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Development and Performance Investigation of a Single-Channel 160 Gbps Free Space Optics Transmission Link Using Higher Order Modulation Scheme

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Abstract
This article reports the development of a high bit rate terrestrial free space optics (FSO) transmission link. Spectral-efficient polarisation division multiplexed-quadrature phase-shift keyed signals are used to transmit high bit rate data. Coherent receiver is proposed to ameliorate the demodulator performance under environmental conditions. Also, digital signal processing techniques at the receiver are used to mitigate the adverse channel effects on the information signal. The bit error rate analysis for different environmental conditions is carried out using numerical simulations and the results demonstrate reliable 160 Gbps transmission. The impact of atmospheric scintillation due to turbulent channel conditions on the link performance is also investigated. Further, the transmission performance is compared with previous reported studies which shows that the system demonstrates better achievable range and information bit rate performance. The reported work provides a suitable reference to realize bandwidth-efficient high-capacity FSO links under dynamic weather conditions.

Keywords PDM · FSO · DSP · QPSK · Environmental factors

1 Introduction

Keeping up with the rapid evolution in the information technology, there can be seen an enormous rise in the high data rates and channel bandwidth services, which can only be sustained by future generation wireless information transmission systems. Optical fibre communication (OFC) technology, which was conventionally exploited to cater to high bandwidth demands for enabling digital video broadcasting in terrestrial wireless access networks, cellular mobile networks, and other services though had numerous merits over traditional radio frequency-based links, but suffered from many limitations regarding excessively high installation cost and right of the way permissions [1–4]. In the case of OFC transmission links, digging and trenching of the Earth's surface for laying the optical

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fibre cables was very difficult in inaccessible rough terrains like mountains and even in heavily crowded urban areas. This led to the problem of last-mile bottleneck, where the data rates in the core network based on optical fibre trunk lines and in local area networks within the building was high (> 2.5 Gbps), but the broadband access network between them based on traditional technologies such as digital subscriber lines, dial-up modem etc. had low transmission rates (~ 0.3–1.5 Mbps) [5, 6]. Also, the cost and time requirement for optical fibre installation and maintenance is very high.

Therefore, over the past few years, free space optics (FSO) is been contemplated as a feasible technological framework to mitigate the limitations faced by OFC links and to provide high-speed wireless networks. FSO is a pivotal and viable information transmission technology to transmit high-speed data over optical carrier signals for last-mile users, local area networks, Wi-Fi applications, live video-streaming, fast internet, and high-definition television, etc. It has the advantage of redeploy ability and provides high information transmission rates as in the case of OFC links [7]. For catering to the demand of high channel bandwidth and low latency networks in 5th generation wireless links and Internet of Things applications, FSO is a crucial technology. Furthermore, enhanced security, mitigation to interference, lower requirement of mass and power, and simple design of transceiver units etc. are few other merits of FSO links which make it an important technology to deal with spectrum congestion issue [8].

Despite of many merits of FSO technology, the channel attenuation as a result of adverse environmental conditions like fog, rain, smog, haze, cloud, storm, and snow, etc. causes the absorption and scattering of the laser beam which affects the line-of-sight configuration between the transmitter and receiver, degrading the link quality and ultimately leading to link failure. Furthermore, the non-ideal characteristics and inefficiencies in the optical transmitter and receiver units deteriorate the received information signal performance. Moreover, the increasing size of optical beam due to diffraction as it propagates the channel, also referred as beam divergence results in signal power loss, which limits the effective transmission range [9]. Atmospheric turbulence is another pivotal environmental factor which degrades the FSO link performance. It is the random variations of the optical intensity and phase at the receiver input plane due to inhomogeneities in the refractive index profile of the channel as a results of varying temperature, height, and pressure. Many statistical channel models have been proposed and investigated in previously published theory estimating the impact of turbulence on the optical signal. In the proposed study, gamma–gamma channel model is used as it reliably estimates the channel characteristics for weak to strong turbulent regimes [10, 11].

