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A spectral-efficient 1 Tbps terrestrial free-space optics link based on super-channel transmission

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Abstract
We propose a novel 1 Tbps super-channel terrestrial free-space optics (FSO) link using nine distinct Nyquist-wavelength division multiplexed (WDM) sub-carriers with 14 Gbaud symbol rate. Nine independent 112 Gbps polarisation multiplexed-16-quadrature amplitude modulated data streams are transported over each sub-carrier. Further, the sub-carriers are Nyquist-spaced using pre-filter with 15 GHz bandwidth, which is approximately equal to symbol rate. Through numerical simulations, we investigate the transmission range performance for varying attenuation levels due to external climate conditions. Bit-error rate (BER), optical signal to noise ratio (OSNR), and error vector magnitude (EVM %) are used as the evaluation metrics. The proposed Nyquist-WDM FSO transmission link demonstrates 7.46 bits/sec/Hz 1 Tbps information transmission. The proposed link exhibits large-bandwidth capacity to efficiently carry high-speed data for next generation long-haul optical wireless networks.

Keywords FSO · Nyquist-WDM · PM-16-QAM · Super-channel

1 Introduction

In recent years, the augmentation of large channel bandwidth demanding services such as ultra-high definition videos, fast-internet, cloud computing, video-networking, internet gaming, live streaming, and mobile conferencing etc. have resulted in radio frequency (RF) spectrum congestion which is sparsely available and very expensive to acquire. This has challenged the existing RF based wireless transmission system. Free-space optics (FSO)

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is an information transmission technology in which free-space is used as propagation medium and optical signals are used as information carrier, which do not require any spectrum licensing and are underutilized (Singh and Kumar 2013). FSO is similar to optical fiber communication (OFC) links since both utilize optical signals to transport data but, they differ in the medium of transmission i.e. free-space in FSO links and fiber cables in OFC links. Due to this, FSO links can be deployed in areas where deployment of optical fiber cables is impossible or very expensive and thus solves the problem of last-mile access in remote areas (Khalighi and Uysal 2014). Other merits include high-speed information transmission links, high-bandwidth, secure transmission, narrow beam size, quick installation procedure, low deployment cost, small mass equipment, low power needs, immunity to RF and electromagnetic interference, and dense spatial reuse capabilities etc. (Nykolak et al. 1999; Singh and Malhotra 2019). FSO links have been deployed for terrestrial links, inter-vehicular links, building-to-building interconnectivity, inter-satellite communication links, deep space links, storage area networks, fiber backhaul, military access, and for last-mile access etc. (Mahdy and Deogun 2004). The main reason of signal deterioration in FSO links is the signal attenuation as a result of scattering and absorption phenomenon due to different sized particles in the air under different climate conditions. This may lead to random variations of signal power at the receiver front and result in total link failure (Chandra et al. 2017).

Research groups recently have reported the deployment of wavelength division multiplexed (WDM) systems with different modulation formats for increasing the information capacity of FSO links. Zhao et al. in (2018) report an experimental demonstration of 200 Gbps FSO links with eight channels WDM architecture for 5G wireless networks. The results presented report a successful transportation of 8 $\lambda\times$ 25 Gbps PAM-4 signals over 50 m link distance between two buildings with clear eye diagrams and good bit-error rate (BER). A bidirectional WDM-FSO architecture to transmit 4 $\lambda\times$ 10 Gbps on–off keying (OOK) data over 25 km single mode fiber and 6 m FSO link has been experimentally demonstrated by Ye et al. in (2019). N. Badar et al. in (Badar et al. (2018)) report the modeling of an eight channel WDM-FSO link incorporating return-to-zero differential phase shift keying. The results of the simulative study report a successful transportation of 8 $\lambda\times$ 10 Gbps information up to 3 km link distance under the combined effect of dynamic environmental conditions and atmospheric turbulence with faithful BER performance. The improved performance of 25 Gbaud four channels WDM FSO architecture by using 2-D photo detector array to achieve 100 Gbps transmission has been experimentally reported by Umezawa et al. in (2019). The work by Tsai et al. in (2016) reports a 320 Gbps dense WDM (DWDM) based FSO link using afocal scheme for light based Wi-Fi applications. The results presented report that 8 $\lambda\times$ 40 Gbps transmission is successfully achieved over 50 m link distance.

