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A 2×40 Gbps Mode Division Multiplexing Based Inter-satellite Optical Wireless Communication (IsOWC) System

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Abstract
The incorporation of optical wireless communication technology in inter-satellite links, also referred as inter-satellite optical wireless communication (IsOWC) is a key technology capable of providing seamless high-speed information transportation all around the globe. The key factors affecting the IsOWC link performance are transmission range and pointing error angle losses (space turbulence). Further, mode division multiplexing (MDM) is regarded as a spectral-efficient cost-effective technology to transmit high-speed information by exploiting distinct spatial modes of a single laser beam. This works reports the modeling and simulative investigation of a novel MDM based IsOWC link where two independent 40 Gbps channels are transported over distinct Laguerre Gaussian modes of a single laser beam at 6000 km transmission range. Further, we numerically investigate the proposed MDM based IsOWC link performance under the impact of pointing error angle losses and demonstrate a faithful transmission up to 2 μrad pointing error angle. Based on these insights, we propose an IsOWC link tailored for high-speed spectral-efficient information transmission.

Keywords Inter-satellite optical wireless communication (IsOWC) · Mode division multiplexing (MDM) · Laguerre Gaussian (LG) modes · Pointing error · Transmission range

1 Introduction

Inter-satellite optical wireless communication (IsOWC) technology is an emerging data transmission technique using which high-speed information can be transported between two satellites orbiting either in same/different orbits using vacuum as medium and optical carrier signals [1, 2]. IsOWC links are gaining considerable stature in research community due to their many advantages including (a) large channel capacity, (b) secure data transmission, (c) high-speed links, (d) resistance to electromagnetic and radio frequency intrusion,

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(e) low mass and power requirement, (f) cost-effectiveness, (g) no need of spectrum licensing, (h) low beam divergence, (i) low security upgrades, (j) quick and easy deployment, etc. [3–5]. Maintaining LOS configuration for transceivers is an obligatory clause for reliable information transmission using IsOWC links. The performance of IsOWC link is degraded by any misalignment between the transmitter and the receiver unit which may be due to mechanical vibrations of the satellite platform, background noise radiations, solar noise, and optoelectronic disturbances [6, 7]. Any misalignment between the transmitter and the receiver unit will lead to degradation in the quality of the received information signal and ultimately may lead to complete link failure. This effect is known as pointing error loss (space turbulence) [8].

Recently, much work has been reported by many researchers on the information carrying capacity enhancement of IsOWC links using wavelength division multiplexing (WDM), orthogonal frequency division multiplexing (OFDM), polarization division multiplexing (PDM), optical code division multiple access (OCDMA) and advanced modulation techniques. The work in [9] discusses the performance of 120 Gbps IsOWC link at 1000 km range by using hybrid WDM-polarization interleaving-non return to zero (NRZ) scheme with transmitting pointing errors increasing from 1 to 5 μrad. The simulative analysis of the proposed link shows faithful transmission in terms of signal to noise ratio, total power and eye diagram of the received information signal. Similarly, the deployment of hybrid WDM-polarization interleaving scheme incorporating alternate mark inversion modulation to transmit 160 Gbps information at 1000 km range under the impact of 4 μrad transmitting pointing error with acceptable signal to noise ratio, bit error rate (BER), total power, and eye diagram of the received signal is reported in [10]. The performance evaluation of 4-level quadrature amplitude modulation and 4-level phase shift keying modulation format in a 10 Gbps-4000 km OFDM-IsOWC link has been discussed in [11]. The results demonstrate a superior performance of 4-level quadrature amplitude modulation format in terms of signal to noise ratio, total power, and constellation plots of the received information signal. In another work [12], hybrid spectral amplitude coding, OCDMA and PDM techniques have been incorporated in an IsOWC link to transport 100 Gbps information at 26,000 km range without pointing errors whereas the range limits to 6000 km under the influence of 3.2 μrad pointing errors. The work in [13] discusses the performance analysis of return-to zero and NRZ modulation schemes in a hybrid WDM-PDM based IsOWC link. The results report that NRZ scheme performs betters and the proposed link transmits 120 Gbps information at 5000 km range with fair performance. The authors in [14] discuss the performance of a 100 Gbps multiplexed IsOWC link incorporating hybrid coherent detection and OFDM technique along with dual-polarized quadrature phase shift keying with forward error correction coding. The proposed link transports 1.6 Tbps information at 15,600 km range under the influence of 1.1 μrad pointing errors with fair performance. In another work [15], hybrid differential phase shift keying and Manchester coding schemes are deployed in an IsOWC link to transmit 40 Gbps information at 19,100 km range with faithful performance of the link. A large-capacity IsOWC link incorporating a novel hybrid 2-dimentional modulation scheme and WDM technique has been reported in [16]. The reported results show 1.6 Tbps transmission at 25,000 km range without considering pointing errors whereas the range limits to 10,000 km under the influence of 2.7 μrad pointing errors. In another work [17], the authors discuss the impact of operating wavelength, transmission power, and modulation format in a hybrid coherent detection-OFDM–PDM based IsOWC link with improved signal detection technique.

