Performance Evaluation of a 4x20 Gbps OFDM-based FSO Link Incorporating Hybrid W-MDM Techniques

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Abstract- Free space optics has been envisioned as an crucial technique to meet the high-bandwidth requirements in future wireless information transmission links and a feasible solution to the last-mile bottleneck problem. This research work reports the designing and simulative evaluation of the performance of high-speed orthogonal frequency division multiplexing-based free space optics link by incorporating wavelength division multiplexing of 2 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). 4 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 increasing beam divergence angle.

Index Terms- FSO; WDM; MDM; HG modes; atmospheric weather conditions; beam divergence

1. Introduction

Recent years have seen significant increase in network traffic due to the growth in the use of multimedia applications consuming high channel bandwidth like video conferencing, fast internet, live streaming etc., which has challenged the limited and congested radio frequency (RF) spectrum-based conventional wireless transmission systems [1]. Free space optics (FSO) can be considered as a promising solution in order to meet the high capacity and large transmission rates 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, large speed network, secure data transmission and license-free spectrum availability [2-5]. Orthogonal frequency division multiplexing (OFDM) is a subset of multi-carrier modulation technique, using which a high bit rate signal is transported over several low-speed sub-carriers, 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 [8-10] reports the design and performance investigation of OFDM based FSO terrestrial link under the effect of different atmospheric conditions. In order to increase the data carrying capacity of the link, wavelength division multiplexing (WDM) can be used which transmits a number of 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 which capitalizes on different spatial modes of a single laser beam to transport independent data signals over the same channel. The authors in [15-17] report optical signal processing techniques to generate and de-multiplex different laser modes. The application of spatial light modulator to multiplex and de-multiplex optical spatial laser beams has been reported in [18, 19]. Y. Jung et al. proposed the application of dual-fused optical fiber for MDM transmission applications in [20]. A. Amphawan et al. reports the application of a photonic crystal fiber with a single-core to generate different linear polarized (LP) modes. In recent years, the incorporating of MDM in optical fiber links has been extensively investigated to realize high-speed transmission. A. Juarez et al. reported a MDM system capable of realizing high-speed data transmission in multi-mode fiber (MMF) links using linear polarized (LP) modes [22]. The authors reported a feasible transportation of 120 Gbps data with 3 GHz-km bandwidth-length product over a 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 × 4 phase-shift keyed optical codes × 10 Gbps on-off keyed data streams over 42 km fiber length using single-mode and multi-mode fiber without the application of dispersion compensation. T. Masunda et al. proposed a hybrid MDM and WDM architecture to realize high-speed MMF interconnects [24]. 6 independent vertical cavity surface emitting laser diodes are used, where each wavelength generates 3 distinct Laguerre Gaussian (LG) modes to realize 18 parallel channel transmission. The authors report feasible 60 Gbps transmission over 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 inter-connects in data centers [25]. The authors reported feasible transportation of 44 Gbps data using 2 helical-phased ring modes over 1550.12 nm channel and 2 radially offset Hermite Gaussian (HG) modes over 1551.72 nm channel along a MMF of 1500 m with acceptable bit error rate of the system. E. Hamed et al. reported the performance comparison of 3 different types of optical fibers i.e. step-index few mode fiber (FMF), graded-index FMF, and transversal-index FMF in a spectral-efficient MDM system [26]. 3 distinct LP modes, where each mode carries 10 Gbps quadrature amplitude modulated (QAM) data are transmitted over all the 3 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 with respect to signal to noise ratio (SNR) at receiver. 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 200 Gbps polarization division multiplexed (PDM)-16-level-QAM-OFDM data signals has been proposed in the system. The authors reported feasible data transmission of 4 wavelength channels × 6 spatial modes × 200 Gbps QAM data signals along a 37 km MMF with 7 cores with acceptable performance. The application of 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 [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 non-linear coefficients [29]. Also, the authors reported the fabrication on 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 non-linear 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 [30]. K. Ingerslev et al. reported a feasible transportation of 12 OAM modes, where each modes carries 10 Gbaud quadrature-phase shift keyed (QPSK) signals over 1.2 km MMF link with good performance [31]. Further, the authors have demonstrated ultra-high 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 3 distinct OAM modes, where each mode transported 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 6 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 [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 [35]. The use of OAM multiplexing for deep space applications and for multi-gigabit near-Earth optical networks has been reported by I. Djordjevic in [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 the 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 using 2 independent 40 Gbps QPSK modulated OAM beams [38]. Z. Zhao et al. reported an ultra-high capacity FSO communication system on strong atmospheric turbulence conditions by incorporating hybridization of OAM multiplexing, polarization multiplexing and frequency multiplexing [39]. The research works in [40-44] reports the simulative analysis of MDM based high capacity radio over fiber (RoF) links. The present work discusses the simulation designing and evaluation of OFDM-FSO link with high-speed data transmission capabilities using WDM and MDM techniques under different weather conditions. The link design is reported in Section 2 and the simulative evaluation results are discussed in Section 3. Section 4 concludes this research work.

