Performance comparison of Hermite Gaussian and donut transverse modes in MDM-based FSO transmission system

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The rising demand for channel bandwidth as a result of drastic rise in the number of mobile users and high-bandwidth utilizing applications has congested the traditional networks. Free space optics (FSO) links guarantee to offer huge bandwidth for various types of present 5G wireless networks to share massive amount of data at high transmission rates for multiple users. In this work, a 2×10 Gbps mode division multiplexing (MDM)-FSO transmission system has been suggested and investigated. The performance of the proposed link is compared for distinct Hermite Gaussian (HG) modes and Donut Transverse (DT) modes. Further, the link is investigated under the impact of different weather conditions i.e. clear, light fog, moderate fog, and heavy fog. The results illustrate that DT modes perform better than HG modes under all weather conditions and are more suitable for realizing long-reach FSO links. The proposed system can suitably meet the demands of high channel-bandwidth in backhaul and front-haul links in future 5G services.

1. Introduction

This decade has witnessed a massive improvement in the technologies for the optical communication systems considerably well. The ever-escalating bandwidth requirements due to multifarious online services and video proliferation has encouraged initiation of latest optical schemes to adapt to the growth in the number of sub-carriers. In 2015, International Telecommunication Union (ITU) registered 5.5 billion mobile users [1] [2]. Thus, due to increase of explosive data traffic among mobile users', it is an ever-growing challenge for the network operators to assign the licensed, restricted bandwidth, expensive, noisy, and interfered radio frequency (RF) spectrum among several users [3] [4]. Consequently, free space optics (FSO) is an aspiring wireless technology to provide the transmission of high-speed data and secure, economical, and licence free spectrum-based large bandwidth wireless optical links for backhaul and front-haul networks required in future 5th generation (5G) cellular services and internet of things (IoT) applications. FSO links take advantage of optical modulated

information transmission over atmosphere as the transmission channel without optical fiber installation. Moreover, FSO is an engrossing as a viable worldwide platform for persistent wireless networks to enhance the feasible information-capacity of the existing networks promptly and decrease the deployment cost efficiently [5] [6]. Also FSO links offer a viable and effective solution to the last mile access issue in rural areas and urban areas where the fiber installation is impractical and licencing cost is much high. Besides these advantages, the primary factors which deteriorate the FSO links' performance are external atmospherics conditions like rain, haze, snow, fog etc. since FSO links are located in tropospheric region. These environmental conditions causes the absorption and scattering of data carrying photons, effect the signal quality at receiver side, restricts the transmission link and reduces the performance of the system [7] [8] [9]. Considerable research activity in FSO has focused on statistical modelling [10] and experimental measurements [11] under the impact of different atmospheric conditions and turbulence levels. Majority of these FSO systems adopt wavelength division multiplexing (WDM) [12] and

Eigen modes in mode division multiplexing (MDM) [13] for improving the channel capacity over long-reach wireless access [10]. MDM is a novel technology which helps to transmit the parallel data traffic using different modes by providing another dimension for numerous data channels multiplexing through an optical fiber along with intensity, wavelength, time, phase, and polarization. Various types of modes have been examined for MDM such as spatial light modulators as well as fiber Bragg grating generated Laguerre-Gaussian (LG), passive beam shaper produced Hermite-Gaussian (HG) and phase plates, deflecting mirrors, etched fiber and spatial light modulators generated Donut Transverse (DT) modes [14] In [15] optical code division multiplexing (OCDMA)-FSO system over 10km link range at 10 Gbps transmission rate under serve environment conditions has been reported. Also in [16] dense WDM (DWDM)-FSO over 9.5 km range has been demonstrated. Although, MDM is extensively studied in [17] [18] [19] [20] [27] optical fiber systems, but its implementation in FSO networks in less

reported. Furthermore, FSO ensures improving the channel capacity by utilizing MDM technology, which is used to transfer the optical beams in the form of different kinds of modes such as LG, HG, spot, helical–phase and DT modes through the channel. In recent works, researchers have design and investigated the MDM in FSO links to enhance the system capacity [21] [6]. In this work, we investigate the FSO-MDM system for enhancing the channel capacity in the presence of different weather condition such as clear, light fog, moderate fog, and heavy fog. Also, the competitive performance of HG and DT modes is computed over FSO link.