2 Related Works

Various research studies on the application of FSO technology for information transmission in terrestrial links [12–21], space links [22–24], underwater links [25, 26], and indoor links [27, 28] have been reported. The work in [12] reports the effect of laser power and operating wavelength on the transmission efficiency of FSO link and illustrates that high input power results in a long-reach FSO transmission. Also, the results presented show that 1550 nm outperforms 850 nm wavelength. Jeeyaseelan et al. in [13, 14] reports the performance investigation of polarisation-shift keyed (PolSK), amplitude-shift keyed, and binary phase-shift keyed signals in a wavelength division multiplexed (WDM) FSO link with 10 Gbps transmission for last-mile users. The analysis of return-to-zero (RZ) pulse carved differential phase-shift keyed (DPSK) signals in an 80 Gbps FSO link with WDM transmission is reported by Badar et al. in [15]. The application of WDM demultiplexer enabled spectrum-slicing technique to attain 6.24 Gbps data transmission using non return-to-zero (NRZ) signals in a single-laser spectral-efficient FSO system is discussed by Prabhu et al. in [16]. The application of space division multiplexing (SDM) based on photonic crystal fibres for mode excitation to transmit independent 2.5 Gbps–5 GHz bit streams over Laguerre Gaussian modes along 2.5 km FSO reach has been reported in [17, 18]. The incorporation of SDM and optical code-division multiple access (OCDMA) based on spectral amplitude coding to transmit 10 independent 10 Gbps NRZ-signals along 8 km FSO reach to realize a 100 Gbps transmission network is evaluated by Sarangal et al. in [19]. The implementation of optical orthogonal-frequency division multiplexed (OFDM) signals in a high-capacity FSO system with mitigation to inter-carrier interference and inter-symbol interference is discussed in [20]. The design and analysis of polarisation division multiplexed (PDM) spectral-efficient FSO system with coherent receiver, transporting high-capacity OFDM signals over different environmental conditions is discussed in [21].

In the work reported by Sharma et al. [22], the application of SDM technique to transport two independent 10 Gbps-NRZ signals between two satellites using FSO transmission link has been proposed. A feasible 20 Gbps/1600 km data transportation in inter-satellite link with low bit error rate (BER) is discussed. Alopour et al. in [23] have proposed an ultra-high capacity inter-satellite transmission network based on FSO links incorporating 64-channel WDM architecture. Further, the authors have reported the performance investigation of duo-binary RZ, modified duo-binary RZ, and suppressed-carrier RZ modulation schemes in the link. Reliable 64 × 40 Gbps modified duo-binary RZ transmission is reported at 250 km inter-satellite link. The application of sub-carrier multiplexing to realize an inter-satellite FSO link is reported by Kumar et al. in [24]. Willner et al. in [25] have reported an underwater transmission link using orbital angular momentum multiplexed FSO transmission system. The authors reported the use of blue–green laser signals to transmit high-speed data in underwater turbulent channels and have investigated the link performance under various underwater effects. Wang et al. in [26] experimentally demonstrated a 520 Mbps-100 m underwater information transmission using NRZ-encoded FSO link employing a 520 nm green light emitting diode. Sharma et al. in [27] reported a detailed simulative analysis of a cost-efficient indoor FSO link with movable receiver capabilities. A high data rate indoor FSO link employing optical OFDM has been proposed and investigated by Perez et al. in [28]. Khan et al. in [29] reports a single-channel 4 m/100 Gbps indoor FSO link using quadrature phase-shift keyed (QPSK) signal.

With the growing demand for high-speed links, large channel bandwidth, and spectrum efficiency, advanced modulation formats are gaining significant importance in the research community. Spectrum efficient modulation techniques such as M-ary phase-shift keying (PSK) exploits multiple dimensions of the laser signal to transmit high-speed data [30, 31]. Advanced modulation formats which transmit k data bits/symbol have a spectral efficiency of k bits/s/Hz/polarisation as compared to 1 bit/s/Hz/polarisation for binary modulation formats. In the present work, PDM technique along with QPSK signals is proposed for realizing 160 Gbps terrestrial FSO transmission link incorporating coherent receiver and digital signal processing (DSP). The objective is to realize a spectral-efficient FSO transmission by incorporating hybrid PDM and QPSK signals, thus improving the transmission capacity. Also, coherent receiver and DSP module have been proposed to improve the receiver performance in the presence of free space losses and to enhance the maximum link reach. In Sect. 3, the link and channel modeling is discussed. The results are discussed in Sect. 4 and the conclusion in Sect. 5.