2. Link design of W-MDM-OFDM-based FSO link

Figure 1 presents the schematic design of the proposed FSO link. Optisystem^{TM} simulation software v.15 has been used for the designing and evaluation of the FSO link.

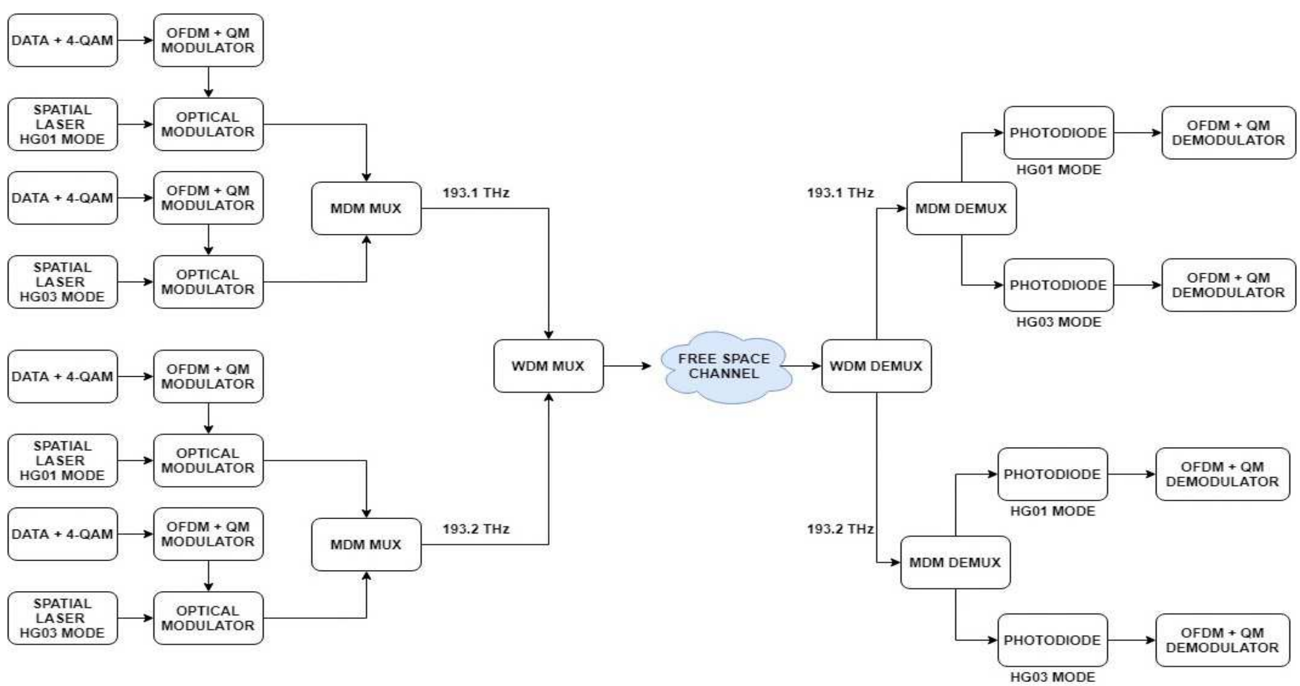


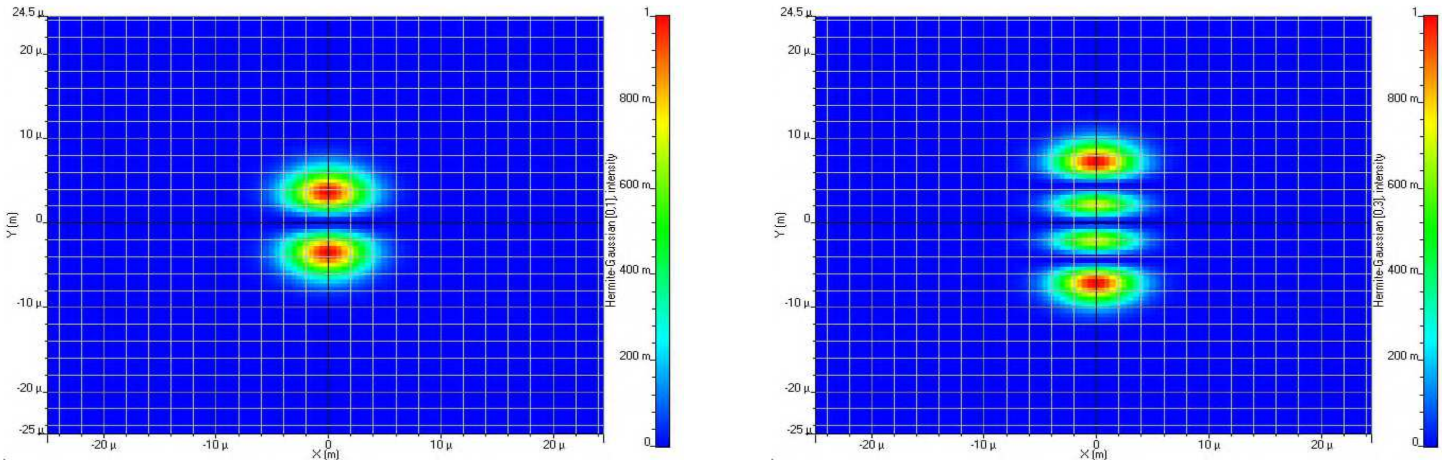
Fig.1 Schematic design of the proposed link

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

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

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

where r is the dependency of mode profile on X-axis and s is the dependency of mode profile on Y-axis, radius of beam is denoted by R, the size of optical beam at the waist is denoted by ω_0, and $H_m\ and\ H_n$ denotes Hermite polynomials. Different HG modes are excited using a spatial laser with mode intensity profiles are illustrated in Fig. 2.



(a)

(b)