2. System Design

In proposed work, Optisystem v.15 design tool is used to design and evaluate the MDM-based FSO system. Fig. 1 illustrates the diagram of the proposed system.
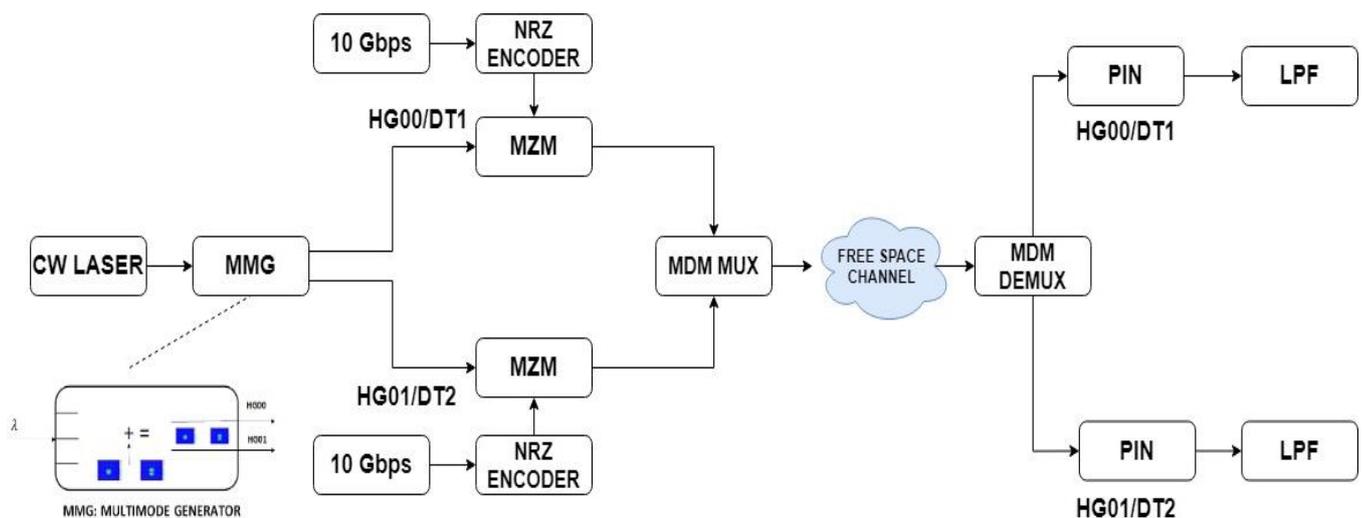
Fig. 1. Schematic of MDM-based FSO transmission system
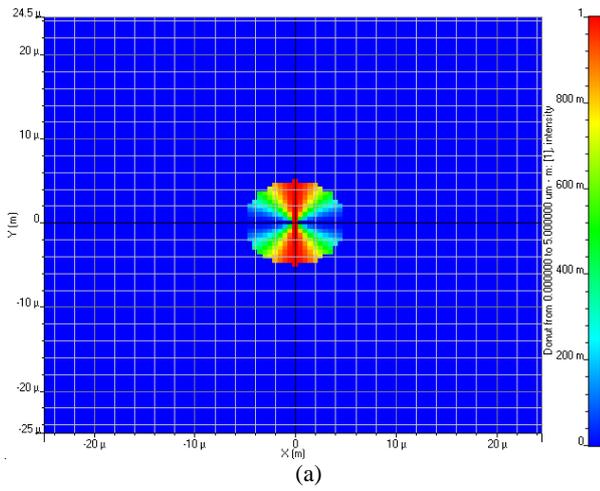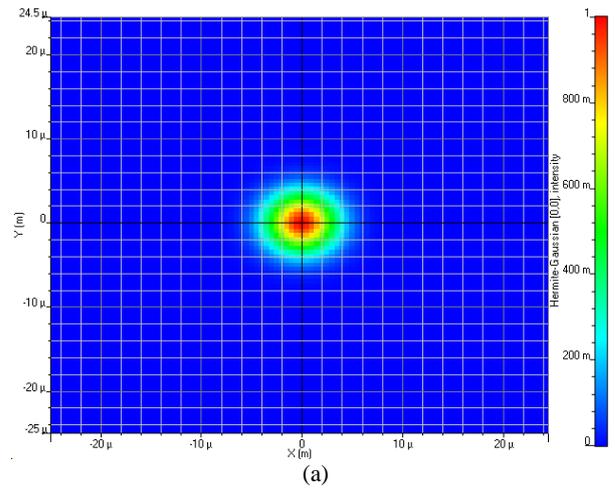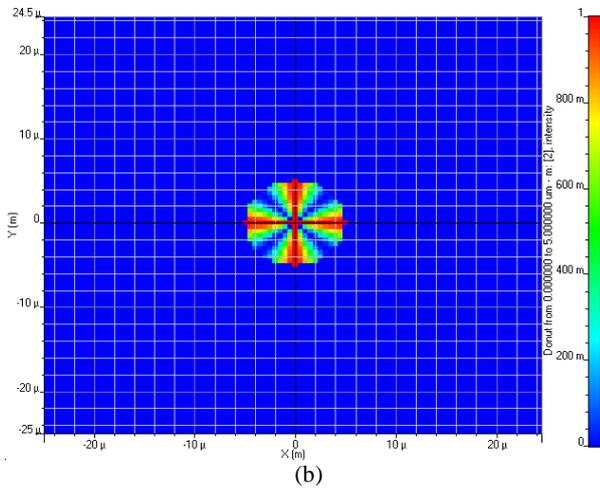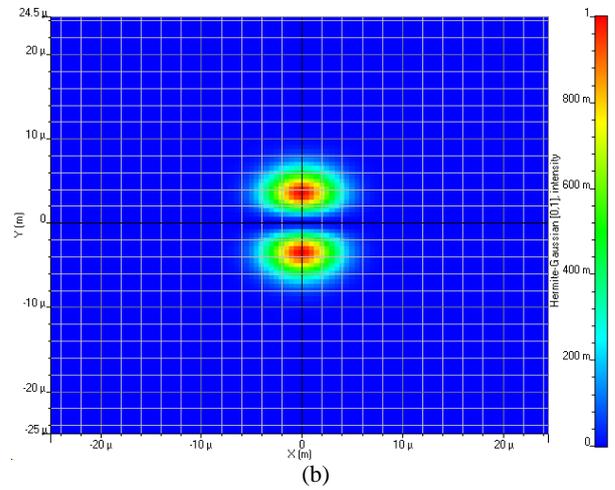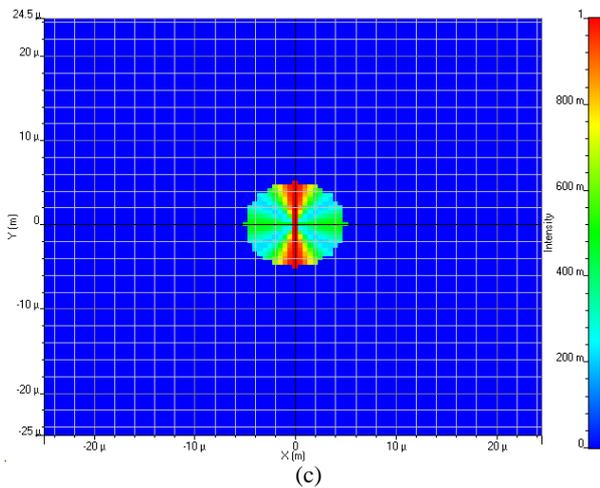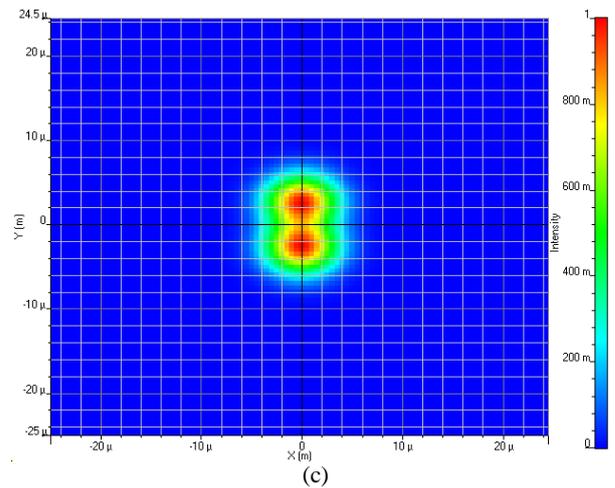
Fig. 2. Spatial profiles of (a) DT 1 (b) DT 2 (c) Summed mode (DT 1 + DT 2) (color online)

