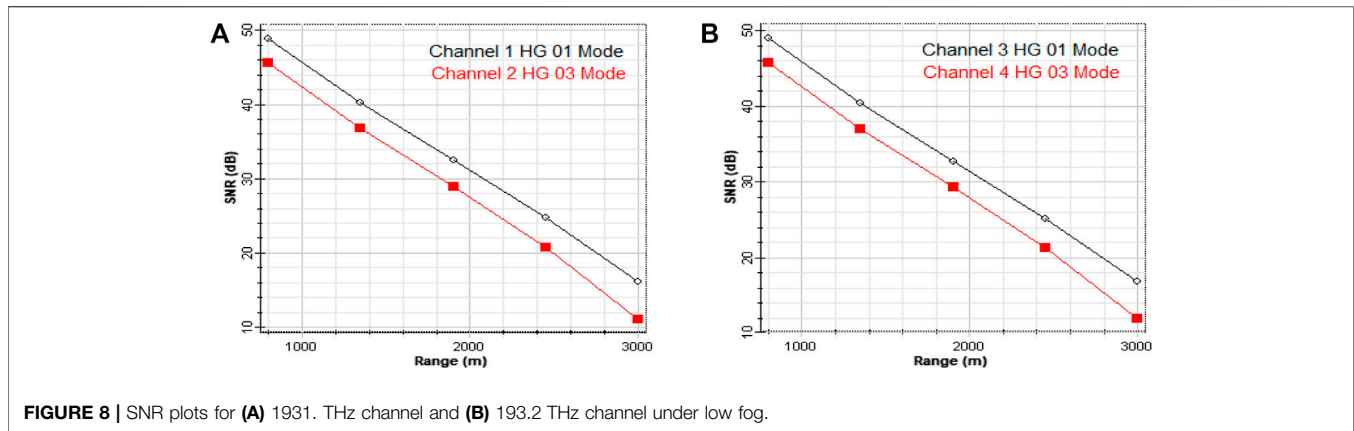


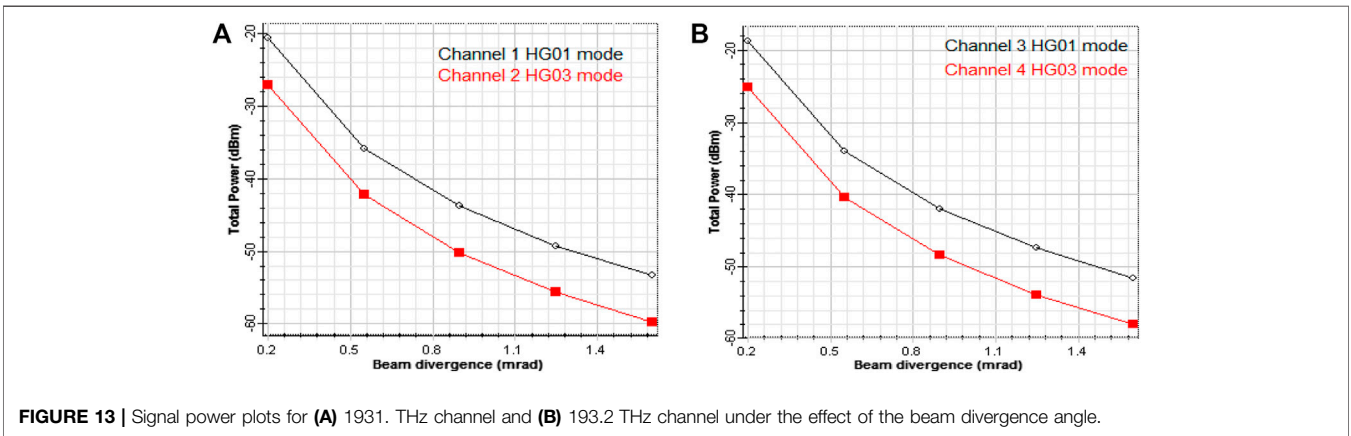
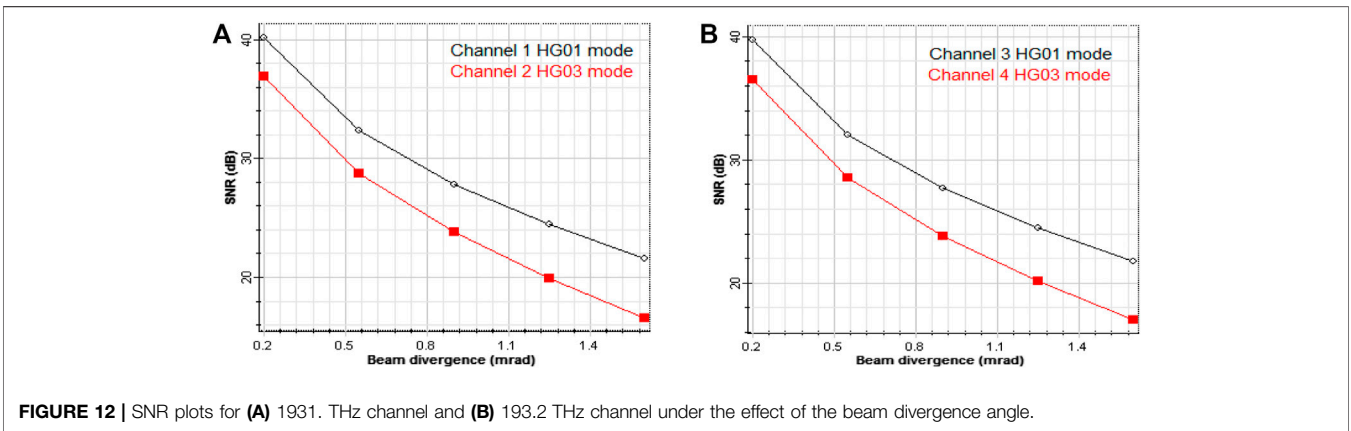
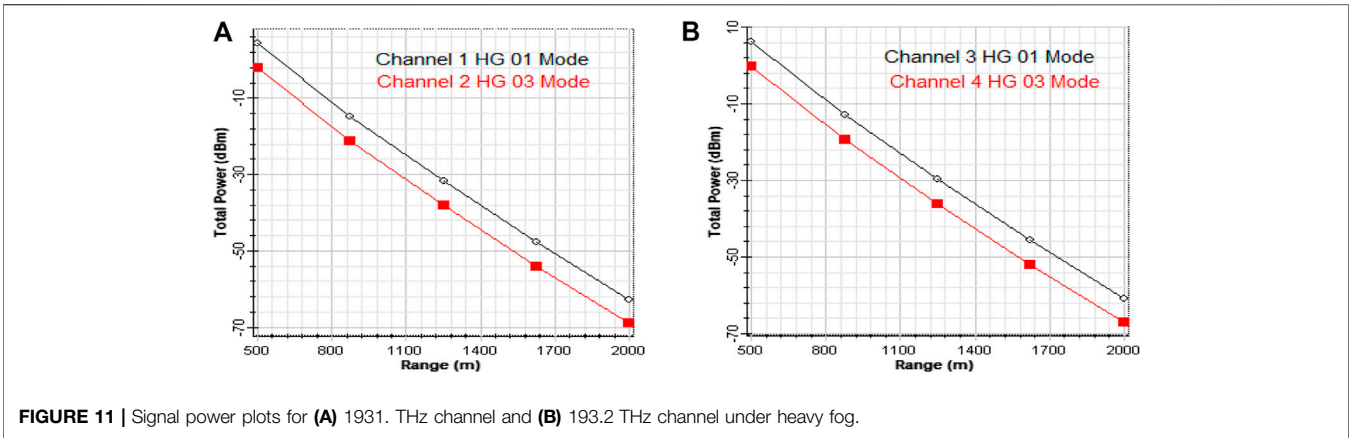
FIGURE 7 | RF power after 32 km range for 193.1 THz channel (A) HG01 mode and (B) HG03 mode; for 193.2 THz channel (C) HG01 mode and (D) HG03 mode.



