

Performance analysis of Hermite Gaussian laser modes in free space optical communication under atmospheric turbulence

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Free Space Optical (FSO) communication is a key technology for high-bandwidth, secure, and efficient wireless communication. This work investigates the performance of Hermite Gaussian (HG) laser modes in FSO systems under varying atmospheric turbulence conditions. Using Mode Division Multiplexing (MDM), four HG modes (HG00, HG01, HG02, HG03) were transmitted over a single wavelength at a data rate of 1 Gbps. The system setup, modelled using Optisystem software, incorporated a Mach-Zehnder phase modulator (MZM) and spatial demultiplexer, operating at a wavelength of 1550 nm. Key Quality of Service (QoS) metrics, including Quality (Q) factor, Bit Error Rate (BER), and Signal-to-Noise Ratio (SNR), were evaluated to assess the impact of turbulence, attenuation, and geometrical losses. The findings indicate that the fundamental mode HG00 consistently outperformed higher-order modes due to its simpler intensity distribution. The four HG modes under consideration shows significant Q factor and BER up to 900 meters under low turbulence conditions. Although under strong turbulence regime HG00 shows Q factor of ≈ 12 for 600 m link range whereas the Q-factor for higher-order HG modes degrades significantly to around 6. The results underscore the need for advanced modulation techniques and adaptive methods to enhance FSO system reliability in challenging atmospheric conditions.

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1. Introduction

Optical Wireless Communication (OWC) technology is a promising age long technology and alternative scheme in emerging broad band access markets [1,2]. With growing internet traffic these technologies suffer limitations like congested spectrum, expensive licensing, lower data rate, high installation cost etc. OWC in particular outdoor Free Space (FSO) is a key technology [3] that uses unlicensed, laser-based communication through free space to connect various locations, such as cities, rural areas, and even satellites, providing high bandwidth, enhanced security, and potential energy harvesting capabilities [4,5]. FSO is highly attractive for temporary installations (emergency or short-time high broadcast situations, such as the Olympic Games), as well as to overcome geometrical restraints (river, seas, etc.) Compared with RF communication technology, laser-based FSO technology has advantages as higher bandwidth, smaller receivers, and narrower beams to enhance security [5,6]. Higher frequency of the optical carrier ($\sim 10^{14}$ – 10^{15} Hz) thereby allows for much higher transmission rates. Achieving high data rate is always a technological issue. With optical communication, Wavelength Division Multiplexing (WDM) and Mode Division Multiplexing (MDM) are techniques used to achieve the target. In WDM where multiple channels with different wavelengths are transmitted over single wireless

channel, in MDM different spatial modes of laser are used to transfer the information over single channel [7,8] with different spatial modes. Unique properties of OAM beams, such as their amplitude and phase structures, which enable multiplexing and encoding for increased link capacity is analysed in [9]. It also addresses the challenges like atmospheric turbulence and discusses mitigation strategies to ensure reliable communication. MDM based FSO transmission system incorporates polarization shift keying (PolSK) to enhance information-carrying capacity. Numerical simulations demonstrate the transmission of two independent 40 Gbps signals over a 90 km FSO link under clear environmental conditions. It also examines the impact of weather conditions like rain, haze, and fog on system performance [10]. Analysis of LG00, LG0,20 laser modes for clear, haze, rain and fog is performed and reported a transmission distance of 750 m for heavy haze condition [11]. Effect of turbulence for HG00, HG01, HG10, HG11 laser modes is studied in [12] and reported Log (BER) measurements fluctuation from 12 to 7 for 1 Km to 5 Km distances, respectively under clear (no scintillation) weather condition.