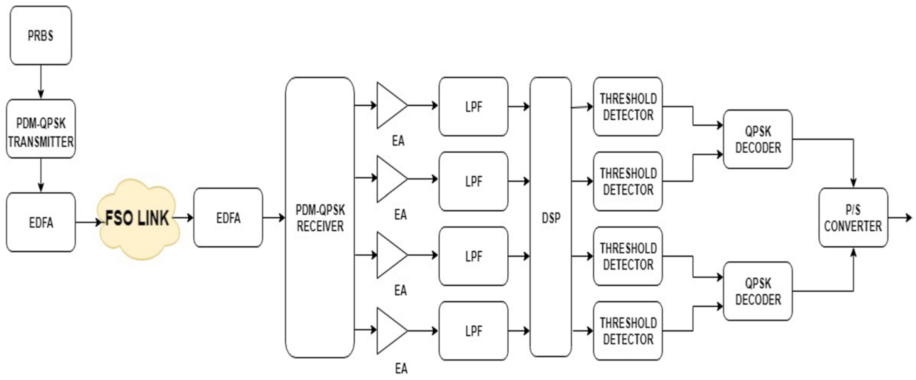

Fig. 1 PDM-QPSK-based FSO link

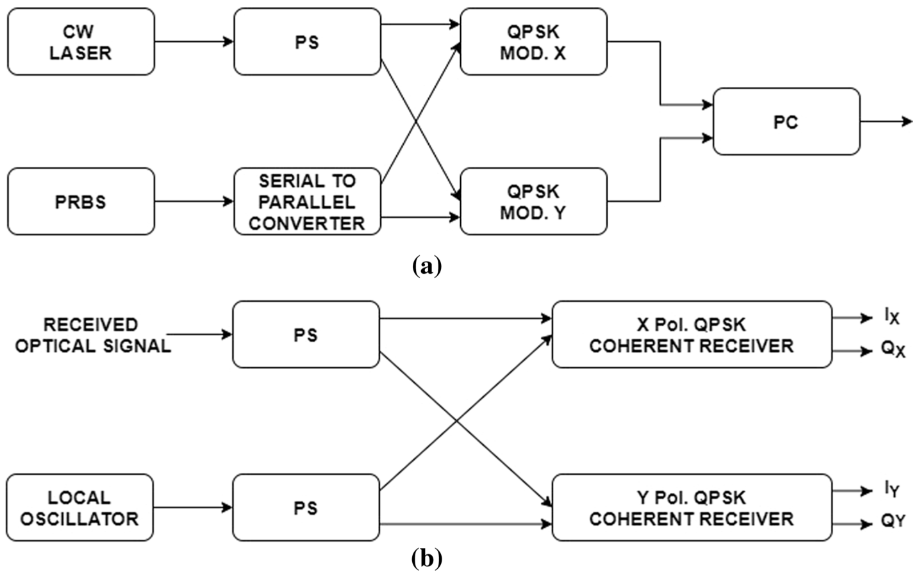

Fig. 2 PDM-QPSK **a** transmitter **b** receiver

3 Link Model and Parameters

The schematic model of 160 Gbps terrestrial FSO link using PDM and QPSK signals is reported in Fig. 1. We have used Optisystem for developing and evaluating the link performance.

160 Gbps binary data is generated in this work employing a pseudo-random bit sequence (PRBS) generator as shown in Fig. 2a. The binary data is then directed towards PDM-QPSK transmitter section. The 160 Gbps data is divided into two independent 80 Gbps parallel streams. A continuous wave (CW) laser with 0.1 MHz line width produces a 10 dBm beam and a polarisation splitter (PS) divides it into horizontal (X) and vertical (Y) orthogonal beams. Independent 80 Gbps data stream is modulated over each X

and Y polarised laser beam using a QPSK modulator and then combined by a polarisation combiner (PC). 160 Gbps PDM-QPSK information signal is generated at thsis point. An erbium-doped fibre amplifier (EDFA) having a gain of 20 dB and a noise figure of 4 dB amplifies the signal before transmitting it to free space channel. The FSO link is described as [32]:

$$P_{Received} = P_{Transmitted}\left(\frac{d_R^2}{\left(d_T + \theta Z\right)^2}\right)10^{-\sigma Z/10} \tag{1}$$

where d_R-receiving antenna diameter (10 cm), d_T-transmitting antenna diameter (10 cm), σ-attenuation coefficient for different external weather conditions (dB/km), θ-divergence angle (0.25 mrad), $P_{Transmitted}$-transmitted optical power (10 dBm), $P_{Received}$-received optical power (dBm), Z-range (km).

Various models such as log-normal model, negative exponential distribution, gamma–gamma model, double weibull distribution, etc. have been proposed in the previous literature to approximate the impact of turbulence on the phase and intensity of the optical beam carrying information. In this work, we have considered gamma–gamma model since it is capable of reliably estimating various channel conditions and is the most commonly used model [10, 11]. Mathematically, the probability density function $f(I)$ for gamma–gamma model is given as [33, 34]:

$$f(I) = \frac{2(\alpha\beta)^{(\alpha+\beta)/2}}{\Gamma(\alpha)\Gamma(\beta)} I^{[(\alpha+\beta)/2]-1} K_{\alpha-\beta}\left(2\sqrt{\alpha\beta I}\right) \tag{2}$$

where $\alpha and \beta$ represent the number of large scale eddies (Eq. 3) and number of small scale eddies (Eq. 4) respectively, the gamma function and Bessel function are denoted by Γ and $K(.)$ respectively.

$$\alpha = \left\{ \exp\left[\frac{0.49\sigma^2}{\left(1 + 1.1\sigma^{12/5}\right)^{7/6}}\right] - 1 \right\}^{-1} \tag{3}$$

$$\beta = \left\{ \exp\left[\frac{0.51\sigma^2}{\left(1 + 0.69\sigma^{12/5}\right)^{5/6}}\right] - 1 \right\}^{-1} \tag{4}$$

where σ^2 represents the Roytov variance and is given as:

$$\sigma^2 = 1.23 C_n^2 k^{\frac{7}{6}} Z^{\frac{11}{6}} \tag{5}$$

where k is the wave number and C_n^2 denotes the index refractive structure.