In this work, we report a novel high-speed long-haul IsOWC transmission link by incorporating mode division multiplexing (MDM). MDM is a spectrum-efficient multiplexing technique which capitalizes in the orbital angular momentum dimension of the optical carrier signal to transmit multiple independent high-speed information signals simultaneously over distinct spatial modes [18, 19]. The main objective of the paper is as follows: (1) to develop a spectrum-efficient high-capacity long-reach IsOWC link by using MDM of distinct Laguerre Gaussian modes (2) to study the performance of the IsOWC link under the impact of increasing link range and space turbulence. The rest of the paper is structured as follows: Sect. 2 reports the link design of the proposed MDM based IsOWC system and Sect. 3 describes its numerical simulative investigation followed by the conclusion in Sect. 4.

2 Link Design and Parameters

The link design of the proposed system is reported in Fig. 1.

In the proposed work, two distinct 40 Gbps information signals are transported between two satellites separated in outer space using distinct LG modes which can mathematically be described as [20]:

$$\varphi_{m,n}(r,\emptyset) = \left(\frac{2r^2}{w_o^2}\right)^{|n/2|} L_m^n\left(\frac{2r^2}{w_0^2}\right)\exp\left(\frac{r^2}{w_0^2}\right)\times\exp\left(j\frac{\pi r^2}{\lambda R_0}\right)\left\{\begin{array}{l}\sin\left(|n|\emptyset\right), n \geq 0\\ \cos\left(|n|\emptyset\right), n < 0\end{array}\right\} \tag{1}$$

where m and n represent mode dependencies on x-polarization axis and y-polarization axis respectively, r represents the curvature radius, w_o represents spot size, L_m^n represents the Laguerre polynomial. In the proposed work, a 30 dBm continuous wave spatial laser followed by a multimode generator are used to excite distinct LG modes. Figure 2 shows the spatial profiles of distinct LG modes.

As illustrated in Fig. 1, independent 40 Gbps binary information for each channel is generated using a pseudo random bit sequence generator (PRBS). This binary information is converted into electrical domain using a NRZ line encoder. In the proposed work, we have generated distinct LG modes (LG00 and LG01) of same 850 nm wavelength channel using spatial laser. Each distinct mode modulates independent 40 Gbps information channel using a Mach Zehnder modulator (MDM) with 30 dB extinction ratio operating in push–pull state. Here, we achieve two independent 40 Gbps optically modulated signals which are combined using an optical combiner and then transmitted to outer space using transmitter lens. The IsOWC link equation [21] along with transmitter and receiver pointing loss factors can be described in Eqs. 2–4:

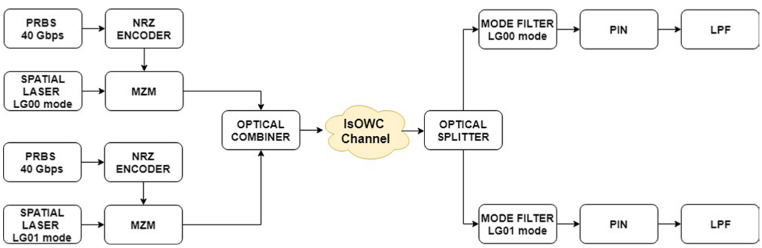


Fig. 1 Link design of the proposed MDM-IsOWC transmission system

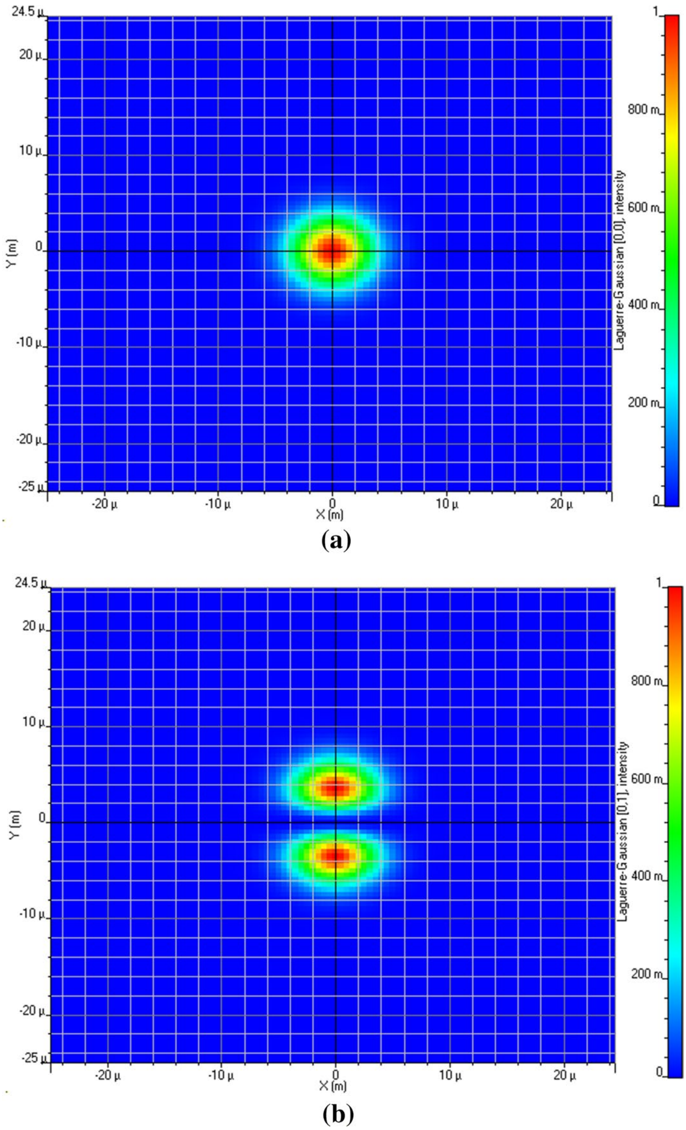


Fig. 2 Excited LG modes **a** LG00, **b** LG01

$$P_R = P_T \eta_T \eta_R \left(\frac{\lambda}{4\pi Z} \right)^2 G_T G_R L_T L_R \tag{2}$$