To cater the needs of high data rate transmission over optical channel, WDM is an extensively used methodology. Using C-band comparison of data multiplexing techniques like WDM, OAM and MDM have been compared [13]. A

comparison of FSO and RF wireless communication in terms of data rate, efficiency and limitations are discussed and a hybrid model is designed for greater throughput and reliability [14]. Performance of FSO link using WDM-PolSK modulation under turbulent weather conditions is analyzed which highlights the impact of atmospheric factors on signal quality and proposes strategies to enhance system reliability [15]. This emphasizes the importance of robust modulation techniques for maintaining communication efficiency in adverse environments. The performance of fundamental HG and Laguerre-Gaussian (LG) laser modes for varying weather conditions are predicted where HG00 and HG 01 modes under different modulation schemes at speed of 1-4 Gbps is performed [16]. The performance of fundamental HG and LG modes for varying conditions of fog is depicted in [17]. The performance of FSO communication systems using Gaussian beam waves is investigated focusing on factors like beam divergence and atmospheric turbulence. It highlights optimization techniques to enhance signal efficiency and data transmission reliability in such systems. The effect of receiver diversity and optical filters are also studied. The MDM technique for achieving higher data rate in optical fibers for a wavelength of 850 nm for different modulation technique is presented. Major challenge encountered in designing and implementation of FSO link includes uncertain weather conditions like fog, mist, rainfall, air turbulence etc. As the modes propagates in free space, atmospheric effects like turbulence, temperature gradient, humidity, dust particles, aerosols etc. affects the beam intensity distribution. Effect of uncertain atmospheric conditions on the received signal is analysed by measuring the Quality-of-service parameters including Q-factor, BER and SNR etc. Q factor quantifies how well the system can differentiate between transmitted signal levels, is a crucial metric used to evaluate the reliability of optical transmission through the atmosphere [16]. Bit error rate is the ratio of number of bits received in error to the total number of bits transmitted. BER evaluates the performance and reliability of FSO communication link especially when atmospheric conditions greatly impact the quality of signal transmission. BER of 10^{-9} or lower is considered acceptable for high quality communication in free space optics [1]. SNR and BER are related to each other in FSO system. Higher SNR indicated better signal quality which lowers the BER and improves communication reliability. Beam shaping, effective modulation technique, proper wavelength selection can improve the SNR of the system.

The proposed work highlights the performance of 4 HG modes (HG00, HG01, HG02 and HG03) transmitted over a single wavelength in free space at a data rate of 1Gbps each. The analysis is done by simulating the MDM transmission model using Optisystems software. Free space optical communication (FSO) link considered at operating

frequency of 1550nm that is preferably chosen as in this wavelength region, eye safety requirements are more relaxed and interference due to ambient light source is considerably reduced [1]. The performance of these modes under varying attenuation, scintillation, geometrical losses and mild, moderate and dense turbulence is studied. Analysis for higher Q factor and Bit error rate for the four transmitted modes reveal that higher order modes with complex intensity distribution are more susceptible to atmospheric fluctuations. With no optical gain filter in the communication channel all the modes can be propagated well up to a distance of 900 m.

The paper is organized as follows: Section II discusses the detailed System Architecture, including transmitter design, FSO channel modeling, and receiver configuration. Section III presents the Results and Discussion part, analyzing the performance of HG modes under varying turbulence conditions using metrics like Q factor, BER, and SNR. Finally, Section IV concludes the study with key findings and recommendations for enhancing FSO communication reliability.

2. System architecture

The system architecture models the behavior of Hermite Gaussian (HG) laser modes in a Free Space Optical (FSO) communication link. It includes a transmitter, an FSO channel, and a receiver.

Fig. 1 shows that transmitter generates HG modes that are spatially distributed laser modes represented in Cartesian coordinates. These modes are orthogonal, ensuring minimal interference between them. The system uses a spatial laser with a power output of 5 mW, operating at a wavelength of 1550 nm for relaxed eye safety requirements and reduced interference from ambient light. Data is encoded at a rate of 1 Gbps using a Non-Return-to-Zero (NRZ) encoding scheme and fed into a modulator. Mach-Zehnder modulator (MZM) is used in which the spatial mode profile of laser modes is preserved and only the temporal phase is modulated. Therefore, all HG modes experience the same global phase modulation. The power of four HG modes (HG00, HG01, HG02, HG03) is combined using a power combiner. Fixed beam divergence of 1mrad is employed instead of adaptive beam control for the MDM-FSO system to make system simple, stable, and robust. Adaptive beam control techniques require real-time feedback to continuously compensate for atmospheric turbulence and misalignment that significantly increase system complexity, cost, power consumption, and latency in MDM systems. Transmitter aperture diameter is 5 cm, ensuring efficient power transmission into the wireless FSO channel.