The received optical signal is first amplified using a flat-gain EDFA and then directed towards PDM-QPSK receiver as shown in Fig. 2b. The received optical information signal is divided into two orthogonal polarisation signals using a PS. Each distinct polarised information signal is demodulated using a local oscillator and a QPSK receiver. Further, a 20 dB gain electrical amplifier (EA) is used to amplify I and Q components of orthogonal polarised signals along with a low pass filter (LPF) with 40 GHz cut off frequency. Also, a DSP module as illustrated in Fig. 3 is used for compensating the channel effects. The DSP module performs different signal processing techniques including filtering, resampling,

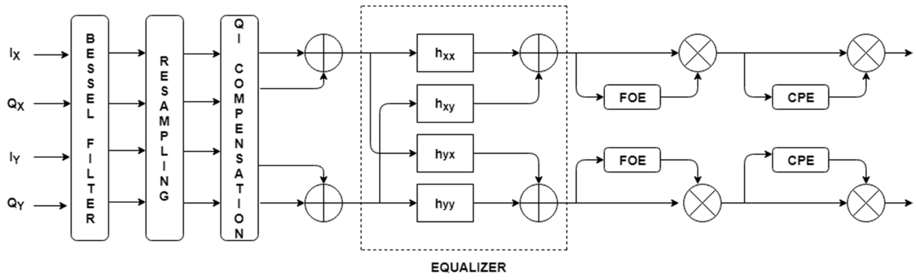

Fig. 3 Various algorithms associated with the proposed DSP module

quadrature imbalance (QI) compensation, equalization, frequency offset estimation (FOE), and carrier phase estimation (CPE). The authors in [35, 36] have reported the application of DSP techniques to compensate for channel effects and to implement optical links with improved performance.

4 Results

The BER transmission analysis of the link for clear weather is shown in Fig. 4 and it is observed that the BER of the system deteriorates with increasing range of transmission. Also, a degradation in constellation diagram can be observed with increasing range. For clear climate, transmission up to 98 km is achievable with log of BER less than −2.46 (i.e. threshold FEC [37]). For better clarity, we report the binary signal at the transmitter terminal and demodulated binary signal at the receiver terminal in Fig. 5. The similarity of the transmitted bits with the demodulated bits reveal feasible 98 km data