The exponentially growing demand for higher channel bandwidth has driven optical communication links to attain higher spectral efficiency (SE). Researchers have reported the use of higher-order modulation formats such as polarisation multiplexed-1024-level-quadrature amplitude modulation (PM-1024-QAM), which are capable of transmitting k -bits/sec/Hz/polarisation in contrast to standard binary schemes transmitting only 1-bit of information per sec/Hz/polarisation to enhance the SE of optical links (Silva et al. 2018). Although, such optical links with higher order modulation formats offer good information transmission capabilities, but the use of ultra-fast digital to analog converters, poor receiver sensitivity, and hardware bandwidth issue may lead to some serious challenges (Chandrasekhar and Liu 2013). Super-channel transmission is an emerging technology which is capable of providing multi-Tbps transmission capabilities with higher SE as compared to conventional WDM links and is envisioned to play crucial role in future optical networks (Bosco et al. 2011). In Nyquist-WDM super-channel transmission systems, the channel spacing is kept close to baud rate so as to guarantee orthogonality between distinct wavelength channels and to offer immunity to inter-carrier interference and inter-symbol interference (Chien et al. 2012). Nyquist-WDM maximizes the SE in optical links by using a pre-filter after each transmitted sub-carrier to realize frequency spacing between adjacent channels nearly equal to transmission system's baud rate (Li et al. 2012). The work in (Rosa, et al. 2014) experimentally demonstrates a Nyquist-WDM PM-quadrature phase shift keying (QPSK) transmission system with SE of 3.73 bits/sec/Hz to transmit 9 channel 10.9 Gbaud information over 320 km unrepeated single mode fiber link. The authors in (Liu et al. 2012) report a 1.5 Tbps-5600 km super-channel transmission over ultra-large-area-fiber incorporating 30 Gbaud orthogonal frequency division multiplexed 16-QAM signals to attain 5.75 bits/se/Hz of SE. A single laser 32.5 Tbps Nyquist-WDM super-channel transmission over 227 km single mode fiber link to attain 6.4 bits/sec/Hz of SE has been reported in (Hillerkuss, et al. 2012). The authors in (Silva et al. 2013) report a 1.15 Tbps no-guard-interval coherent detection OFDM PM-QPSK based super-channel transmission over 4250 km pure silica core fiber with the deployment of erbium doped fiber amplifier. The application of optical frequency combs for super-channel generation to transmit 1.26 Tbps information over 9 distinct 16-QAM Nyquist-WDM sub-carriers over 300 km single mode fiber to attain 7.8 bits/sec/Hz SE has been demonstrated in (Pfeifle et al. 2015). Although, researchers have explored the Nyquist-WDM super-channel technique in OFC links, its application in FSO links is an unexploited area where the most important factor determining the link performance is atmospheric attenuation.

This work proposes a novel 9 × 112 Gbps Nyquist-WDM super-channel transmission with 15 GHz channel spacing over free-space channel. The main motive of this research article is to demonstrate a highly spectral-efficient Nyquist-WDM super-channel FSO information transmission with PM-16-QAM signals and to study the impact of atmospheric attenuation of the maximum supported link reach. The paper is organized as follows: the proposed PM-16-QAM Nyquist-WDM super-channel FSO system design with simulation parameters are discussed in Sect. 2. The results of the transmission performance of the proposed FSO link are discussed is Sect. 3. The final conclusion is drawn in Sect. 4.

2 Proposed FSO link design

Figure 1 elucidates the proposed 9 × 112 Gbps PM-16-QAM Nyquist-WDM super-channel FSO link design, modeled and simulated in Optisystem software.