$$L_T = \exp\left(-G_T \theta_{T^2}\right) \tag{3}$$

$$L_R = \exp\left(-G_R \theta_{R^2}\right) \tag{4}$$

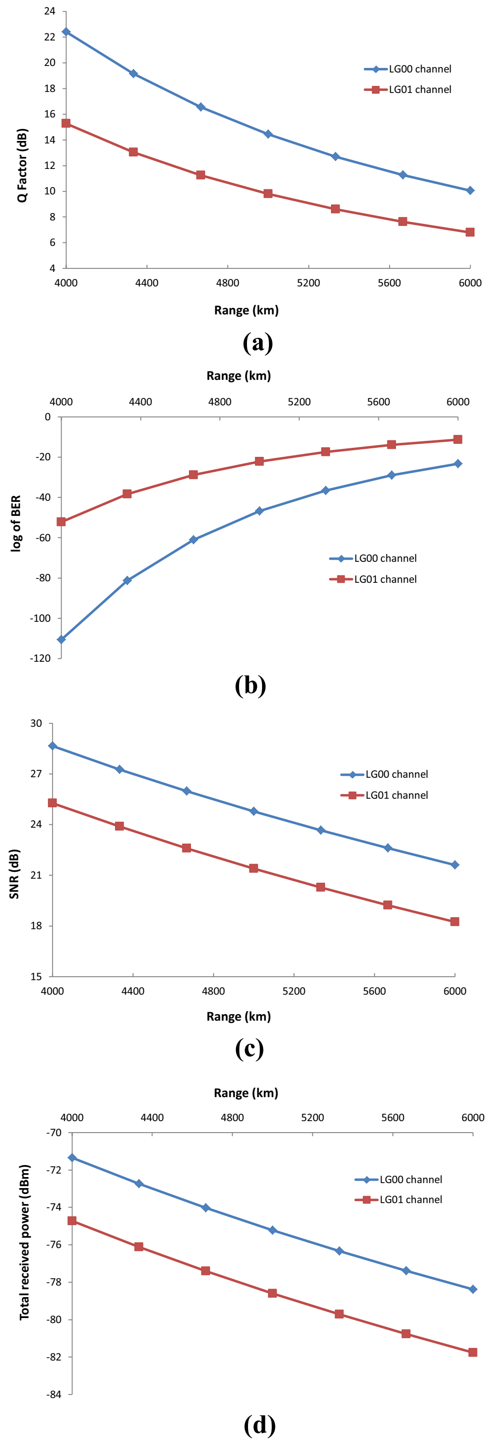
At the receiver terminal, the received optical signal consisting of two independent 40 Gbps information signals is intercepted using receiver lens and independent channels are retrieved using a mode filter. The information from each optical signal is extracted using a PIN photodiode. Further, we have used a low pass filter (LPF) to remove any high-frequency noise present in the received signal. The simulation parameters considered in the proposed work are as follows: operating wavelength is 850 nm, laser line width is 0.1 MHz, transmission power is 30 dBm, bit rate/channel is 40 Gbps, transmitter/receiver aperture diameter is 150 mm, transmitter and receiver pointing error angle is 1.1 μrad, transmitter/receiver optical efficiency is 0.8, sequence length is 65,536, sample per bit is 4, thermal noise power density is 1e−022 W/Hz, photodiode responsivity is 1 A/W, ionization current is 0.9 A, LPF cut off frequency is 0.75 × bit rate/8 and additional Loss (pointing losses, synchronization losses etc.) are considered as 5 dB.

3 Results and Discussion

In this work, Optisystem simulation software has been used to evaluate the performance of the proposed IsOWC link. Figure 3a analyzes the Q factor of received signal for increasing transmission range. The Q Factor for LG00 channel is computed as 22.38 dB, 14.43 dB, and 10.04 dB whereas for LG01 channel is computed as 15.27 dB, 9.79 dB, and 6.80 dB at 4000 km, 5000 km, and 6000 km range respectively. Similarly, Fig. 3b illustrates the log of BER of the received signal as − 110.612, − 46.82, and − 23.32 for LG00 channel and − 52.22, − 22.25, and − 11.29 for LG01 channel at a transmission range of 4000 km, 5000 km and 6000 km respectively. Similarly, Fig. 3c illustrates the signal-to-noise ratio (SNR) of received signal as 28.65 dB, 24.78 dB, and 21.61 dB for LG00 channel and 25.27 dB, 21.39 dB, and 18.22 dB for LG01 channel at a transmission range of 4000 km, 5000 km and 6000 km respectively. Further Fig. 3d shows the received optical power as − 71.34 dBm, − 75.21 dBm, and − 78.37 dBm for LG00 channel and − 74.72 dBm, − 78.59 dBm, and − 81.75 dBm for LG01 channel at a transmission range of 4000 km, 5000 km and 6000 km respectively. The results show that as the IsOWC link range increases, the performance of the proposed system degrades. Also, it can be observed that LG00 channel performs better as compared to LG01 channel since the former is more robust to space turbulence. Figure 4 reports the eye diagrams of the received signals at 6000 km IsOWC link range using the proposed link. The clear eye diagrams with wide eye opening demonstrate a reliable transmission of 2 × 40 Gbps information over 6000 km IsOWC link range using the proposed system with acceptable performance.