Fig. 3. Spatial profiles of (a) HG00 (b) HG01 (c) Summed mode (HG00 + HG01) (color online)

Two distinct non return-to-zero (NRZ) signals supporting 10 Gbps data are contemporaneously transferred over different HG/DT modes. Figs. 2(a), (b), and (c) presents the spatial profile of DT1, DT2 and summed (DT1+DT2) mode respectively, which can be described as:

$$\emptyset_m(r,\theta) = \begin{cases} \begin{cases} \cos(|m|\theta), n \geq 0 \\ \sin(|m|\theta), n < 0 \end{cases} r_{inner} \leq r \leq r_{outer} \\ \qquad 0, r < r_{inner}, r > r_{outer} \end{cases}$$

$$(1)$$

where m denotes the azimuthal index, r_{inner} and r_{outer} are the inner and outer radii of each mode respectively. Figs. 3(a), (b), and (c) depict the spatial profile for HG00, HG01 and summed (HG00+HG01) mode respectively, which can be expressed as [22] [23]:

$$\emptyset_{a,b}(x,y) = H_a\left(\sqrt{2}x/\omega_{0,x}\right) exp\left(-\frac{x^2}{\omega_{0x}^2}\right) exp\left(j\frac{\pi x^2}{\lambda R_{0x}}\right)$$

$$H_b\left(\sqrt{2}y/\omega_{0,y}\right) exp\left(-\frac{y^2}{\omega_{0y}^2}\right) exp\left(j\frac{\pi y^2}{\lambda R_{0y}}\right) \qquad (2)$$

where x and y denote the mode dependencies on X- and Y-polarization axis respectively, R is the curvature radius, ω_0 presents spot size and H_x and H_y represent the Hermite polynomials. Here, a spatial continuous wave (CW) laser at central wavelength of 1550 nm and a multi-mode generator (MMG) is utilized to generate the four independent modes. The generated 10 Gbps binary information using a PRBS is encoded through a NRZ converter and then sent towards a Mach-Zehnder-modulator (MZM) [24]. After the MZM modulation of the input signal over an optical carrier signal of 1550 nm wavelength, both output MZM signals are combined using an MDM multiplexer (MUX) and transmitted over the FSO channel utilizing transmitting lens. Mathematically, the FSO channel is expressed as [23]:

$$P_r = P_t \frac{d_r^2}{(\varepsilon L + d_t)^2} 10^{-\alpha L/10} \qquad (3)$$

where P_t and P_r are the transmitted and received optical power respectively. L is the FSO transmission range, d_t and d_r represent the antenna diameter of transmitter and receiver respectively, ε and α denote the divergence angle and attenuation (atmospheric) value respectively [25] [26]. Table 1 presents the simulation parameters used in this work [21] [6]. At the receiver side, distinct modes are obtained using MDM demultiplexer (DEMUX) followed by a PIN photodiode to recover the received signal. Low pass filter (LPF) is used to reduce the noise and to attain a high quality signal.

Table 1. Simulation Parameters

Parameter	Value
Laser frequency (THz)	193.1
Laser power (dBm)	10
Laser linewidth (MHz)	0.1
Bit rate/ channel (Gbps)	10
Transmitter aperture diameter (cm)	5
Receiver aperture diameter (cm)	20
Divergence angle (mrad)	1.5
PIN responsivity (A/W)	1
Dark current (nA)	10
Sequence Length	1024
Samples per bit	32
Attenuation coefficients (dB/km)	0.14 (for clear air) 34 (for Light fog) 85 (for Medium fog) 340 (for Heavy fog)

3. Results and discussion

Fig. 4 shows the simulative evaluation results of the MDM-based FSO link under clear weather conditions and weak turbulence level in terms of log of BER and Quality Factor (Q Factor) as performance metrics.

(a)

(b)
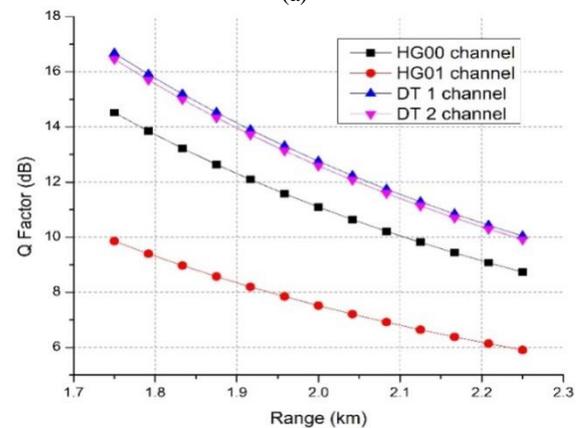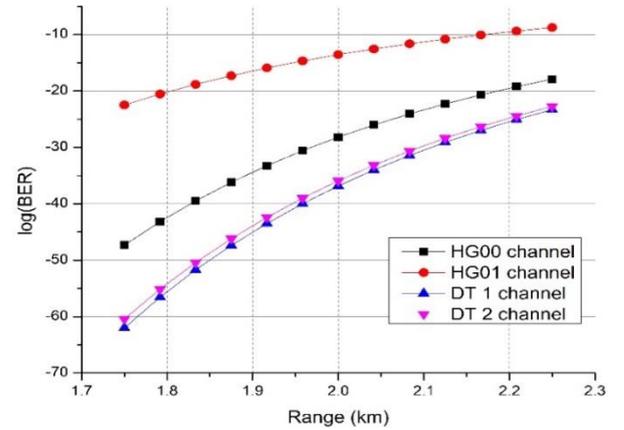
Fig. 4. (a) log(BER) (b) Q Factor v/s Link Range under clear conditions (color online)

(a)

(b)

(c)

(d)
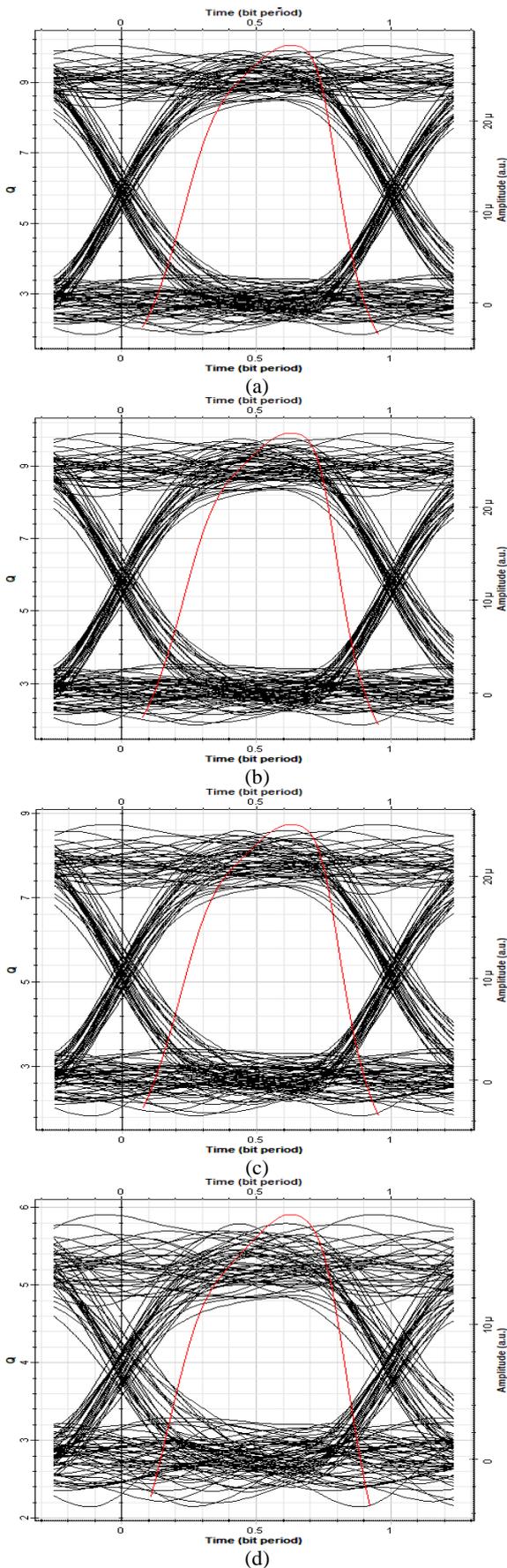
Fig. 5. Eye diagram of the received signal at 2.25 km link distance under the impact of clear conditions for (a) DT 1 (b) DT 2 (c) HG00 (d) HG01