Fig. 2 Mode intensity profile of (a) HG01 (b) HG03

For each channel, 20 Gbps data from the information source is mapped onto 4-QAM symbols, where 2-bits are transmitted per symbol. This signal is further OFDM modulated in electrical domain. The specification of OFDM modulators are: 1024 Inverse Fast Fourier Transformation points, 512 orthogonal sub-carriers, cyclic prefix of value 32, and average power of 15 dBm. This signal is up-converted using 7.5 GHz quadrature amplitude (QM) modulator. For each frequency channel, the 4-QAM-OFDM spatially modulated signals are combined using MDM multiplexer (MUX). The frequency channels are then multiplexed using WDM MUX (Fig. 3) and the information signal is transmitted using transmitter lens.

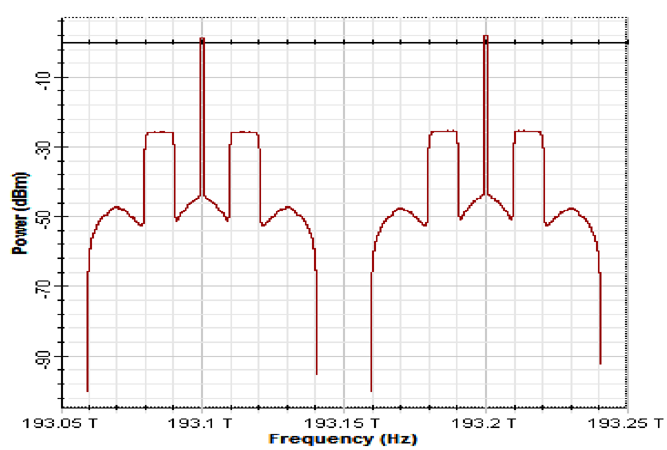


Fig. 3 Optical spectrum of the transmitted signal

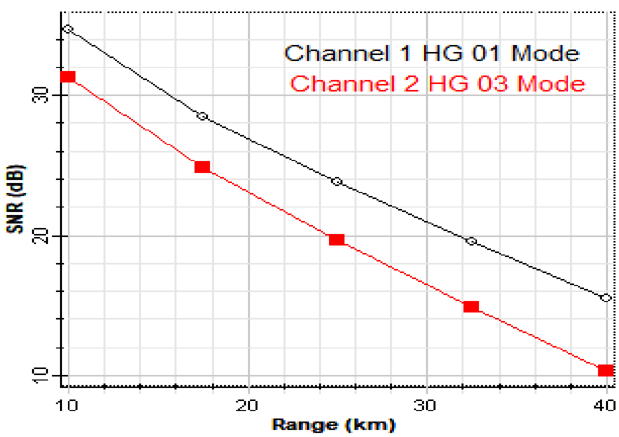
The link equation can be described as [46]:

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

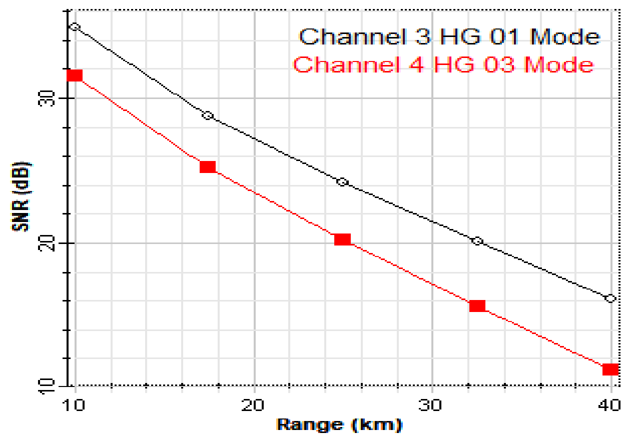
where d_R denotes the aperture diameter of receiver lens (100 mm), d_T denotes aperture diameter of transmitter lens (100 mm), θ denotes the size of optical beam/divergence angle (0.25 mrad), Z denotes the FSO range, and σ is the values of attenuation due to varied climate conditions. The attenuation for low fog, heavy fog, and clear conditions is 9, 22, and 0.14 dB/km [47]. At the receiver, individual frequency channels are separated using 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.

3. Numerical results

Figure 4 and 5 present plots for SNR value and signal power with increasing link range in the proposed link under clear weather.

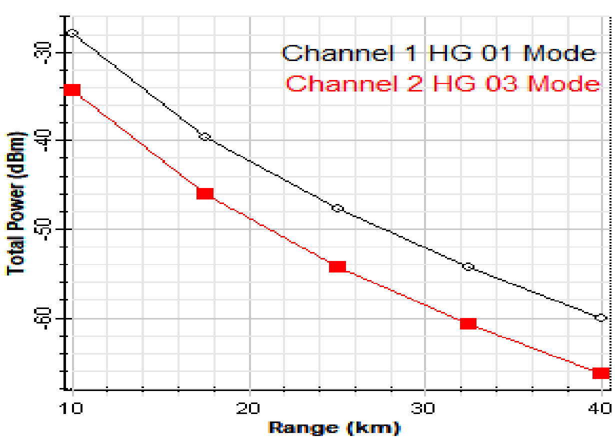


(a)

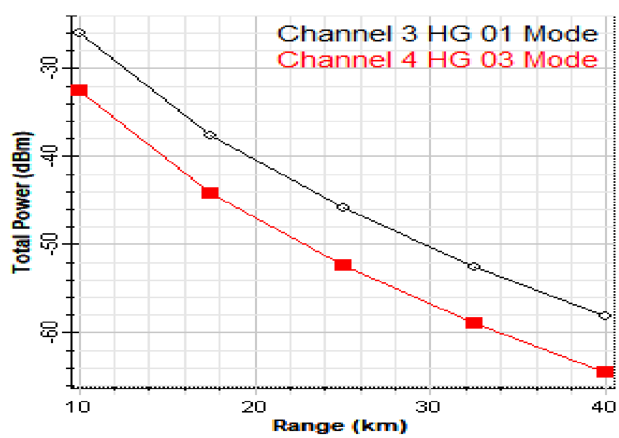


(b)

Fig. 4 SNR for (a) 1931. THz channel (b) 193.2 THz channel under clear weather



(a)

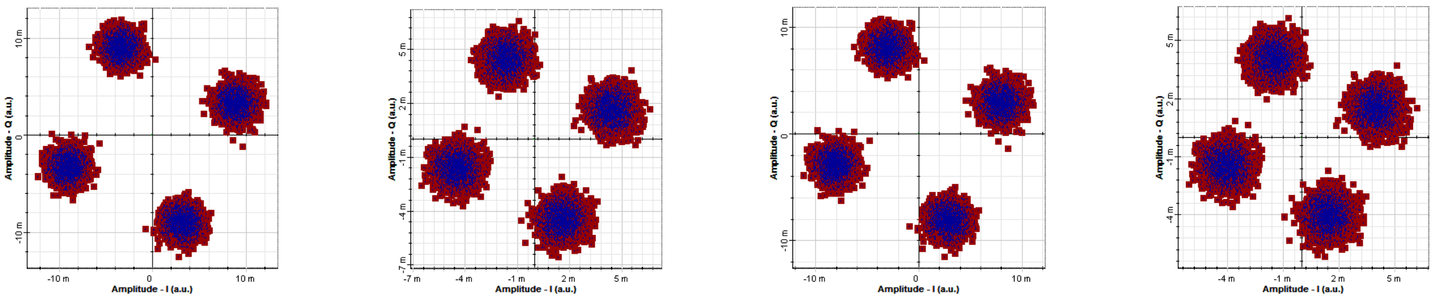


(b)