In the proposed work, 9 distinct PM-16-QAM 112 Gbps subcarriers with 14 Gbaud rate are combined to generate a 1 Tbps superchannel. The range of optical subcarrier frequencies are from 194.070 THz to 194.190 THz with channel spacing of 15 GHz. A Gaussian band pass filter (BPF) with 15 GHz frequency is used for Nyquist pre-filtering of each sub-carrier which is approximately equal to the symbol rate. These distinct subcarriers are then multiplexed using a WDM multiplexer (MUX) followed by an amplifier before transmitting into free-space channel. In this work, we have added external noise to make the system more practical. In FSO links, the received power is given as (Kolev et al. 2012):

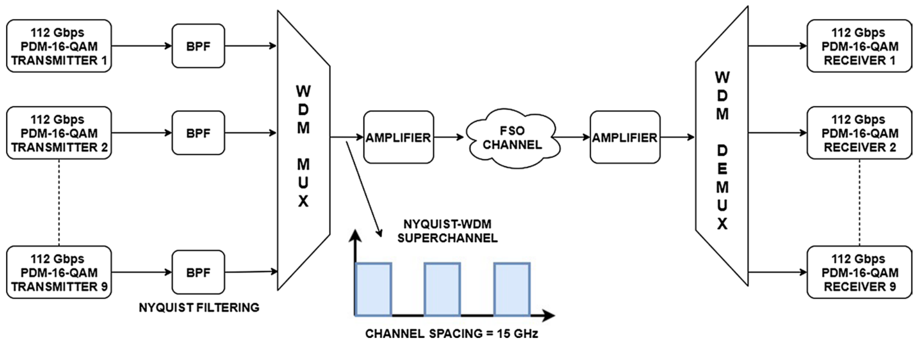

Fig. 1 Design of the 1 Tbps FSO link

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

where,

$P_{Received}$ – optical power collected at the receiver.

$P_{Transmitted}$– optical power transmitted (10 dBm).

d_R– size of the receiving antenna (5 cm).

d_T– size of the transmitting antenna (10 cm).

θ– size of the optical beam (0.25 mrad).

Z– transmission range.

σ– attenuation constant depending on the external weather.

At the input of the receiver, the optical beam is amplified by an amplifier having a gain of 20 dB and a noise figure of 4 dB. A WDM de-multiplexer (DEMUX) to separate distinct subcarriers is used. The information from each subcarrier is retrieved using coherent detection followed by a digital signal processing (DSP) unit, which is used for improving the signal quality in the presence of channel effects (Lu et al. 2017). The link is analyzed using BER and error vector magnitude (EVM) of the received signal under varying climate conditions. The link parameters while performing the simulation are considered as per real-life FSO link scenario as reported by the authors in (Kakati and Arya 2019; Karaki et al. 2013; Sarangal et al. 2017; Malik and Singh 2015). Figure 2a, b, and c exhibits the PM-16-QAM transmitter unit, internal schematic of 16-QAM modulator, and PM-16-QAM receiver unit respectively. Figure 3 exhibits the DSP unit schematic. The DSP unit performs various key algorithms to improve the received signal quality including filtering, the compensation imbalances between the quadrature and phase components of the received signal (QI compensation), blind adaptive equalization, frequency offset estimation (FOE), and carrier phase estimation (CPE). A detailed discussion on PM-16-QAM transmitter unit, receiver unit, and DSP unit has been reported in (Kakati and Arya 2019).

3 Results

This section discusses the simulative investigation of the proposed 1 Tbps PM-16-QAM Nyquist-WDM super-channel FSO link performance. Figure 4a reports the optical spectrum of the transmitted 9 × 112 Gbps super-channel after WDM MUX. For the sake of