The plots show that the log of BER for HG00, HG01, DT1 and DT2 mode channels is computed as -17.91, -8.76, -23.31 and -22.74 respectively at a FSO range of 2.25 km. Likewise at same FSO range, Q Factor for HG00, HG01, DT1 and DT2 mode channels is 8.73 dB, 5.90 dB, 10.04 dB, and 9.91 dB respectively under clear conditions. The results illustrate that with the rise in link range, the performance of the system decreases. In addition, the computed results report that the performance of DT1 and DT2 modes are considerably better HG00 and HG01 modes as DT mode profile has more channel fading tolerance capability over large transmission range. The results reported demonstrated a faithful transmission of 2×10Gbps data using spatial laser modes over 2.25 km FSO link distance with minimum acceptable Q Factor limit of 6. Fig. 5 presents the eye diagrams of the retrieved data signals at the user end.
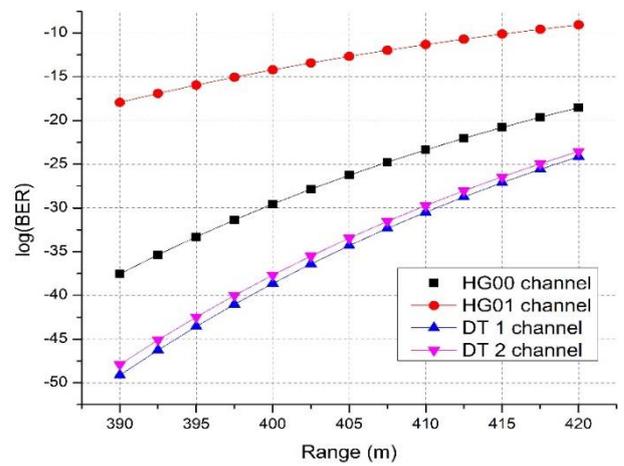
(a)
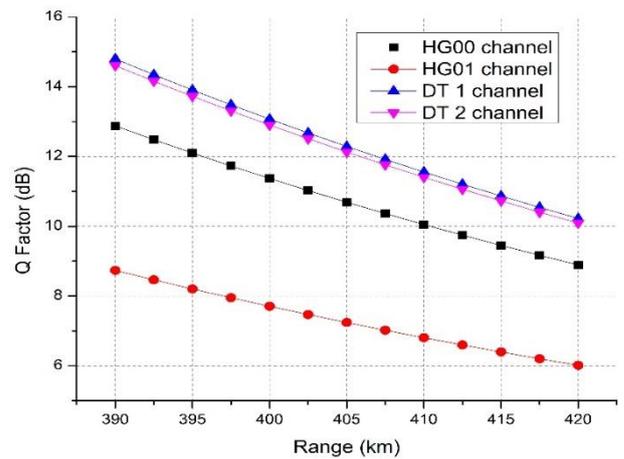
(b)

Fig. 6 (a) log(BER) (b) Q Factor v/s Link Range under light fog conditions (color online)

(a)

(b)

(c)