The performance of the proposed IsOWC link under the impact of increasing receiver pointing errors (space turbulence) has been also investigated in this work. Figure 5 describes the performance of the proposed system in terms of increasing receiver pointing error angle from 1 to 2 μrad at a link distance of 4000 km. Figure 5a illustrates that the Q Factor of received signal for LG00 channel is computed as 23.83 dB, 16.36 dB, and 9.58 dB whereas for LG01 channel the values are 16.27, 11.11, and 6.48 dB at pointing error angle of 1 μrad, 1.5 μrad, and 2 μrad respectively. Similarly, Fig. 5b illustrates the log of BER of the received signal as − 125.2, − 59.75, − 21.35 for LG00 channel and − 59.14, − 28.29, and − 10.37 for LG01 channel at pointing error angle of 1 μrad, 1.5 μrad, and 2 μrad respectively. Similarly, Fig. 5c illustrates the SNR of received signal as 29.21 dB, 25.88 dB, and 21.20 dB for LG00 channel and 25.83, 22.49, and 17.82 dB for LG01 channel at pointing error angle of 1 μrad,

Fig. 3 Computed **a** Q factor, **b** log of BER, **c** SNR, **d** received power versus IsOWC transmission range



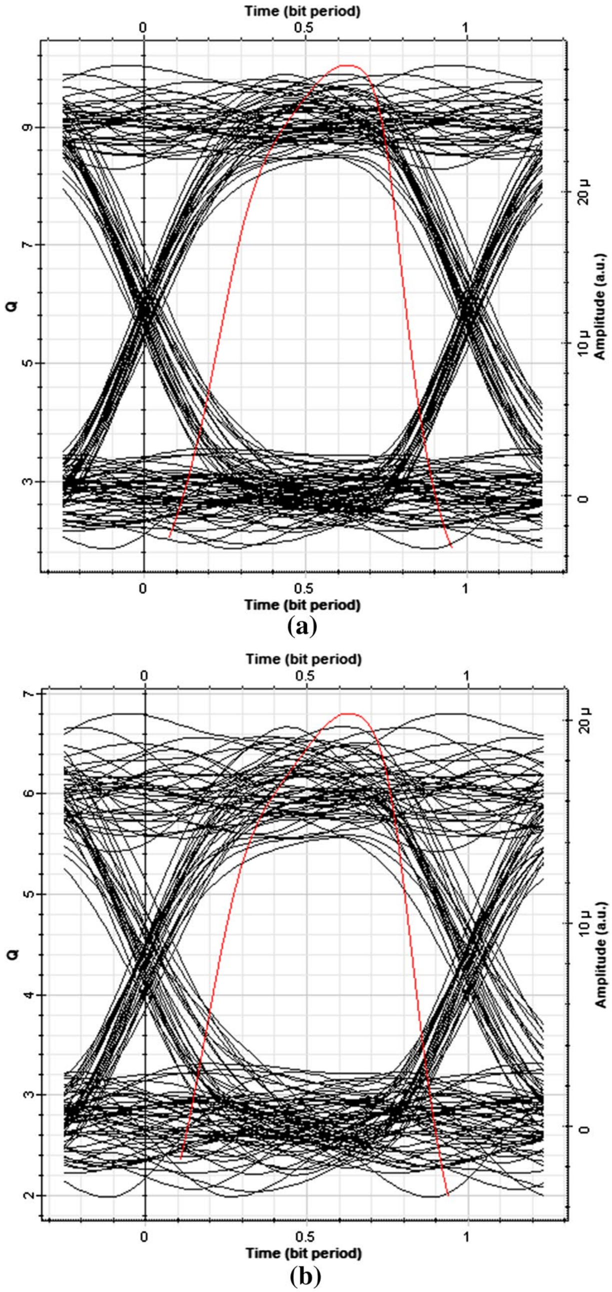
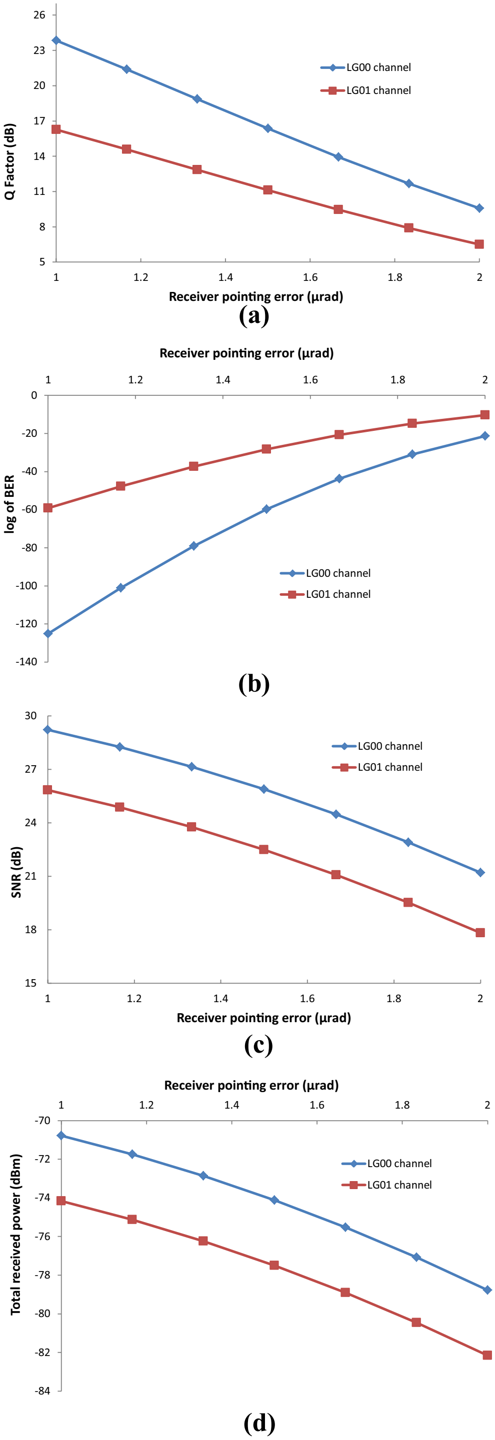