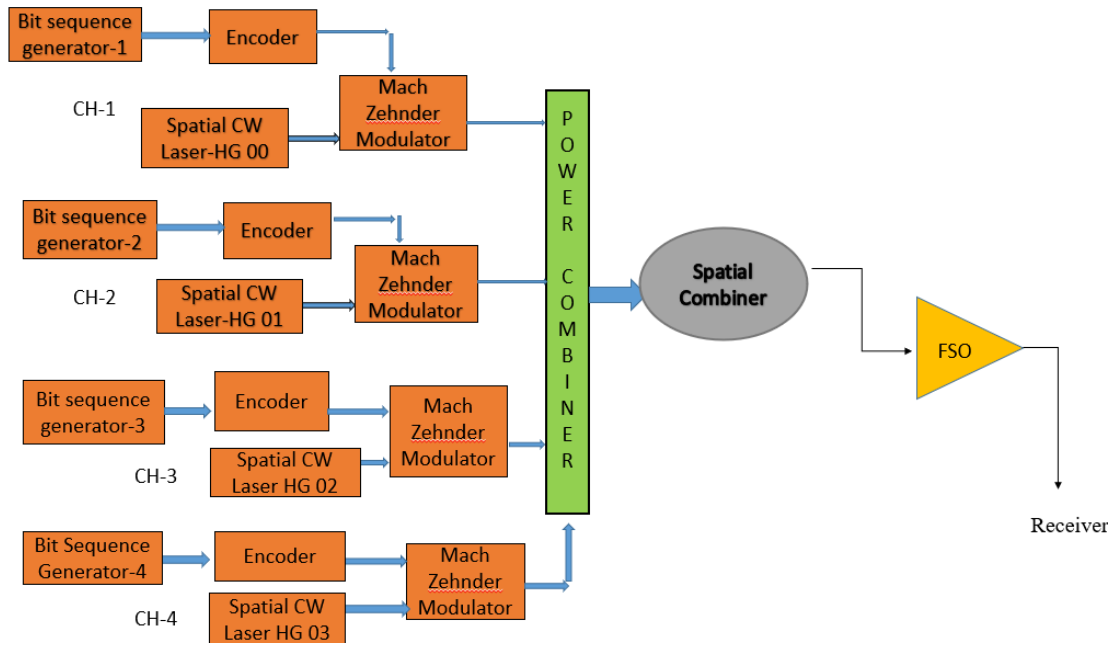


Fig. 1. Transmitter block diagram for HG modes in FSO communication (colour online)