where r is the dependency of mode profile on the X -axis, s is the dependency of mode profile on the Y -axis, the radius of the beam is denoted by R , the size of the optical beam at the waist is denoted by ω_0 , and H_m and H_n denote Hermite polynomials. Different HG modes are excited using a spatial laser, and the mode intensity profiles are illustrated in **Figure 3**.

For each channel, 20-Gbps data from the information source is mapped onto 4-QAM symbols, where two bits are transmitted per

symbol. This signal is further OFDM modulated in the electrical domain. The specification of the OFDM modulator is 1,024 inverse fast Fourier transformation points, 512 orthogonal subcarriers, a cyclic prefix of value 32, and average power of 15 dBm. This signal is up-converted using a 7.5-GHz quadrature amplitude (QM) modulator. For each frequency channel, the 4-QAM-OFDM spatially modulated signals are combined using an MDM multiplexer (MUX). The distinct frequency channels are then



multiplexed using a WDM MUX (Figure 2), and the information signal is transmitted using a transmitter lens.

The link equation can be described as [46]:

$$P_{Received} = P_{Transmitted} \left(\frac{d_R^2}{(d_T + \theta Z)^2} \right) 10^{-\sigma Z/10}, \quad (2)$$

where d_R denotes the aperture diameter of receiver lens (100 mm), d_T denotes aperture diameter of transmitter lens

(100 mm), θ denotes the size of the optical beam/divergence angle (0.25 mrad), Z denotes the FSO range, and σ is the attenuation coefficient for varying climate conditions. The attenuation coefficient for low fog, heavy fog, and clear conditions is 9, 22, and 0.14 dB/km, respectively [47]. At the receiver, individual frequency channels are separated using the WDM de-multiplexer (DEMUX), and for each frequency channel, independent spatial channels are separated using

MDM DEMUX. An APD photodiode converts the optical signal into its electrical equivalent. Originally transmitted message bits are recovered using OFDM and QM demodulator sections.