Fig. 4 Eye diagram at 6000 km IsOWC transmission range for **a** LG00 channel, **b** LG01 channel

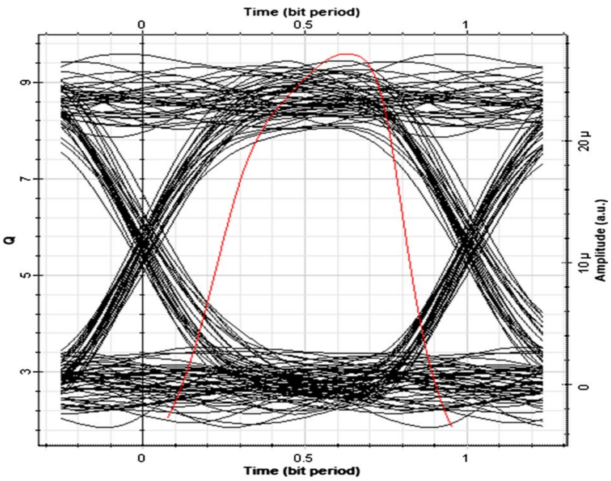
1.5 µrad, and 2 µrad respectively. Further, Fig. 5d illustrates the received optical power as − 70.78 dBm, − 74.11 dBm, and − 78.78 dBm for LG00 channel and − 74.16 dBm, − 77.49 dBm, and − 82.15 dBm for LG01 channel at pointing error angle of 1 µrad, 1.5 µrad, and 2 µrad respectively. The results show the degradation in performance with increase in receiver pointing error angle. The clear eye diagrams of the received signals

Fig. 5 Computed **a** Q factor, **b** log of BER, **c** SNR, **d** received power versus receiver pointing error angle at 4000 km IsOWC transmission range



at 4000 km link range under 2 μrad receiver pointing error angle in Fig. 6 demonstrates a successful transmission of 2 × 40 Gbps information signal.

The modal decomposition of LG00 and LG01 channels into fiber linear polarized (LP) modes at receiver terminal has been described in Fig. 7. It can be observed that in the case of LG00 channel, maximum power is being transferred to LP01 mode (82.05%) followed by LP02, LP03, LP04, and LP05; whereas for LG01 channel, maximum power is transferred to LP11 mode (67.37%) followed by LP12, LP13, LP14, LP15, LP34, LP33, LP53, and LP32. The results show that LG01 channel has higher intermodal power coupling as compared to LG00 channel which agrees well with the link performance demonstrated in Figs. 3, 4, 5 and 6.