Fig. 5 Signal power for (a) 1931. THz channel (b) 193.2 THz channel under clear weather

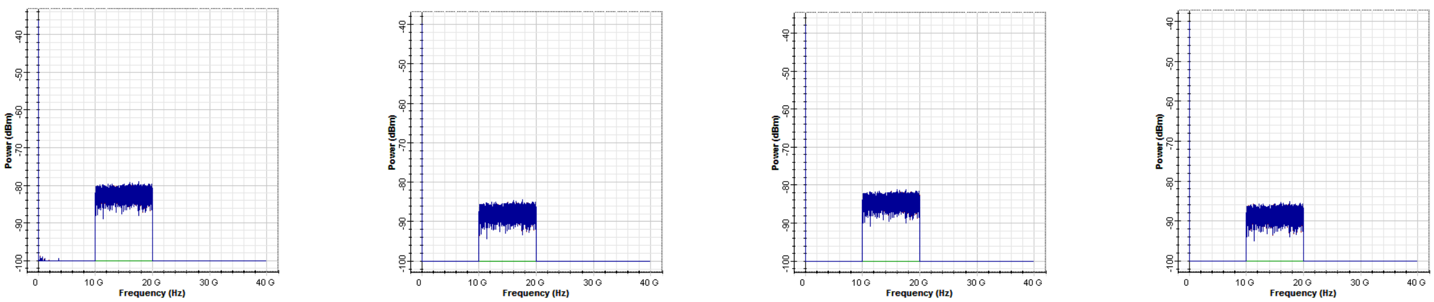
Fig. 4 (a) shows that the channel 1 transmitted over HG01 mode performs notably better in comparison to to channel 2 transmitted over HG03 mode at 193.1 THz frequency. For channel 1, the SNR value at the receiver terminal is measured as 34.67, 23.75, and 15.44 dB; whereas for channel 2, SNR is reported as 31.29, 19.62, and 10.31 dB at 10, 25, and 40 km respectively. Fig. 4 (b) shows that for the 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 193.2 THz frequency channel, HG01 modes outperforms HG03 mode.

Fig. 5 (a) 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. Fig. 5 (b) 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-32 km information is indicated from the results presented with fair performance metrics (SNR~ 20 dB). Fig. 6 reports constellation plots and Fig. 7 reported RF power of the signals at 32 km.



(a) (b) (c) (d)

Fig. 6 Constellation plots after 32 km range for 193.1 THz channel (a) HG01 mode (b) HG03 mode; 193.2 THz channel (c) HG01 mode (d) HG03 mode

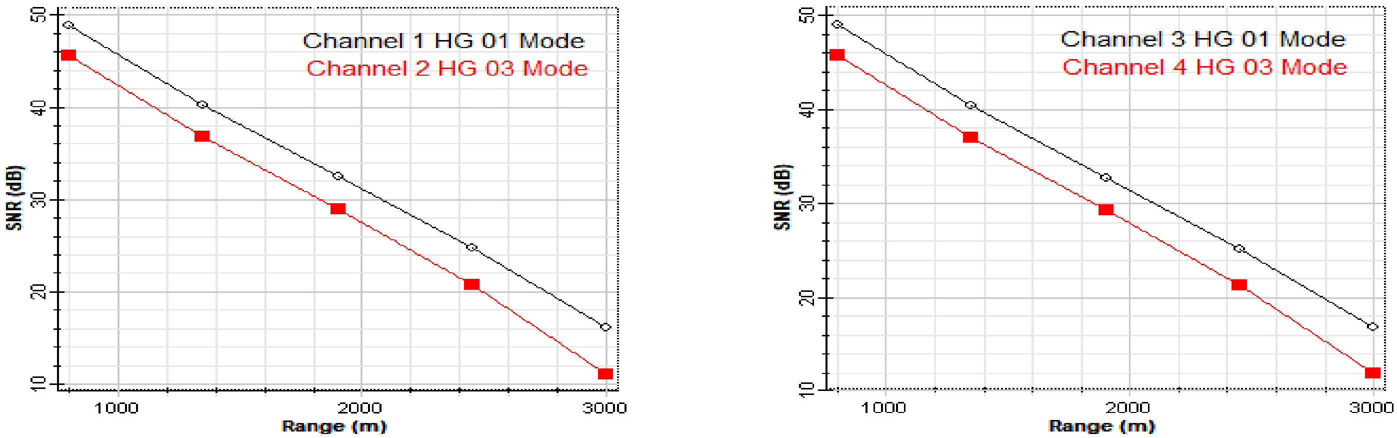


(a) (b) (c) (d)

Fig. 7 RF power after 32 km range for 193.1 THz channel (a) HG01 mode (b) HG03 mode; 193.2 THz channel (c) HG01 mode (d) HG03 mode