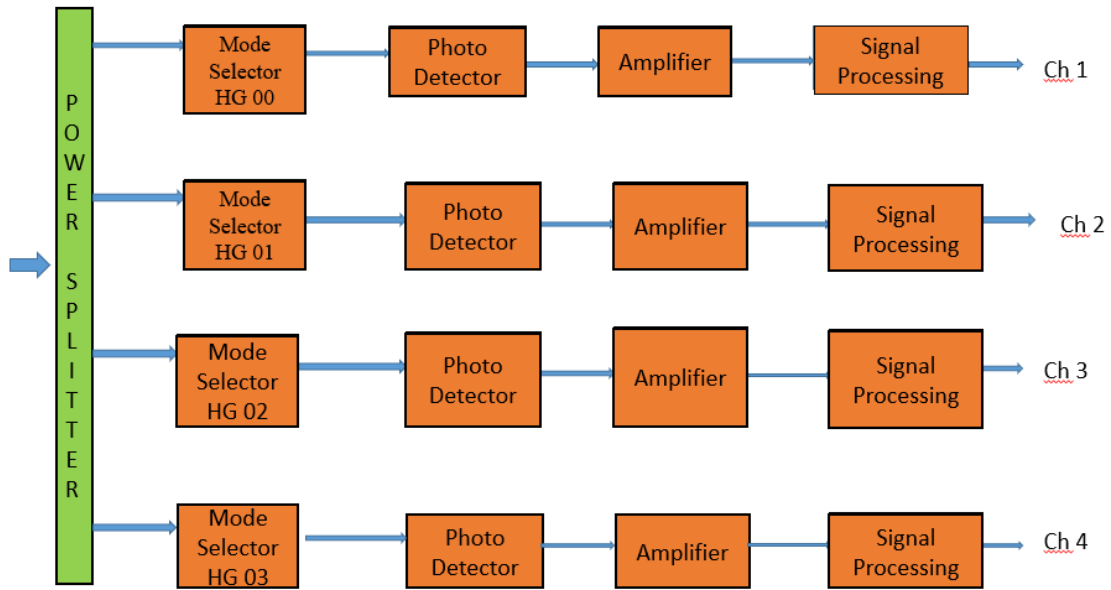


Fig. 2. Receiver architecture with spatial demultiplexer and APD (colour online)

The wireless FSO channel introduces atmospheric attenuations, geometrical losses, and turbulence effects. The channel is modeled for weak, moderate, and strong turbulence. Kolmogorov turbulence model is used in the research work that provides the fundamental physical description of random refractive-index fluctuations in the atmosphere through the refractive-index structure parameter C_n^2 and the corresponding spatial power spectrum. These effects simulate real-world conditions such as fog, rain, and scintillation, impacting the transmission and reception of laser modes. Attenuation caused by APD shot noise, Signal ASE noise and thermal noise are also

considered while modelling the receiver section Fig. 2 shows that the receiver captures and processes the received signal using a circular aperture with a receiver aperture diameter of 25 cm. Optical signal so received is splitted using a power splitter and demultiplexed into individual HG modes using a spatial demultiplexer. An Avalanche Photodiode (APD) serves as the photodetector, chosen for its high sensitivity and ability to handle low-intensity signals. The received signal undergoes demodulation to generate the electrical equivalent signal, followed by a decision-making circuit that reconstructs the transmitted bit pattern. Key metrics such as SNR, Q- factor, and BER are

evaluated for performance analysis. The spatial intensity distribution of the four HG modes HG00, HG01, HG02, and HG03 is illustrated in Fig. 3. HG00 represents the fundamental mode with a smooth Gaussian intensity profile. HG01, HG02, and HG03 exhibit more complex

intensity patterns characterized by orthogonal nodal lines separating intensity lobes. This orthogonality ensures that these modes do not interfere with one another when transmitted simultaneously, enabling MDM for efficient data transmission.