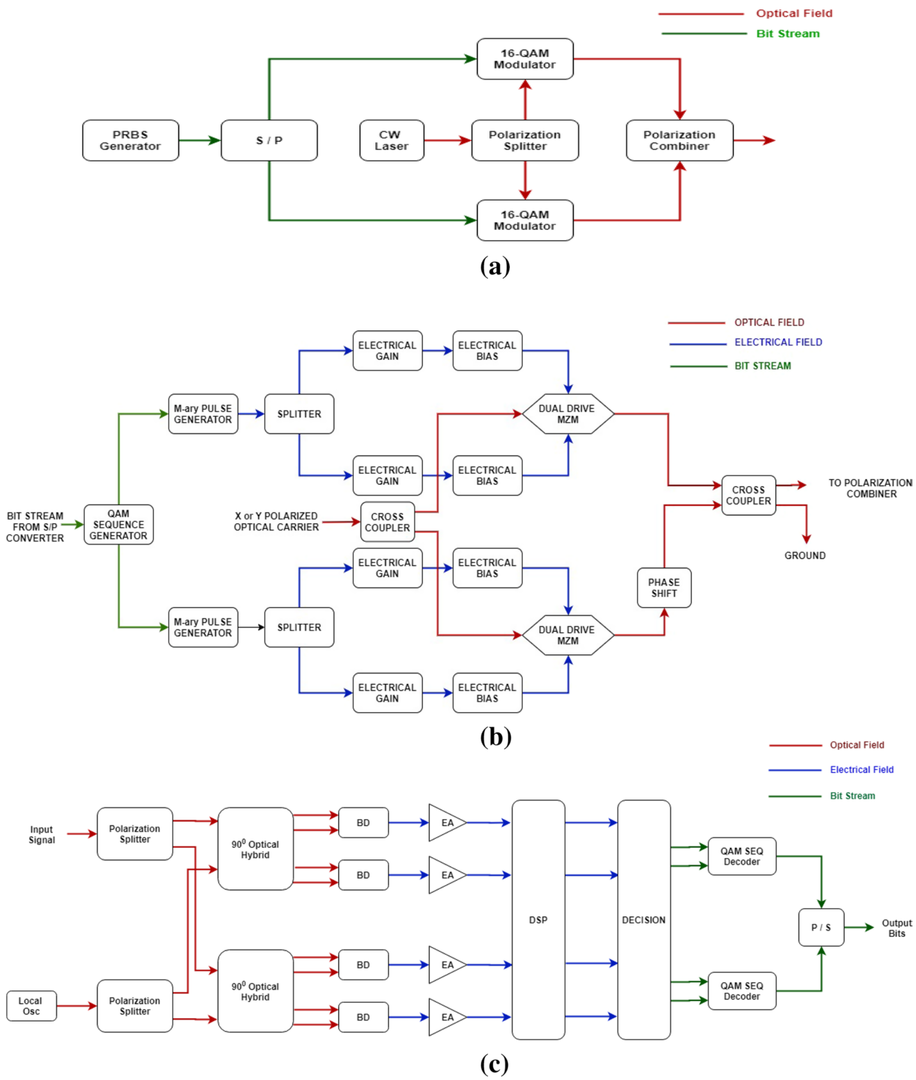

Fig. 2 Schematic of **a** PM-16-QAM transmitter **b** internal 16-QAM modulator **c** PM-16-QAM receiver