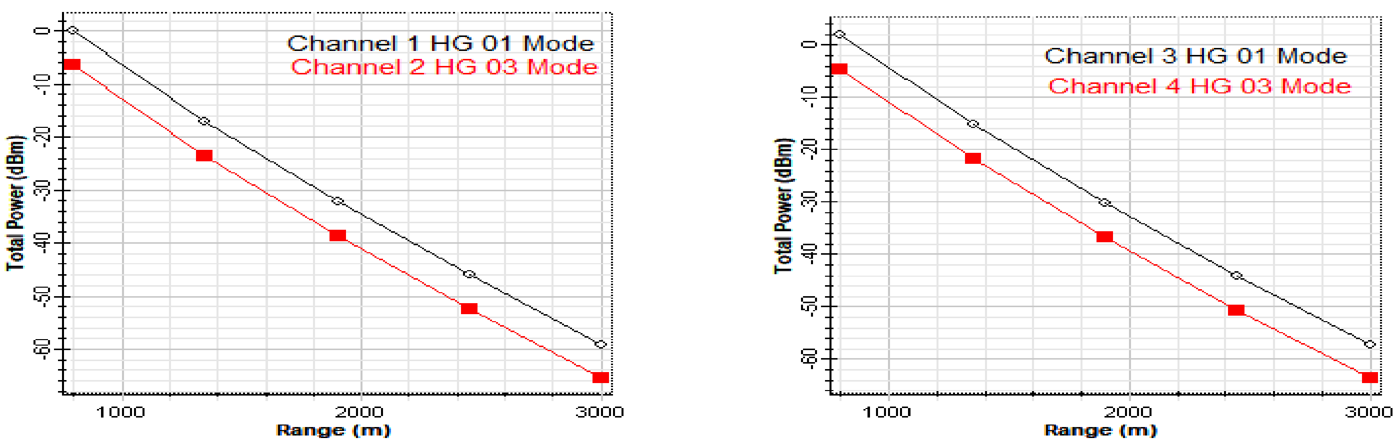
Further, the W-MDM-OFDM-based FSO link is evaluated for low and heavy fog conditions. Fig. 8 and 9 present SNR value and signal power plots for different channels under low fog conditions in the proposed link. Fig. 8 (a) and (b) show that the SNR value reduces from [48.83, 45.59, 49.01, 45.77] dB to [16.13, 11.07, 16.82, 11.96] dB for channel 1, 2, 3, and 4 respectively for link increasing from 800 m to 3000 m under low fog conditions. Similarly, Fig. 9 (a) and (b) show that the signal power reduces from [0.04, -6.41, 1.94, -4.51] dBm to [-59.12, -65.44, -57.23, -63.60] dBm for channel 1, 2, 3, and 4 respectively for link increasing from 800 m to 3000 m under low fog conditions .

Fig. 10 and 11 presents SNR value and signal power plots for different channels under heavy fog conditions. Fig. 10 (a) and (b) show that the SNR value reduces from [50.96, 47.72, 51.14, 47.90] dB to [13.36, 8.01, 14.17, 9.01] dB for channel 1, 2, 3, and 4 respectively for link increasing from 500 m to 2000 m under heavy fog conditions. Similarly, Fig. 11 (a) and (b) shows that the signal power reduces from [4.29, -2.16, 6.18, -0.26] dBm to [-62.67, -68.87, -60.81, -67.09] dBm for channel 1, 2, 3, and 4 respectively for link increasing from 500 m to 2000 m under heavy fog conditions. It can be observed that for low fog, the link prolongs to 2800 m whereas for heavy fog, 1750 m range is supported with fair performance (SNR~ 20 dB).



