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ORIGINAL PAPER

Performance investigation of a 3.84 Tb/s WDM-based FSO transmission system incorporating 3-D orthogonal modulation scheme

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Abstract
The present work discusses the development and simulative investigation of a high-capacity wavelength division multiplexed free space optics (FSO) transmission system. A novel 3-D orthogonal modulation scheme is proposed, which simultaneously capitalizes on different signal properties of an optical laser beam, i.e., intensity, phase, and state of polarization to transmit three independent 40 Gb/s data streams on a single optical carrier signal, realizing a net 120 Gb/s transmission rate per wavelength channel. 32 such independent wavelength channels are multiplexed in the proposed FSO system and its performance is numerically investigated over different climate conditions with respect to range, Quality factor, bit error rate, and eye diagrams of the information signal using Optisystem simulation software. Through numerical simulations, we report faithful 3.84 Tb/s transmission over free space channel with maximum link range varying from 1.6 to 40 km depending on the external climate conditions.

Keywords Free space optics · Wavelength division multiplexing · Orthogonal modulation scheme · Atmospheric attenuation · Bit-error rate

1 Introduction

With the exponential growth in the demand for high-speed links and channel bandwidth, free space optics (FSO) has emerged as a viable technology to manage the issue of spectrum congestion in the traditional wireless networks since it capitalizes on the underexploited and unlicensed portion of the electromagnetic spectrum. Miscellaneous FSO link merits include high-speed links, secure information transmission, low-security upgrades, large channel bandwidth, tolerance to radio frequency (RF) and electromagnetic waves interference, quick and easy deployment, low-cost, lightweight equipment, last-mile access, and low beam divergence [1–3]. But the quality of the received signal in FSO links is degraded due to certain factors including channel fading effects, signal absorption, scattering, scintillation, atmospheric turbulence, pointing errors, beam wandering, etc. [4]. But the most crucial parameter which limits the FSO link reach is the atmospheric attenuation for varying climate affairs which may range from 0.14 dB/km in the case of clear weather to 300 dB/km in the case of dense fog conditions. In tropical countries like India, rain weather is the most important atmospheric condition which determines the FSO link reach [5].

The current research in FSO systems is focused on maximizing the data transmission capability and bandwidth efficiency of the links. Different techniques have been reported for the development of high-capacity FSO systems. The authors in [6–12] propose mode division multiplexing (MDM) technique in FSO system, where multiple information signals are transmitted by capitalizing on the spatial laser modes to enhance the system capacity and further studied the impact of different climate affairs on the link performance. Further, the integration of the orthogonal frequency division multiplexing (OFDM) technique to transmit high-speed data over FSO links while mitigating inter-symbol interference and inter-carrier interference is discussed in [13–15]. The authors in [16] explore the incorporation of hybrid optical code division multiple access (OCDMA) and polarization division multiplexing (PDM) techniques to

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increase the FSO system transmission capacity. In another work [17], a PDM-coherent detection-OFDM-based FSO system is modeled and investigated for varying atmospheric turbulence conditions. The authors in [18] explore a spectral amplitude coded (SAC)-OCDMA-based FSO system with double diagonal weight (DDW) code for improved performance under adverse climate conditions. The works in [19, 20] report the incorporation of wavelength division multiplexing (WDM) in FSO system to transmit multiple information signals simultaneously through the same channel. Modulation scheme plays a pivotal role in influencing the transmission performance of a communication system. To meet the ever-rising demand for high data transmission rates, it becomes imperative to propose modulation schemes that increase the information capacity per channel and enhance the bandwidth efficiency of the system. Although different modulation schemes have been reported to maximize the data-carrying efficacy of communication links [21], orthogonal modulation scheme provides better results since it not only provides enhanced speed per channel but also increases the number of users [22]. In previous literature, different orthogonal modulation schemes such as dark-return to zero/ frequency shift keying/differential phase shift keying (DRZ/FSK/DPSK), (DPSK/DRZ), DPSK/non-return to zero (DPSK/NRZ), DPSK/code shift keying (DPSK/CSK), amplitude shift keying/FSK (ASK/FSK), and ASK/DPSK have been reported to improve the spectral efficiency and transmission speed of optical fiber links [23–27].