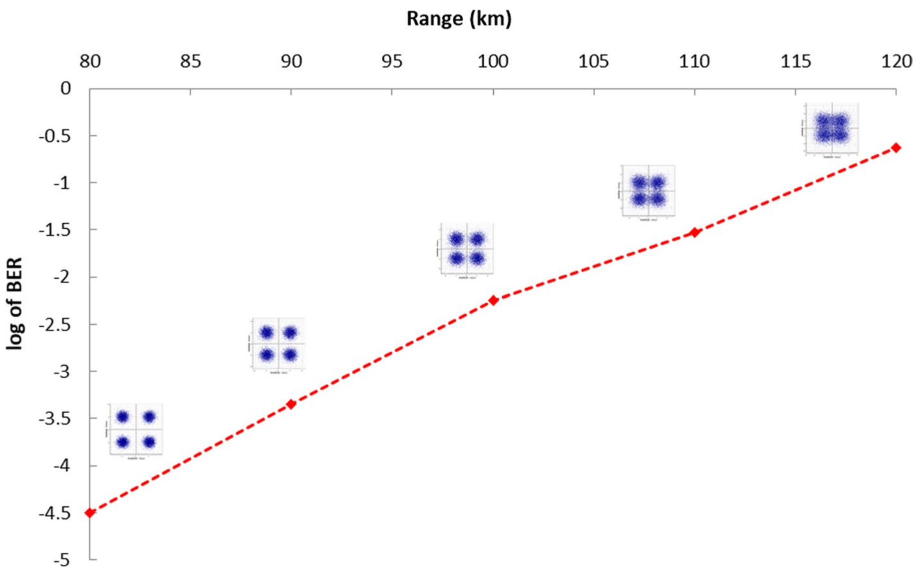

Fig. 4 Transmission performance for clear weather

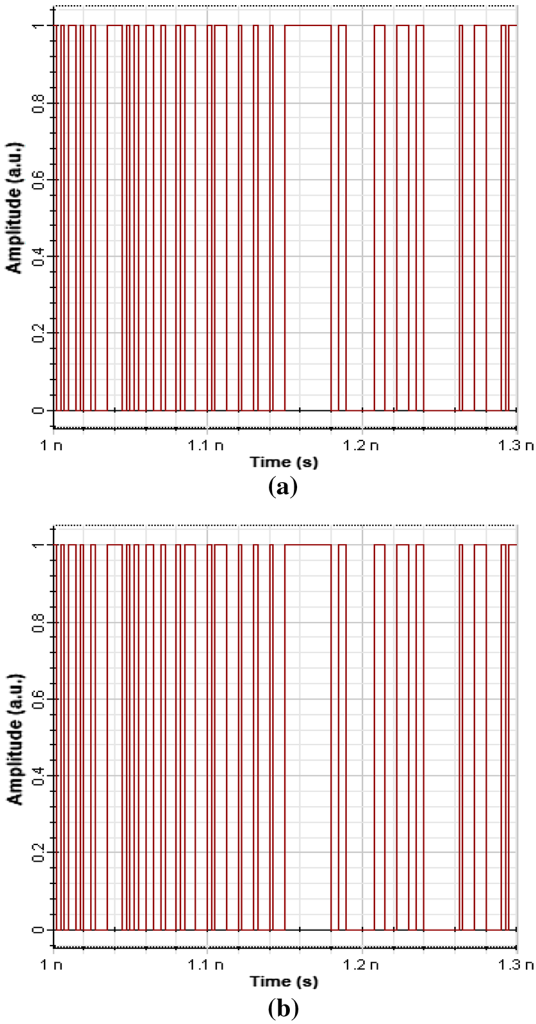

Fig. 5 Binary sequence of the **a** transmitted signal **b** recovered signal at the receiver terminal at 98 km

transportation. The constellation diagram of the QPSK signal at different steps in the proposed FSO link is shown in Fig. 6.

Figure 7a–c discusses the transmission performance of the link for increasing levels of hazy climate, rainfall climate, and foggy climate respectively. It can be noted that with increasing attenuation, the transmission performance in terms of BER degrades. For hazy climate, the attenuation coefficient is 1.537, 4.285, and 10.115 dB/km for low, mild, and heavy haze respectively [4]. The achieved range with acceptable BER is 18.4, 8.15, and 4 km for low, mild, and heavy haze respectively. For rainfall climate, the attenuation coefficient is 6.27, 9.64, and 19.28 dB/km for light, moderate, and heavy rain respectively [38]. The achieved range with acceptable BER is 6, 4.2 and 2.3 km for light, moderate, and heavy rain respectively. For foggy climate, the attenuation coefficient is 9, 16, and 22 dB/km for thin, thick, and heavy fog respectively [17, 18]. The achieved range with acceptable BER is 4.45, 2.75, and 2.1 km under thin, thick, and heavy fog respectively.