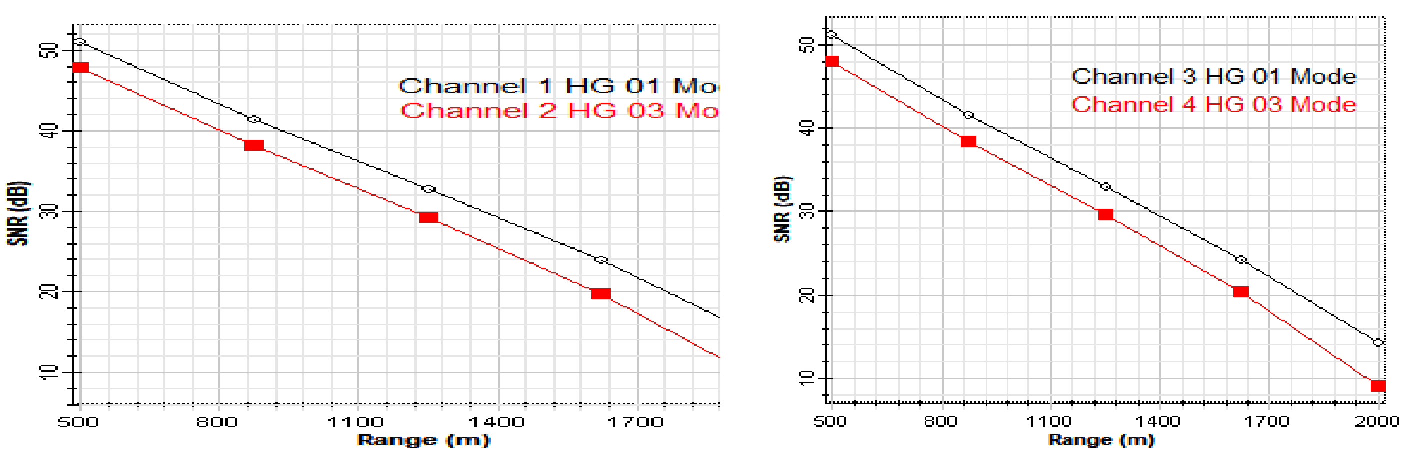
(a) (b)

Fig. 8 SNR plots for (a) 1931. THz channel (b) 193.2 THz channel under low fog



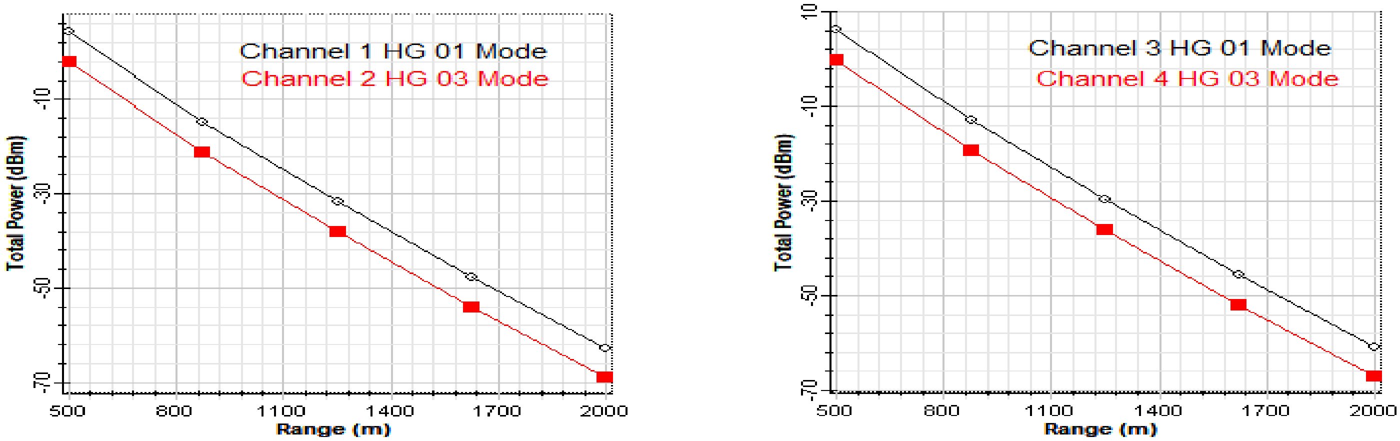
(a) (b)

Fig. 9 Signal power plots for (a) 1931. THz channel (b) 193.2 THz channel under low fog



(a) (b)

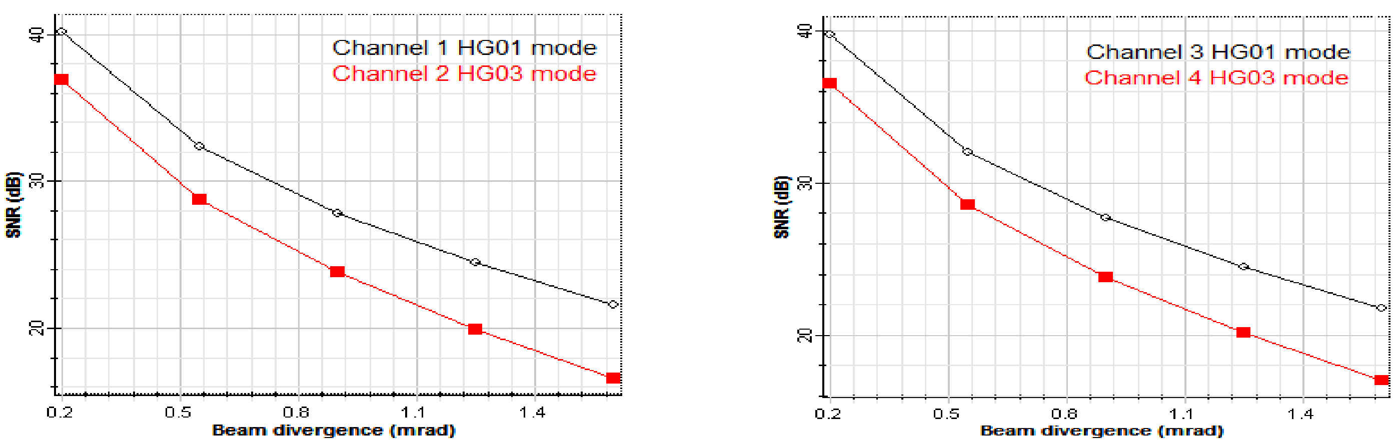
Fig. 10 SNR plots for (a) 1931. THz channel (b) 193.2 THz channel under heavy fog