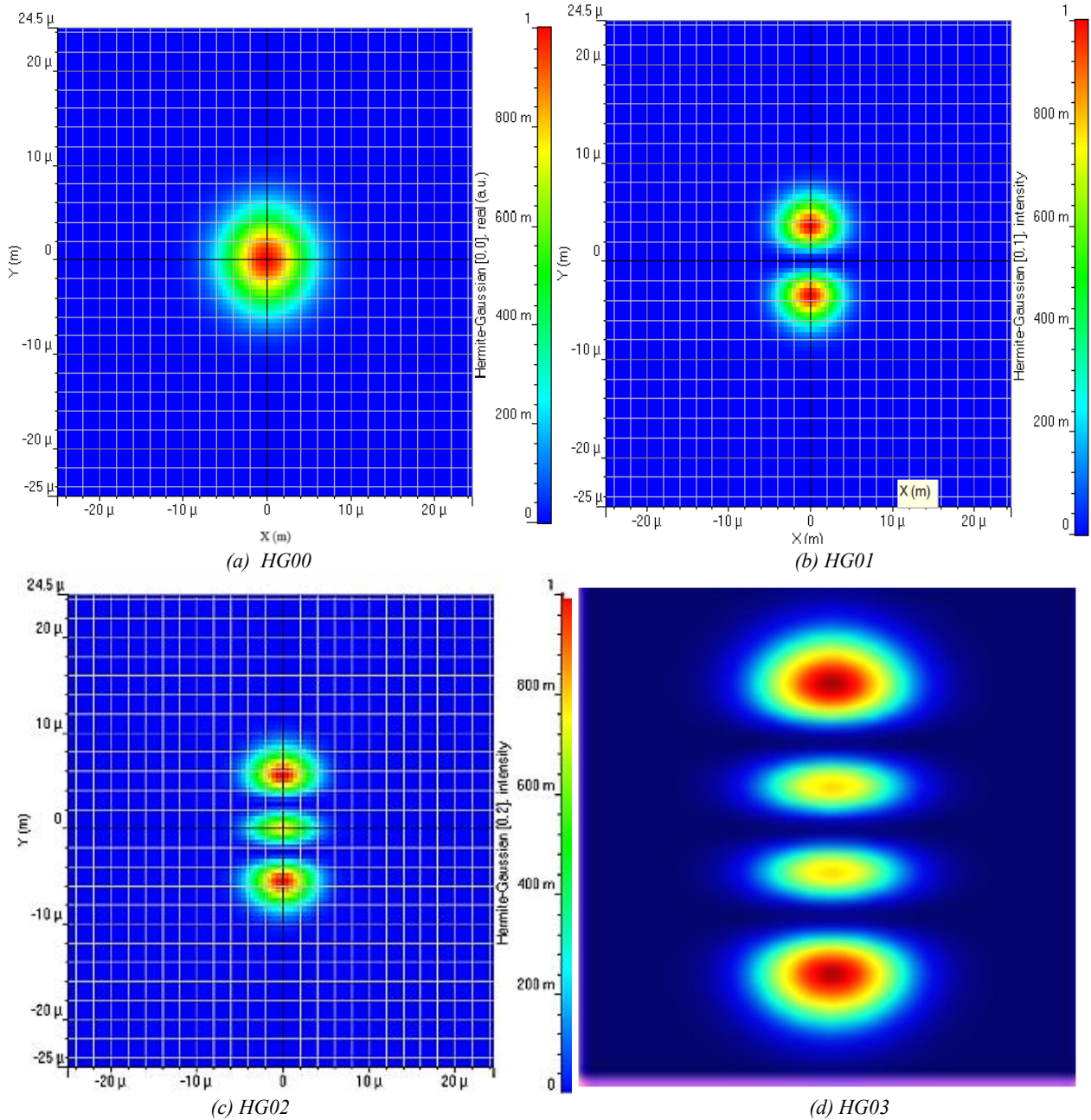


Fig. 3. Spatial intensity distribution of modes: (a) HG00 (b) HG01 (c) HG02 and (d) HG03 (colour online)

3. Results and discussion

The variation of SNR with respect to the link range (800–1200 m) for four HG laser modes (HG00, HG01, HG02, HG03) under low, moderate, and strong atmospheric turbulence conditions is shown in Fig.4. The SNR decreases inversely with the link range, this is attributed to free-space path loss, beam spreading, and accumulated atmospheric

turbulence effects that become more severe at longer propagation distances. The HG00 performs consistently better than higher-order modes (HG01, HG02, HG03) due to its simpler intensity distribution, making it less susceptible to atmospheric distortions. Under low turbulence, all modes exhibit higher SNR values, indicating minimal signal degradation, while moderate and high turbulence lead to significant SNR reductions, particularly

for complex higher-order modes like HG02 and HG03. The slope of SNR reduction becomes steeper under strong turbulence, indicating higher sensitivity to range extension.