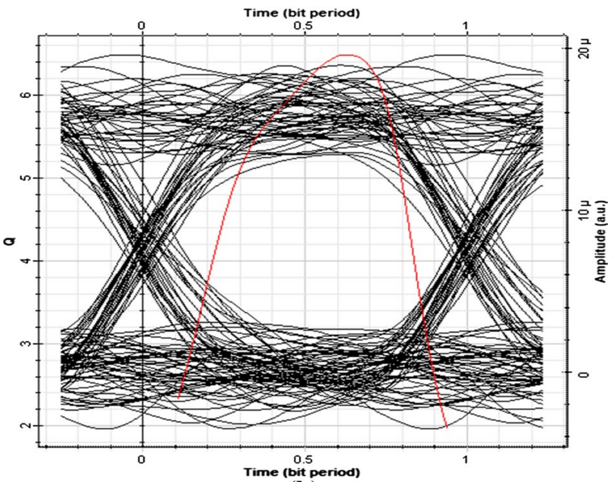
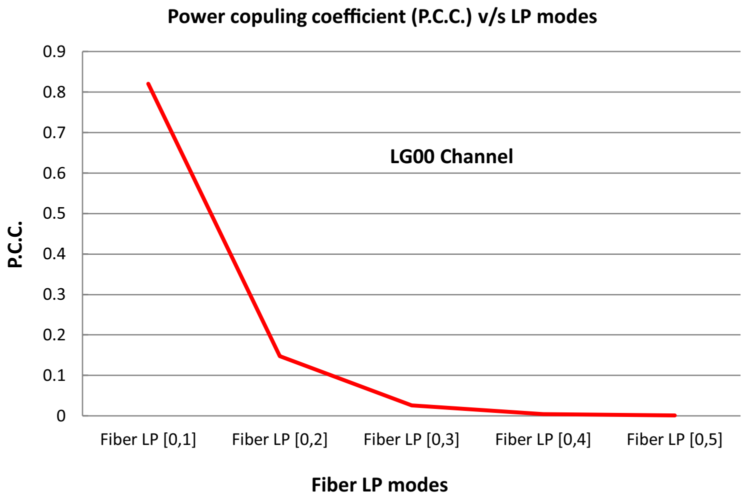
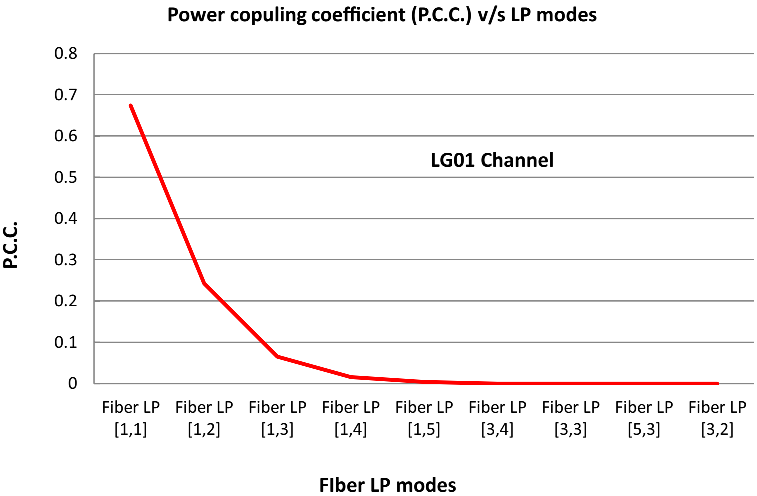


Fig. 6 Eye diagram at 4000 km IsOWC link range under 2 *urad* receiver pointing error angle for **a** LG00 channel, **b** LG01 channel



(a)



(b)

Fig. 7 Modal decomposition **a** LG00 channel, **b** LG01 channel

4 Conclusion

The present work reports the modeling and investigation of a high-speed MDM based IsOWC link. The results of the simulative analysis of the proposed link demonstrate thriving transportation of 2 × 40 Gbps information over 6000 km IsOWC link range with acceptable performance (Q Factor > 6 dB and BER $\leq 10^{-9}$). Further, the impact of increasing pointing errors on the proposed link performance has been numerically investigated and the results exhibit a thriving transportation of 2 × 40 Gbps information over 4000 km IsOWC link range under 2 μrad pointing error angle.

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