(a) (b)

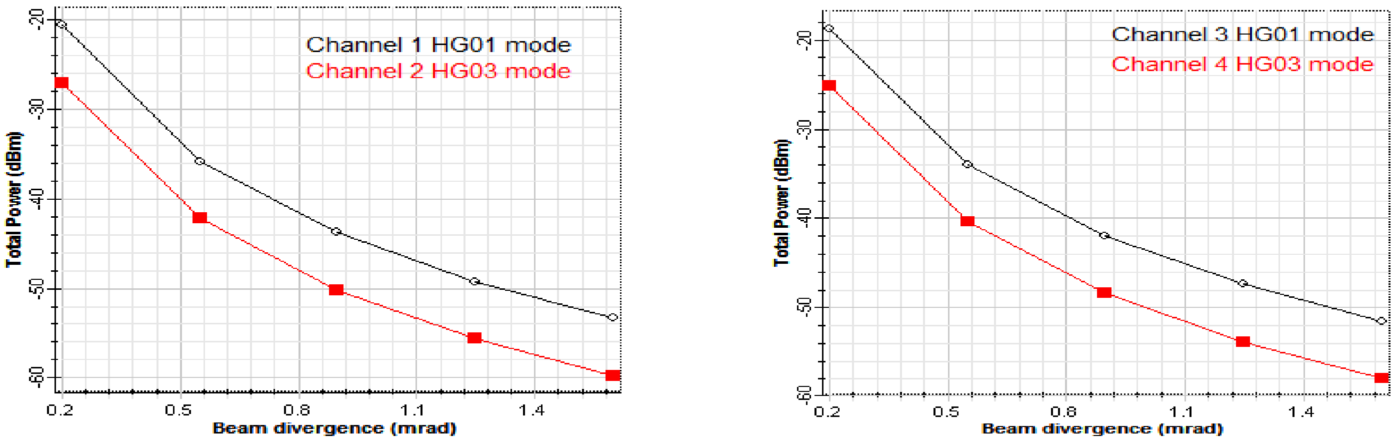
Fig. 11 Signal power plots for (a) 1931. THz channel (b) 193.2 THz channel under heavy fog

In this paper, we also discuss the impact of increasing beam divergence angle on the performance of the proposed link. Fig. 12 and 13 demonstrate SNR and signal power plots respectively with increasing angle of beam divergence. From the results presented, it can be seen that SNR varies from [39.73, 36.85, 40.12, 36.49] dB to [21.57, 17.10, 21.75, 16.57] dB as the beam divergence angle increases from 0.2 mrad to 1.6 mrad for channel 1, 2, 3, and 4 respectively. Alternatively, the signal power reduces from [-20.59, -27.05, -18.73, -25.19] dBm to [-53.35, -59.76, -51.50, -57.92] dBm as the beam divergence angle increases from 0.2 mrad to 1.6 mrad for channel 1, 2, 3, and 4 respectively. A degradation in the received signal quality with 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.



(a) (b)

Fig. 12 SNR plots for (a) 1931. THz channel (b) 193.2 THz channel under the effect of beam divergence angle



(a) (b)

Fig. 13 Signal power plots for (a) 1931. THz channel (b) 193.2 THz channel under the effect of beam divergence angle

4. Conclusion

We report a successful transmission of 4×20 Gbps data over an OFDM-based FSO link by incorporating hybrid WDM and MDM techniques modes 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 2800 m and 1750 m under low fog and heavy fog conditions respectively. Also, HG01 mode performs better than HG03 mode since the former has more immunity against fading effects due to adverse weather conditions. Also, the performance of the proposed link under 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 angles as should be expected.

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