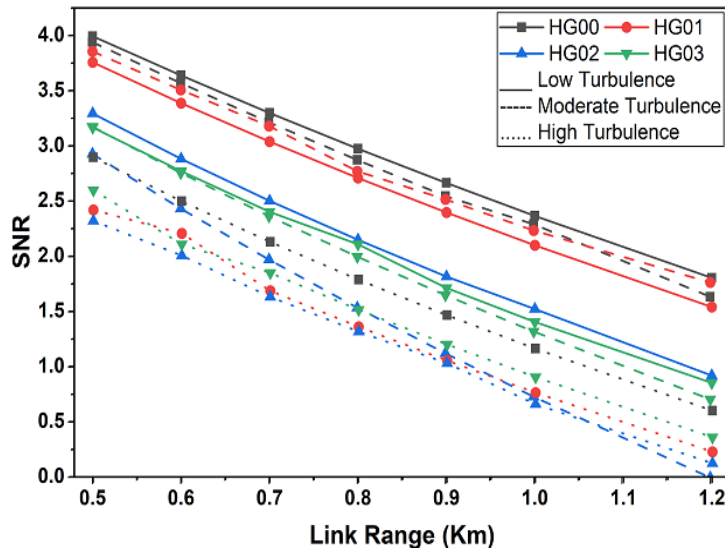


Fig. 4. SNR variation with link range for HG laser modes under turbulence (colour online)

Fig. 5 represents the variation of the Q factor as a function of link range for four HG modes (HG00, HG01, HG02, and HG03) under different turbulence conditions. As the link range increases from 800 m to 1200 m, a consistent degradation in Q-factor is observed for all spatial modes, with HG00 consistently showing the highest performance across low, moderate, and high turbulence due to its simpler intensity distribution and better resilience to atmospheric disturbances. Higher-order modes (HG02,

HG03) exhibit a significant reduction in Q factor, particularly under moderate and high turbulence conditions, due to their complex intensity patterns, which make them more susceptible to scattering and attenuation with increase in link range. All modes demonstrate acceptable Q factor values for distances up to 900m under low turbulence, while performance degrades substantially under moderate and high turbulence.

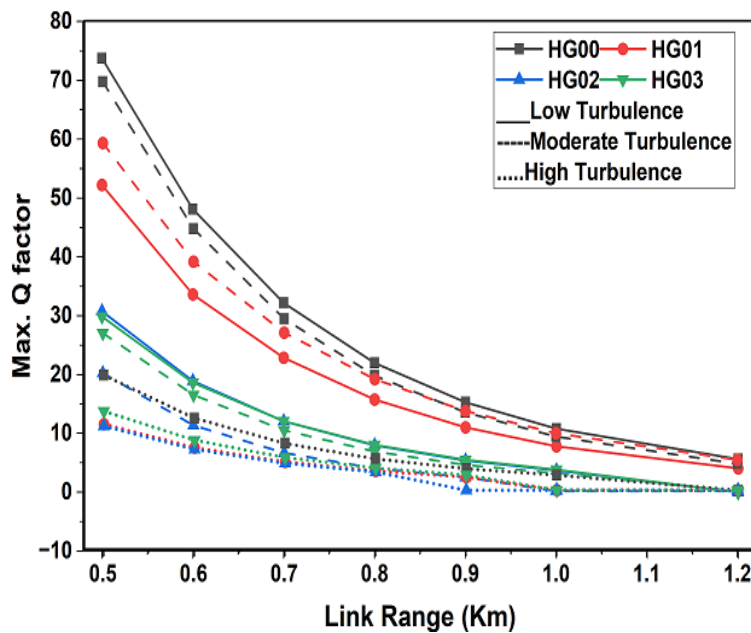


Fig. 5. Q factor performance of HG modes across varying turbulence conditions (colour online)

Fig. 6 illustrates the variation of the minimum logarithmic BER with respect to the link range for four HG

laser modes under different turbulence conditions. BER values increase (logarithmic BER becomes less negative)

with increasing link range, indicating a higher probability of errors due to greater atmospheric distortions. A clear monotonic increase in BER is observed for all spatial modes as the link range increases from 800 m to 1200 m. HG00 laser mode outperforms in all turbulence conditions. Among all modes, HG00 consistently achieves the best BER performance. This performance advantage arises from its higher power concentration at the beam center and reduced sensitivity to wavefront distortions, making it less

susceptible to turbulence effects. Higher-order modes experience a more significant increase in BER, particularly under moderate and high turbulence conditions, due to their complex intensity profiles that are more affected by atmospheric scattering and attenuation. The slope of the BER curves becomes steeper at longer link ranges, indicating that the combined effects of distance-dependent losses and turbulence are more pronounced beyond 1000 m.