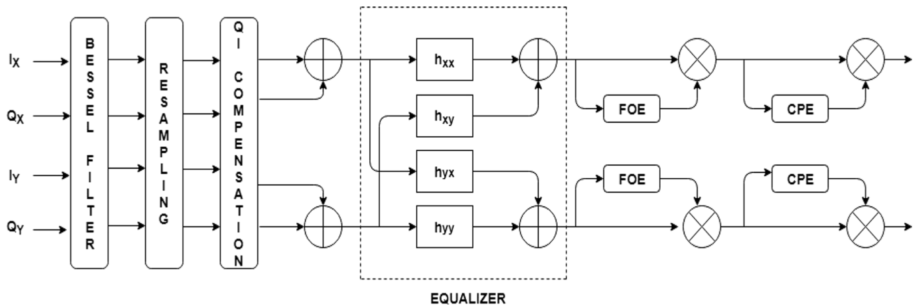

Fig. 3 Internal schematic of DSP unit

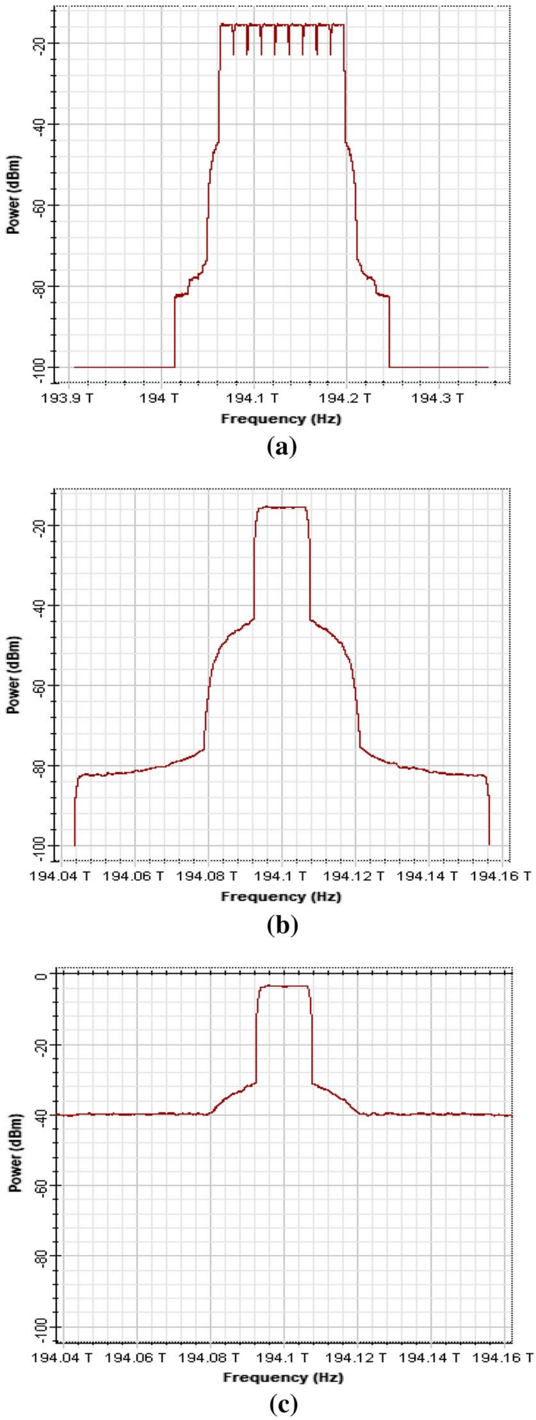

Fig. 4 Optical spectrum of **a** 9 × 112 PM-16-QAM Nyquist-WDM super-channel **b** subcarrier with 194.1 THz center frequency **d** subcarrier with 194.1 THz center frequency after addition of external noise

convenience, we only report the performance of subcarrier with center frequency 194.1 THz as information from other subcarriers can be retrieved using the same process. Figure 4b and c reports the optical spectrum of 194.1 THz subcarrier before and after addition of external noise respectively.

Figure 5a and b report the log of BER and EVM% with increasing optical signal to noise ratio (OSNR) respectively at 10 km transmission under the impact of clear climate with 0.14 dB/km attenuation constant. The results demonstrate that with the increase in OSNR from 10 to 24 dB, the BER performance considerably improves. The log of BER reduces from −0.46 to −3.36 and EVM reduces from 29.47% to 11.67% as the OSNR increases