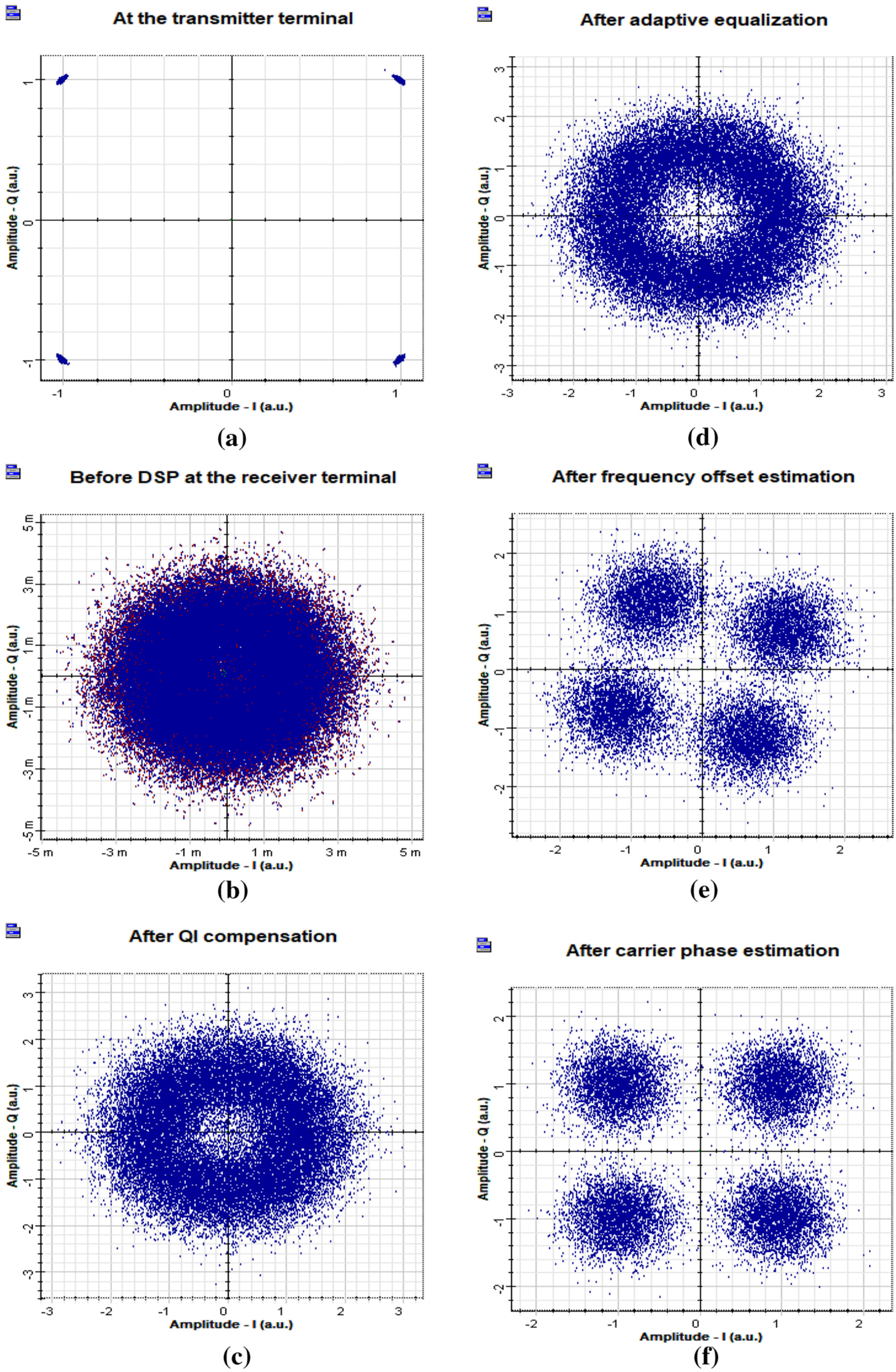

Fig. 6 Evaluation of constellation diagram

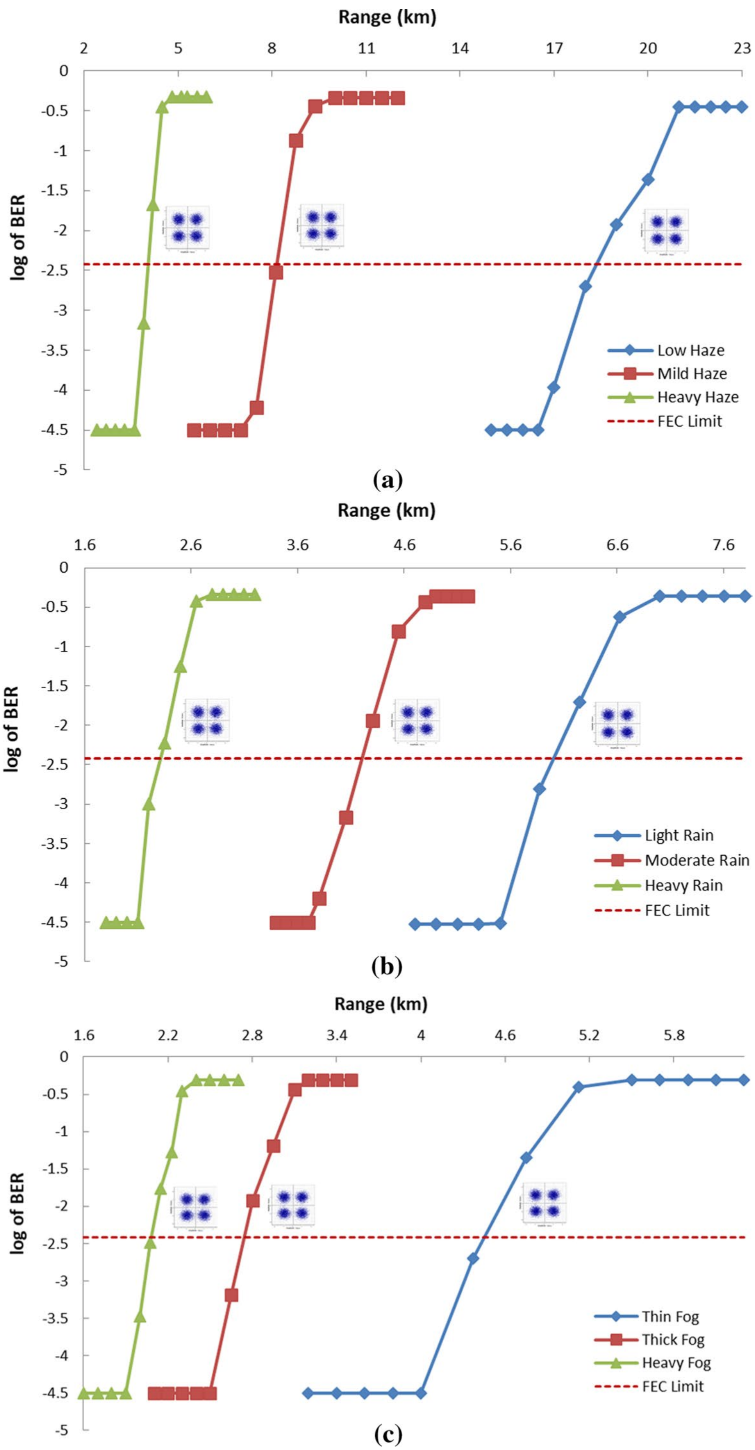

Fig. 7 Transmission performance for **a** hazy climate; **b** rainfall climate; **c** foggy climate