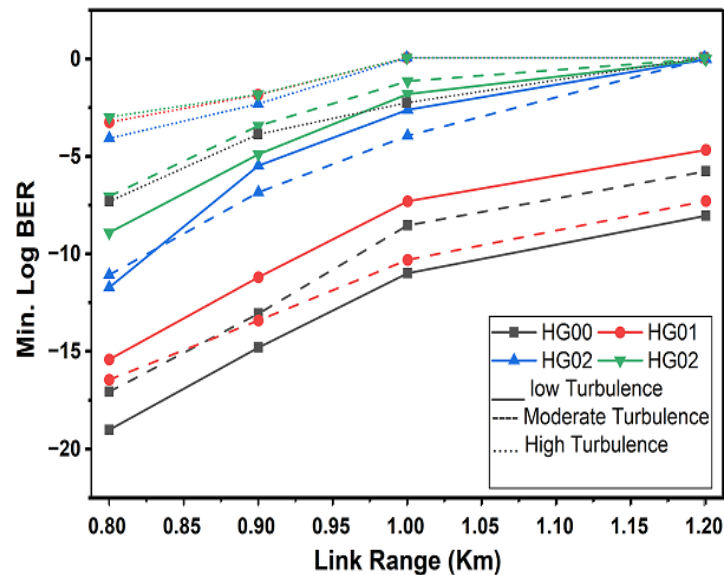


Fig. 6. Variation of Min Log BER with link range for HG modes under turbulence conditions (colour online)

4. Conclusion

MDM in FSO communication is a promising technique for achieving higher data rates to meet growing bandwidth demands. However, the performance of FSO systems is significantly influenced by atmospheric conditions such as turbulence, attenuation, and geometrical losses. This study analysed the performance of HG modes (HG00, HG01, HG02, HG03) under varying turbulence conditions. Table 1 indicates the Q-factor parameter for all the four modes

under low (LT), moderate (MT) and strong turbulence (ST) regime. Under low and moderate turbulence conditions, acceptable performance is maintained up to 900 m for lower-order modes, although a noticeable degradation is observed as the mode order increases. At 600 m, all modes show significantly improved performance, indicating reduced geometrical and turbulence-induced losses at shorter propagation distances. However, under high turbulence conditions, system performance degrades substantially, particularly for higher-order modes.

Table 1. Q factor values for 900m and 600m for all four HG laser modes

	900m				600m			
	HG 00	HG 01	HG 02	HG 03	HG 00	HG 01	HG 02	HG 03
LT	15.38	11.2	6.3	5.7	48.11	38.61	18.90	18.56
MT	14.3	13.7	5.8	2.9	44.5	33.9	16.17	11.17
ST	6.5	4.6	3.62	0	12.38	8.52	7.25	6.98

The results demonstrate that the fundamental mode HG00 consistently outperforms higher-order modes due to its simpler intensity distribution, making it less susceptible to atmospheric distortions. HG00 and HG01 maintain acceptable Q factor and low BER for distances up to 900 meters under low turbulence conditions. In contrast, higher-order modes (HG02, HG03) exhibit a significant decline in Q factor and BER performance, especially under moderate

and high turbulence, limiting their transmission range to 600 meters. Achieved results confirms that while higher-order HG modes can be utilized in MDM-based FSO systems under favourable atmospheric conditions and shorter link ranges, the fundamental HG00 mode is the most reliable choice for extended distances and severe turbulence environments. These findings provide valuable design insights for optimizing MDM-FSO systems, emphasizing

the trade-off between capacity enhancement through higher-order modes and link reliability under realistic atmospheric conditions. To improve system performance under adverse conditions, increasing laser power, optimizing modulation techniques, and employing advanced beam-shaping methods are recommended. Future research should focus on adaptive systems to mitigate turbulence effects dynamically, ensuring reliable FSO communication across varying atmospheric conditions.

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