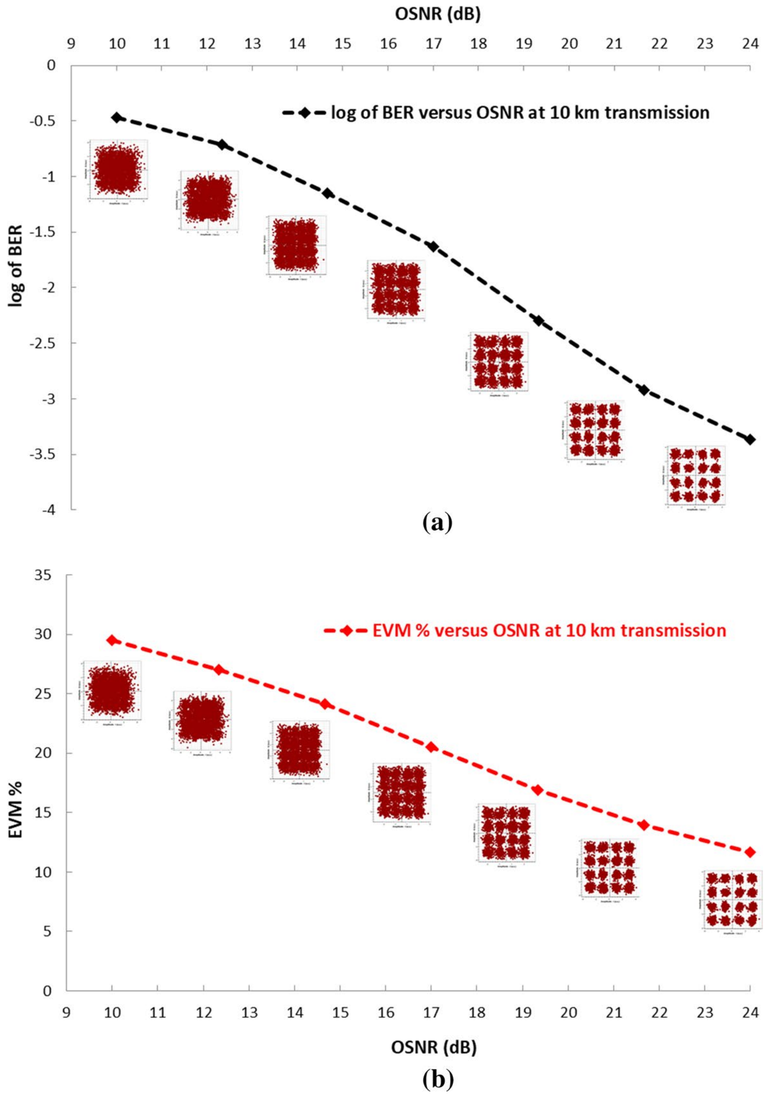

Fig. 5 Computed **a** log of BER **b** EVM % versus OSNR for 10 km transmission over clear weather

from 10 to 24 dB. Also, it can be observed that with the increase in OSNR, the constellation diagram gets clearer with distinct symbols, thus making it easier for the demodulator section to retrieve the message bits faithfully. The OSNR requirement to achieve an acceptable log of BER (-2.42 i.e. FEC Limit (Karaki et al. 2013)) using the proposed link is 20.6 dB. The results presented demonstrate a successful 1 Tbps-10 km transmission under clear climate with a SE of 7.46 bits/sec/Hz. Figure 6 reports the improvement in the constellation diagram and hence overall quality of received signal by employing various steps in DSP unit.

Figure 7a–c reports the transmission performance of the link under different haze, rain, and fog weather conditions respectively. The attenuation constants for different climate conditions have been adopted from the works reported in (Sarangal et al. 2017; Malik and Singh 2015). The results show that with increasing transmission range, the quality of the received signal in terms of BER degrades. The attenuation coefficient under haze and fog conditions is dependent on the wavelength of the signal, the visibility data and the size distribution of the particles whereas the attenuation coefficient under rain weather conditions is dependent on the rainfall rate (Malik and Singh 2015). From Fig. 7a, it can be seen that the maximum transmission range with acceptable BER under low haze having attenuation constant of 1.537 dB/km is 6.5 km; under mild haze having attenuation constant of 4.285 dB/km is 3.5 km; and under heavy haze having attenuation constant of 10.115 dB/km is 1.9 km. Similarly, from Fig. 7b, it can be seen that the maximum transmission range under light rain having attenuation constant of 6.27 dB/km is 2600 m; under moderate rain having attenuation constant of 9.64 dB/km is 1950 m; and under heavy rain having attenuation constant of 19.28 dB/km is 1200 m. From Fig. 7c, it can be observed that maximum transmission range under thin fog having attenuation constant of 9 dB/km is 2000 m; under thick fog having attenuation constant of 16 dB/km is 1370 m; and under heavy fog having attenuation constant of 22 dB/km is 1050 m.