(d)
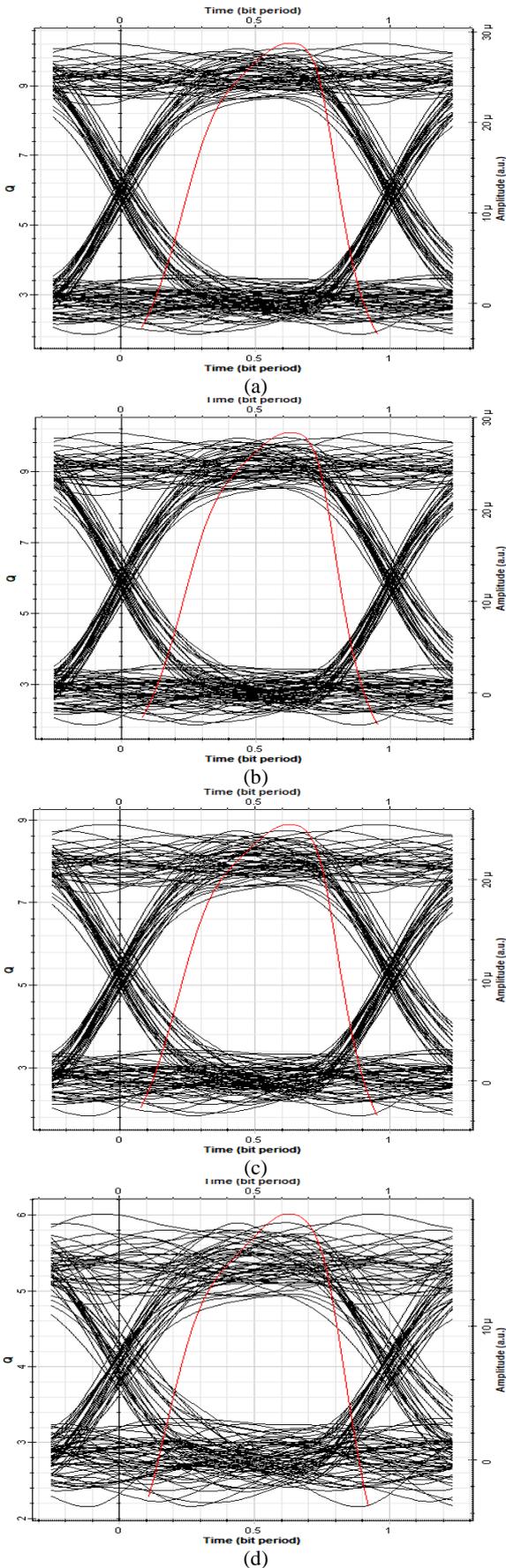
Fig. 7. Eye diagram of the received signal at 420 m link distance under light fog conditions for (a) DT 1 (b) DT 2 (c) HG00 (d) HG01

Further, we analyzed the impact of light, moderate and heavy fog on link performance. Fig. 6 shows that the increase in FSO link ranges degrades the system performance. From Fig. 6, it is noted that log of BER of the received signal for HG00, HG01, DT1 and DT2 mode channels is -18.52, -9.05, -24.12 and -23.53 respectively at a FSO range of 420 m. Similarly, Q Factor for HG00, HG01, DT1 and DT2 mode channels is computed as 8.89 dB, 6.01 dB, 10.22 dB, and 10.09 dB respectively over 420 m link distance under light fog atmospheric weather. The successful transmission range under the impact of light fog weather conditions is 420 m for 2×10 Gbps data transmission using the proposed system. Figs. 7(a), (b), (c) and (d) show that eye diagrams of the HG00, HG01, DT1 and DT2 mode channels over 420 m respectively.
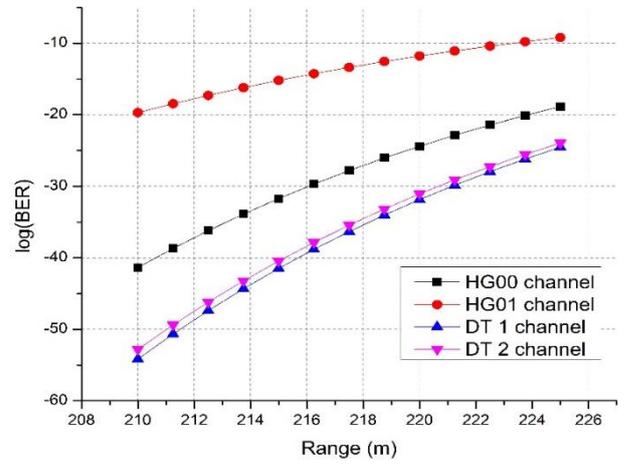
(a)
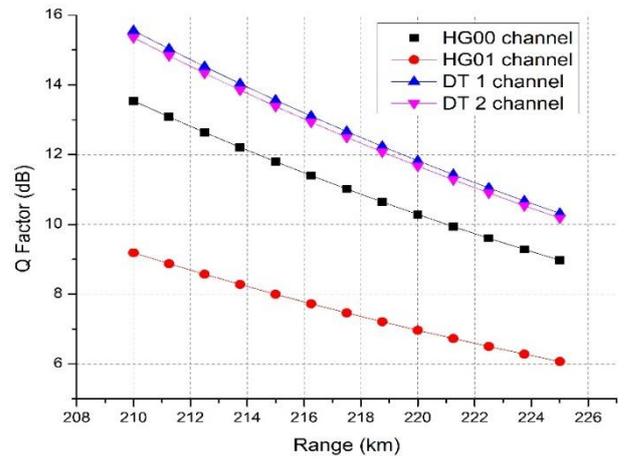
(b)