In this paper, a 3-D orthogonal modulation scheme has been proposed combining NRZ-differential quadrature phase shift keying (DQPSK)-polarization shift keying (PolSK) to transmit 120 Gb/s information over a single wavelength channel in a 32 channel WDM-based FSO system. The main motivation behind this work is to realize a high-capacity bandwidth-efficient FSO system by using a spectral-efficient orthogonal modulation scheme. After the introduction, system design is presented in Sect. 2, followed by the simulation results in Sect. 3, and the conclusions in Sect. 4.

2 Proposed WDM-FSO system design

The schematic of the 32-channel WDM-FSO system incorporating orthogonal modulation scheme is illustrated in Fig. 1a. 32 independent wavelength channels ranging from 193.1 to 196.2 THz with 0.1 THz channel spacing are multiplexed using a WDM multiplexer (MUX) and transmitted simultaneously over free space medium under different climate conditions. The system is modeled and numerically investigated using Optisystem simulation software. At the receiver end, the optical signal is amplified using a flat-gain amplifier with 20 dB gain and 4 dB noise figure. Each wavelength channel is separated by employing a WDM demultiplexer (DEMUX) and then directed toward a distinct receiver section.

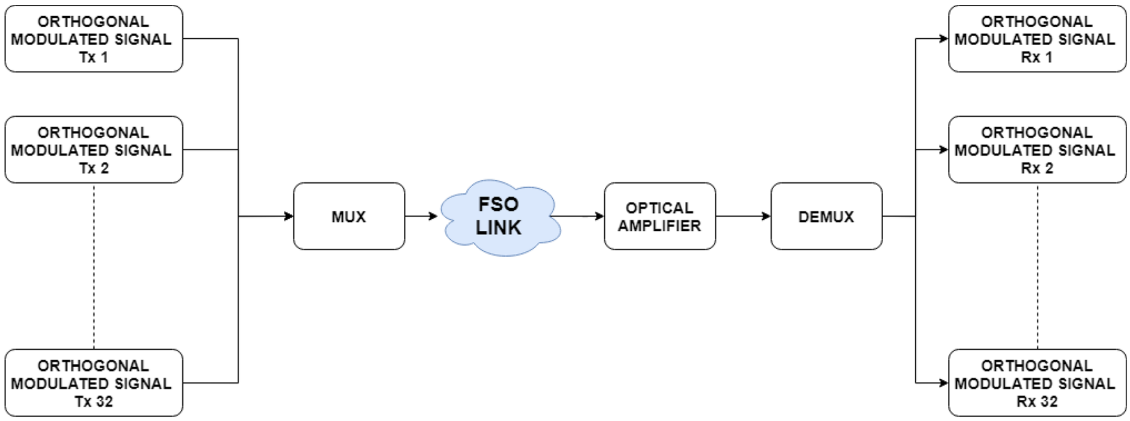
The link equation can be expressed as [28]:

$$S_{\text{Received}} = S_{\text{Transmitted}} \left(\frac{d_R^2}{\left(d_T + \theta R\right)^2} \right) 10^{-\sigma R/10} \quad (1)$$

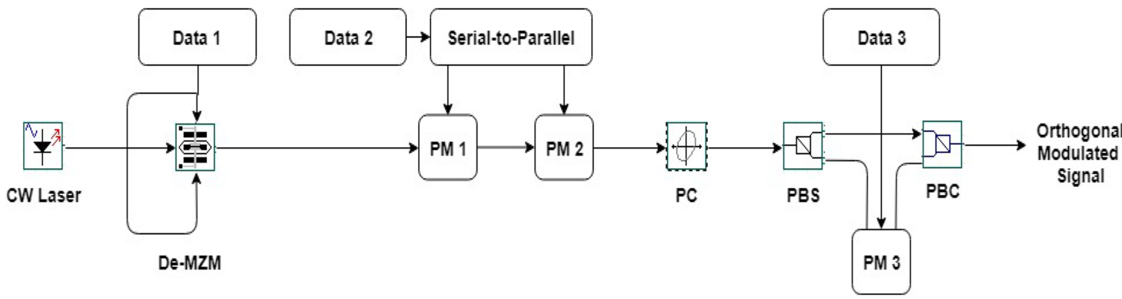
where S_{Received} is the optical power at the receiver aperture; $S_{\text{Transmitted}}$ is the input power of laser beam (0 dBm); R is the link range; θ is the angle of beam divergence (0.25 mrad); d_T is the transmitter antenna aperture diameter (10 cm); d_R is the receiver antenna aperture diameter (10 cm); and σ is the attenuation constant.