NUMERICAL RESULTS

Figures 4, 5 illustrate plots for SNR and the signal power with an increasing range in the proposed link under clear weather. **Figure 4A** shows that channel 1 transmitted over the HG01 mode performs notably better than channel 2 transmitted over the HG03 mode at 193.1 THz frequency. For channel 1, the SNR value at the receiver terminal is measured as 34.67, 23.75, and 15.44 dB, whereas for channel 2, SNR is reported as 31.29, 19.62, and 10.31 dB at 10, 25, and 40 km, respectively. **Figure 4B** shows that for channel 3, the SNR value is 34.88, 24.14, and 16.16 dB, whereas for channel 4, the SNR value is 31.52, 20.16, and 11.23 dB at 10, 25, and 40 km, respectively. It can be seen that for the 193.2 THz frequency channel, the HG01 mode outperforms the HG03 mode.

Figure 5A shows that for the channel 1, the signal power is -27.93 , -47.78 , and -60.02 dBm, whereas for channel 2, the signal power is -34.39 , -54.22 , and -66.32 dBm at 10, 25, and 40 km, respectively. **Figure 5B** shows that for channel 3, the signal power is -26.03 , -45.88 , and -58.14 dBm, whereas for channel 4, the signal power is -32.49 , -52.33 , and -64.49 dBm at 10, 25, and 40 km, respectively. A feasible transmission of 4×20 Gbps information at 32 km with fair performance metrics (SNR ~ 20 dB) [40] is observed from the results presented. **Figure 6** reports constellation plots, and **Figure 7** reports the RF power of the signals at 32 km.

Further, the W-MDM-OFDM-based FSO link is evaluated for low and heavy fog conditions. **Figures 8, 9** report SNR and signal power plots for different channels under low fog conditions in the proposed link. **Figures 8A,B** show that the SNR reduces from 48.83, 45.59, 49.01, and 45.77 dB to 16.13, 11.07, 16.82, and 11.96 dB for channels 1, 2, 3, and 4, respectively, for the link range increasing from 800 to 3,000 m under low fog conditions. Similarly, **Figure 9A,B** show that the signal power reduces from 0.04, -6.41 , 1.94, and -4.51 dBm to -59.12 , -65.44 , -57.23 , and -63.60 dBm for channels 1, 2, 3, and 4, respectively, for the link range increasing from 800 to 3,000 m under low fog conditions.

Figures 10, 11 present SNR and signal power plots for different channels under heavy fog conditions. **Figures 10A,B** show that the SNR reduces from 50.96, 47.72, 51.14, and 47.90 dB to 13.36, 8.01, 14.17, and 9.01 dB for channels 1, 2, 3, and 4, respectively, for the link range increasing from 500 to 2000 m under heavy fog conditions. Similarly, **Figures 11A,B** show that the signal power reduces from 4.29, -2.16 , 6.18, and -0.26 dBm to -62.67 , -68.87 , -60.81 , and -67.09 dBm for channels 1, 2, 3, and 4, respectively, for the link range increasing from 500 to 2000 m under heavy fog conditions. It can be observed that for low fog, the link prolongs to 2,800 m, whereas for heavy fog, 1750 m range is supported with fair performance (SNR ~ 20 dB).

In this study, we also discuss the impact of the increasing beam divergence angle on the performance of the proposed link. **Figures 12, 13** demonstrate SNR and signal power plots,

respectively, with an increasing angle of beam divergence. From the results presented, it can be seen that SNR varies from 39.73, 36.85, 40.12, and 36.49 dB to 21.57, 17.10, 21.75, and 16.57 dB as the beam divergence angle increases from 0.2 to 1.6 mrad for channels 1, 2, 3, and 4 respectively. Alternatively, the signal power reduces from -20.59 , -27.05 , -18.73 , and -25.19 dBm to -53.35 , -59.76 , -51.50 , and -57.92 dBm as the beam divergence angle increases from 0.2 to 1.6 mrad for channels 1, 2, 3, and 4, respectively. Degradation in the received signal quality with the increasing angle of beam divergence can be observed from the reported results. This is because increasing beam size results in lesser optical power collected at the receiver plane and higher power lost to the surroundings, thus degradation in the link performance.

CONCLUSION

In this study, an FSO link is proposed for providing biomedical services, and we report a successful transmission of 4×20 -Gbps data over an OFDM-based FSO link by incorporating hybrid WDM and MDM techniques under different atmospheric conditions. From the results presented, it can be concluded that the proposed link prolongs to 32 km with acceptable performance (SNR ~ 20 dB) under clear weather conditions which reduces to 2,800 m and 1750 m under low fog and heavy fog conditions, respectively. Also, the HG01 mode performs better than the HG03 mode since the former has more immunity against fading effects due to adverse weather conditions. Also, the performance of the proposed link under an increasing beam divergence angle has been discussed. From the results presented, it can be observed that the performance of the proposed link degrades in terms of SNR and signal power of the received signal on increasing the beam divergence angle. In future studies, dual-polarization transmission along with digital signal processing techniques at the receiver side can be incorporated in the proposed system to further enhance the information capacity and link performance under adverse climate conditions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

ACKNOWLEDGMENTS

The researchers would like to thank the Deanship of Scientific Research, Qassim University for funding the publication of this project.

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