4 Conclusion

In this work, a novel 9 × 112 Gbps PM-16-QAM Nyquist-WDM super-channel based FSO transmission link is proposed. Through numerical simulations, we demonstrate a successful 1 Tbps super-channel transmission over link range varying from 1.05 km to 10 km depending on the weather conditions. The proposed link demonstrates a SE of 7.46 bits/sec/Hz. The proposed link can be used for next generation spectral-efficient high-speed optical networks for the development of 5G technology. In future works, the flexibility and elasticity of the proposed link can be improved by incorporating mixed Nyquist-WDM super-channel. Also, the link performance under adverse channel conditions can further be enhanced using adaptive optics along with multi-input multi-output transmission of data signals for maximum reliability.

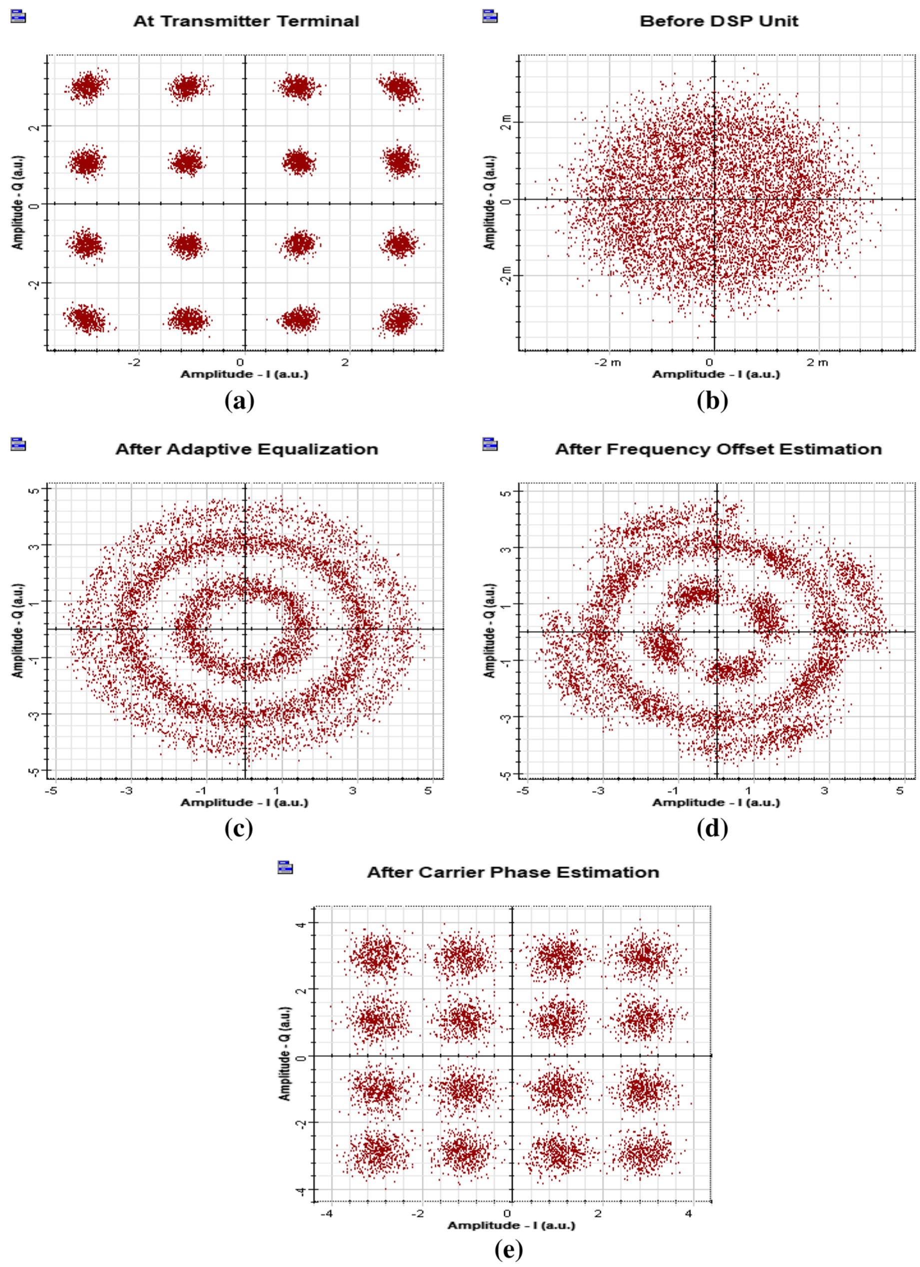

Fig. 6 Improvement in the constellation diagram by employing various steps in DSP unit

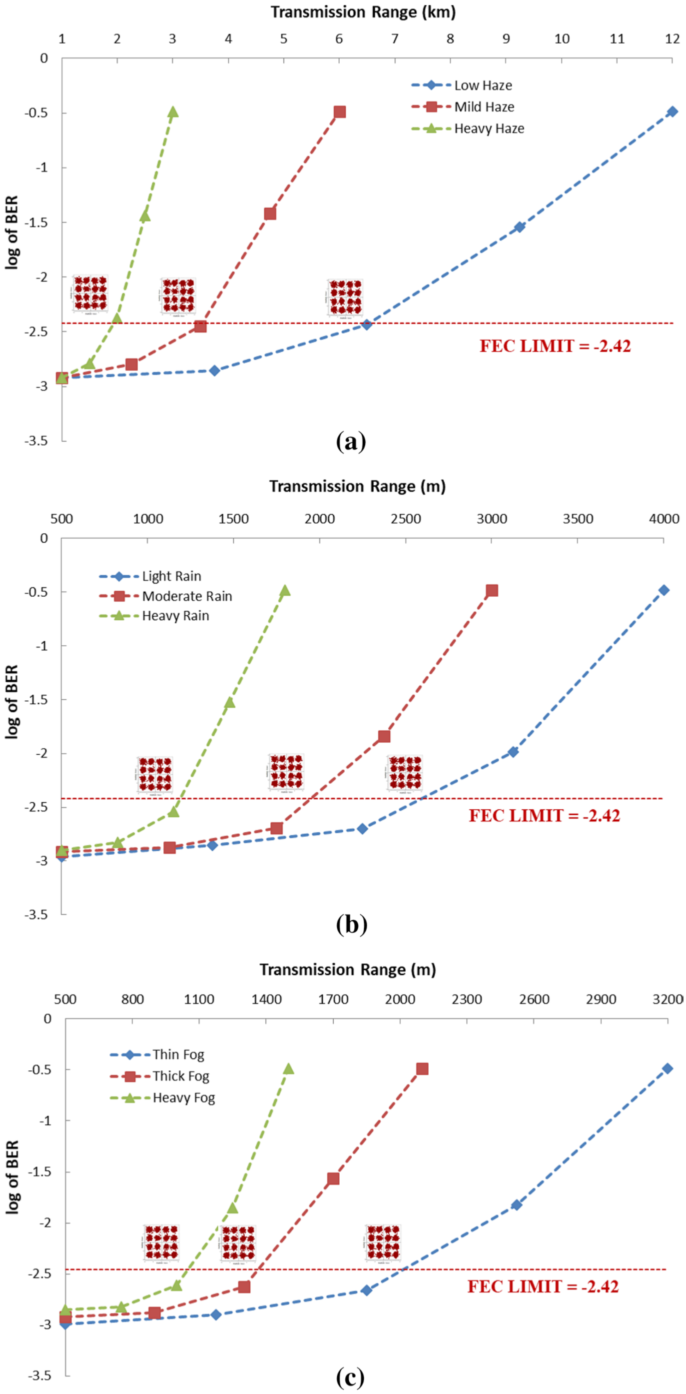

Fig. 7 Transmission performance under **a** Haze **b** Rain **c** Fog conditions

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Code availability This work was performed using Optisystem simulation tool.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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