In each orthogonal modulation transmitter section, three independent 40 Gb/s data signals are modulated over intensity, phase, and state of polarization of a single laser beam to generate a 120 Gb/s orthogonal modulated signal as illustrated in Fig. 1b. The laser beam from a continuous wave (CW) laser is directed toward a dual-electrode Mach Zehnder Modulator (De-MZM) with 30 dB extinction ratio which modulates 40 Gb/s Data 1 to generate an NRZ-encoded signal (Fig. 2a). At the output of De-MZM, we have an NRZ-encoded signal which is directed toward the input of phase modulator 1 (PM 1). 40 Gb/s Data 2 is divided into two parallel streams using a serial-to-parallel converter, and each stream is directed toward a distinct phase modulator (PM 1 and PM 2). PM 1 and PM 2 modulate the phase of the optical carrier to generate DQPSK-encoded signal according to Data 2. PM 1 modulates the phase of the optical carrier signal to 180° and PM 2 adds a 90° phase shift to it. At the output of PM 2, we have an NRZ-DQPSK-encoded signal (Fig. 2b). This signal is linear polarized at 45° using a polarization controller (PC) for PolSK modulation. A third phase modulator (PM 3) placed between the horizontal ports of the polarization beam splitter (PBS) and polarization beam combiner (PBC) modulates 40 Gb/s Data 3 to generate a PolSK-encoded signal. At the output of PBC, we have a 120 Gb/s 3-D NRZ-DQPSK-PolSK modulated signal (Fig. 2c). 32 such orthogonal modulated signals from each transmitter section are multiplexed to realize a 3.84 Tb/s FSO system. Figure 3a and b illustrates the optical spectrum of the signal at the output of WDM MUX and the input of WDM DEMUX, respectively.

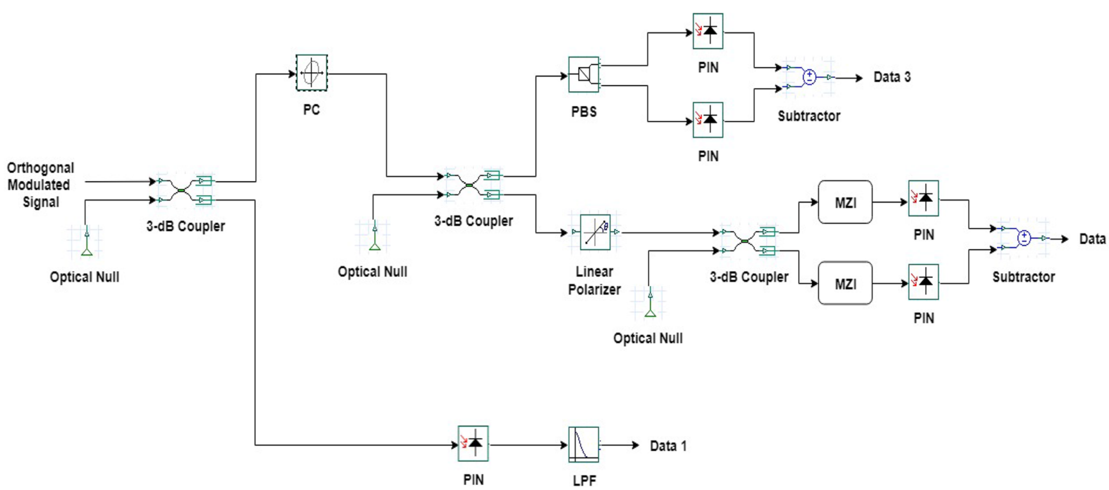
In each orthogonal modulation receiver section, dedicated paths are used for retrieving independent information signals as shown in Fig. 1c. The intensity-modulated Data 1 is retrieved using PIN photodiode with 0.9 A/W responsivity and 1e−022 W/Hz thermal noise power density followed by a Bessel low pass filter (LPF) to remove high-frequency noise. The phase-modulated Data 2 is retrieved using two Mach Zehnder Interferometers (MZI)