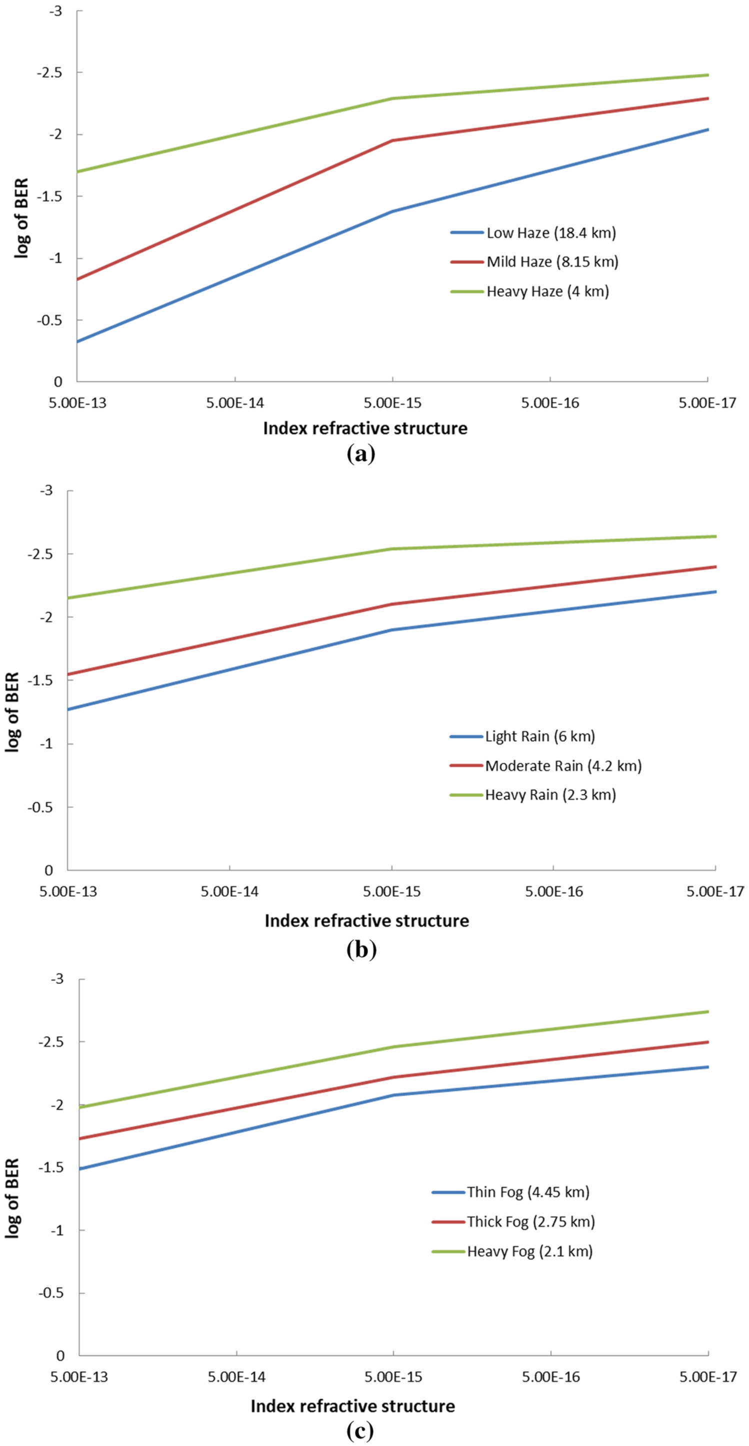

Fig. 8 Effect of increasing turbulence on BER transmission performance for **a** hazy climate; **b** rainfall climate; **c** foggy climate