Fig. 8. (a) log(BER) (b) Q Factor v/s Link Range under moderate fog conditions (color online)

(a)

(b)

(c)

(d)
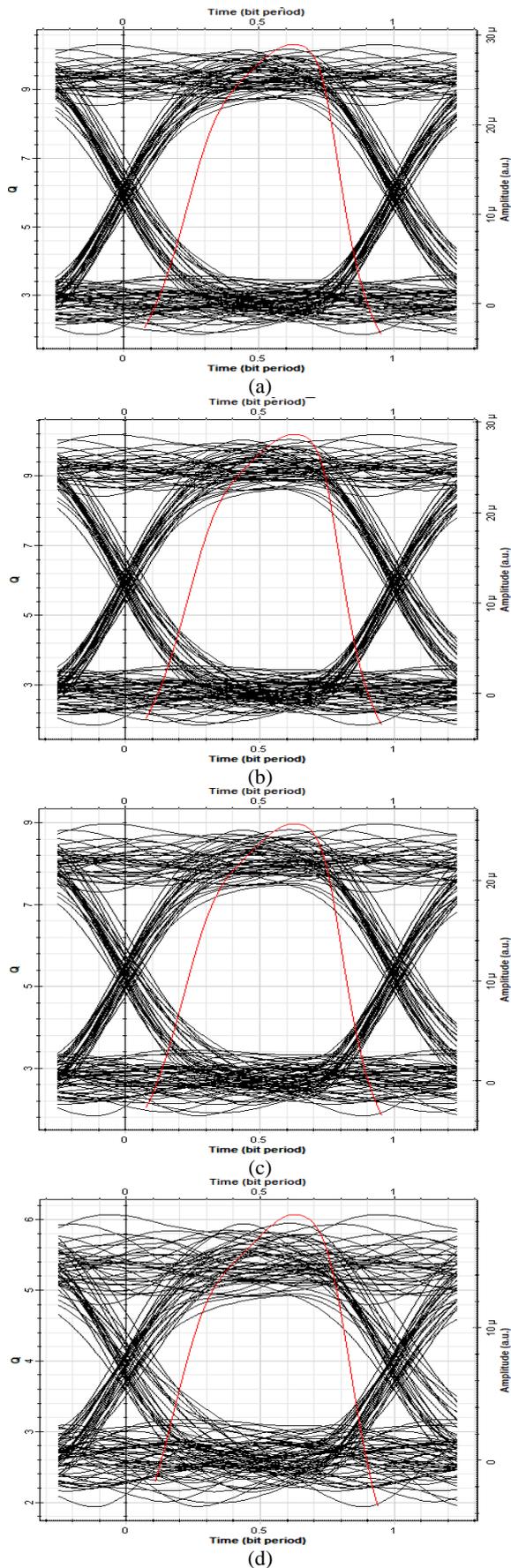
Fig. 9. Eye diagram of the received signal at 225 m link distance under moderate fog conditions for (a) DT 1 (b) DT 2 (c) HG00 (d) HG01

From Fig. 8, it is noted that with the increasing FSO link ranges decreases the transmission link performance. The log of BER of the received optical signal for HG00, HG01, DT1 and DT2 mode channels is computed as -18.84, -9.20, -24.54 and -23.94 respectively under moderate fog over FSO range of 225 m. Also, Q Factor for HG00, HG01, DT1 and DT2 mode channels is computed as 8.97 dB, 6.07 dB, 10.31 dB, and 10.18 dB respectively over 225 m link distance. The successful transmission link range under moderate fog weather is 225 m for 2×10 Gbps data transmission using the proposed system. Fig. 9 (a), (b), (c) and (d) show that eye diagrams of the HG00, HG01, DT1 and DT2 mode channels over 225 m respectively.
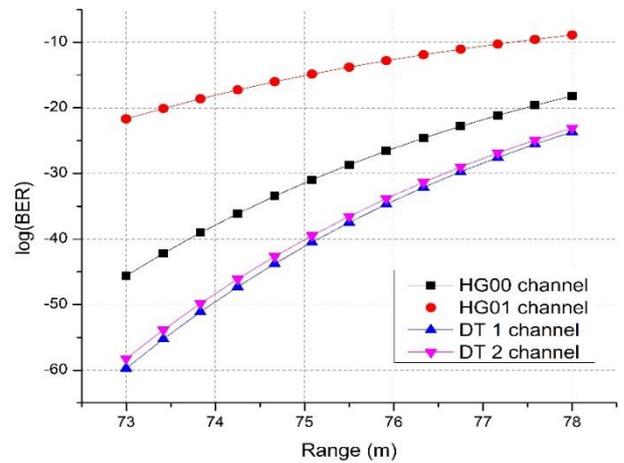
(a)
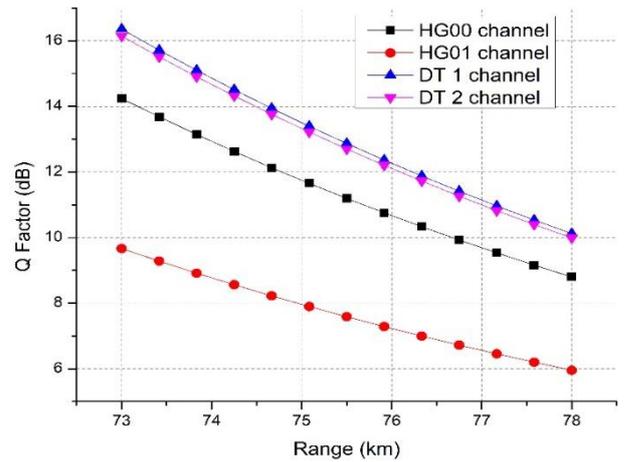
(b)