Table 1 Performance comparison of the proposed link with previously reported works

Technique	Net bit rate	Climate conditions	Maximum FSO range (km)	Bit rate (Gbps) × range (km)
PolSK-WDM FSO transmission Ref [13, 14]	10 Gbps	Clear	275	2750
		Light rain	25.9	259
		Moderate rain	21.4	214
		Heavy rain	15.3	153
		Low fog	7.1	71
		Heavy fog	5.8	58
RZ-DPSK-WDM FSO transmission Ref [15]	80 Gbps	Clear	3	240
		Low haze	3	240
		Thin fog	1.2	96
		Thick fog	0.5	40
NRZ-WDM FSO transmission with spectrum slicing Ref [16]	6.24 Gbps	Clear	140	896
		Light haze	66	411.84
		Heavy haze	19	118.56
		Light rain	8.3	51.792
		Moderate rain	5.7	35.568
		Heavy rain	3.14	19.5936
		Light fog	3.8	23.712
		Heavy fog	2.5	15.6
NRZ-SDM FSO transmission Ref [18]	7.5 Gbps	Clear	2.5	18.75
		Thin fog	0.6	4.5
		Thick fog	0.4	3
		Heavy fog	0.2	1.5

Table 1 (continued)

Technique	Net bit rate	Climate conditions	Maximum FSO range (km)	Bit rate (Gbps) × range (km)
NRZ-SDM-OCDMA FSO transmission Ref [19]	100 Gbps	Clear	8	800
		thin fog	1.5	150
		Thick fog	1.25	125
		Heavy fog	1	100
OFDM FSO transmission Ref [20]	10 Gbps	Clear	185	1850
		Heavy fog	2.5	25
PDM-OFDM FSO transmission Ref [21]	4 Gbps	Clear	5	20
		Fog	2	8
PDM-QPSK FSO transmission with coherent receiver and DSP	160 Gbps	Clear	98	15,680
		Low haze	18.4	2944
		Mild haze	8.15	1304
		Heavy haze	4	640
		Light rain	6	960
		Moderate rain	4.2	672
		Heavy rain	2.3	368
		Thin fog	4.45	712
		Thick fog	2.75	440
		Heavy fog	2.1	336

Further, the effect of increasing weather turbulence on the BER transmission performance is numerically analysed. Figure 8a-c demonstrates the link performance for refractive index structure parameter increasing from weak turbulent weather ($C_n^2 = 5 \times 10^{-17} m^{-2/3}$) to strong turbulent weather ($C_n^2 = 5 \times 10^{-13} m^{-2/3}$) over different climate conditions at different range and demonstrates that the BER increases as the atmospheric turbulence increases from weak to strong turbulence. Also, it can be observed that the effect of atmospheric turbulence on link performance is comparatively less at lower link range than at higher link range. This is because at lower link range, the beam size is comparatively small which results in lower phase distortion.

Table 1 illustrates the performance comparison of the proposed link with previously reported works in the literature. The comparison shows that the proposed link demonstrates higher bit rate, longer achievable FSO range, and a superior figure of merit (bit rate × range) for all climate conditions. Also, it can be seen that the works reported in [13–21] deploy multiple channels to transmit high-speed data over free space medium whereas the proposed FSO link reliably transmits 160 Gbps over a single-channel, thus improving the spectral efficiency of the link. The higher maximum transmission range under all weather conditions with enhanced bit rate and spectral efficiency of the proposed FSO link can be attributed to the deployment of PDM technique with QPSK signals along with coherent receiver and DSP.

5 Conclusion

A spectral-efficient high-speed PDM-QPSK-based terrestrial FSO transmission link has been proposed. Coherent receiver for link reach enhancement is incorporated. Digital signal processing algorithms are employed for compensating free space losses and for carrier phase estimation. The numerical results demonstrate a significant improvement in the optical signal performance under the impact of channel effects using the proposed DSP module. The link is analysed under different climate conditions and feasible 160 Gbps QPSK signal transmission is reported. It can be concluded from the numerical results that an increase in atmospheric attenuation from clear to foggy climate reduces the achievable range from 98 to 2.1 km. The numerical results also demonstrate that increasing atmospheric turbulence degrades the BER. The transmission performance of the link is comparatively analysed with recent reported literature and a better performance is demonstrated. The present study provides a good reference for designing spectral-efficient high-capacity long-haul wireless information transmission links under dynamic weather conditions.

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Code Availability This work was performed using Optisystem tool.

Compliance with Ethical Standards

Conflict of interest None.

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