Fig. 10. (a) log(BER) (b) Q Factor v/s Link Range under heavy fog conditions (color online)

(a)

(b)

(c)

(d)
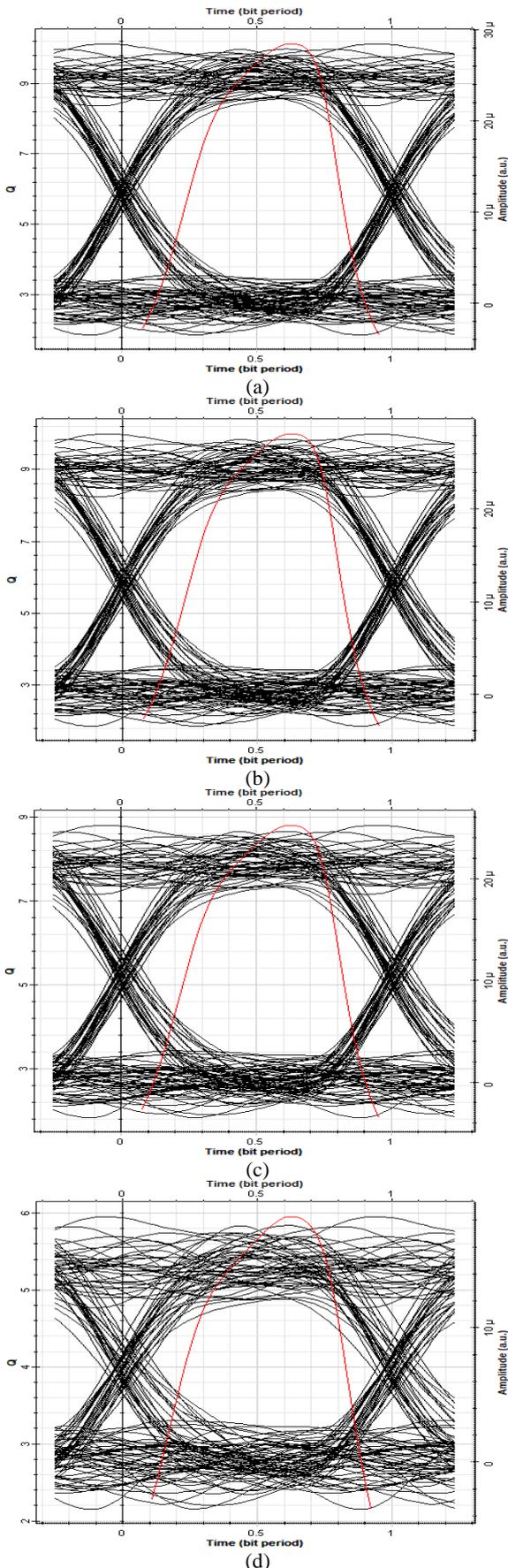
Fig. 11. Eye diagram of the received signal at 78 m link distance under heavy fog conditions for (a) DT 1 (b) DT 2 (c) HG00 (d) HG01

From Fig. 10, it is noted that the log of BER of the received signal for HG00, HG01, DT1 and DT2 mode channels is computed as -18.17, -8.89, -23.66 and -23.08 respectively at a FSO range of 78 m under the influence of heavy fog. Also, the respective Q Factor for HG00, HG01, DT1 and DT2 mode channels is computed as 8.80 dB, 5.95 dB, 10.12 dB, and 9.98 dB respectively over 78 m link distance. The successful transmission link range under the impact of light fog weather conditions is 78 m for 2×10Gbps data transmission using the proposed system. Fig. 11(a), (b), (c) and (d) show that eye diagrams of the HG00, HG01, DT1 and DT2 mode channels over 78 m respectively.

4. Concluding remarks

The comparative simulative evaluation of Donut Transverse modes and Hermite Gaussian modes in a 2×10Gbps mode division multiplexing-based free space optics link under clear air, light fog, moderate fog, and heavy fog weather conditions is reported in this study. The results presented show that Donut Transverse modes performs better than Hermite Gaussian modes under the impact of different atmospheric conditions. Also, for Donut Transverse modes, 2×10 Gbps information is effectively transmitted over 2.25 km range under clear air which degrades to 420 m under light fog, 225 m under moderate fog and 78 m under heavy fog. In future, the proposed system can be used for high-speed backhaul and front-haul transmission required for 5th generation wireless networks and Internet of Things applications.

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