(a) Schematic of the proposed 32 channel WDM-FSO transmission system



(b) Schematic of single-channel orthogonal modulation transmitter



(c) Schematic of single-channel orthogonal modulation receiver

Fig. 1 **a** Schematic of the proposed 32 channel WDM-FSO transmission system. **b** Schematic of single-channel orthogonal modulation transmitter. **c** Schematic of single-channel orthogonal modulation receiver

with a delay of 2 s followed by a balanced detector. Data 3 is retrieved using a PBS followed by a balanced detector and a subtractor.

In this paper, we also analyze the proposed system performance for different levels of rain conditions. The

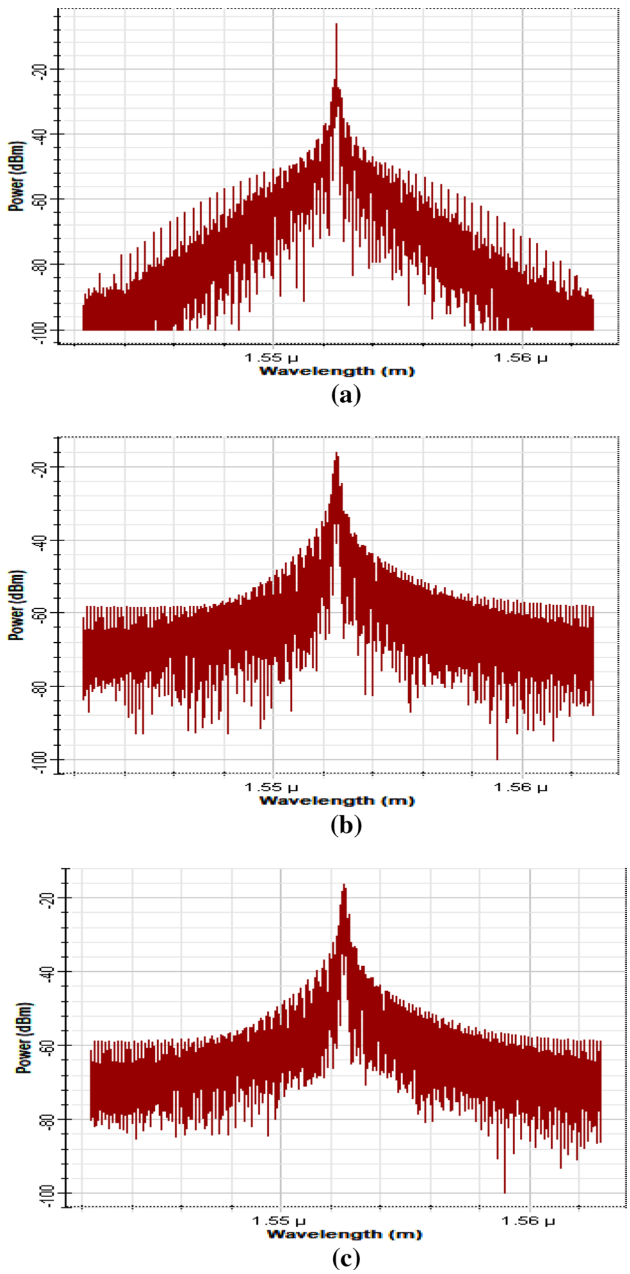


Fig. 2 Optical spectrum of information signal for channel 1 (193.1 THz) at **a** output of De-MZM **b** output of PM2 **c** output of PBC

attenuation due to rain in FSO links can be reasonably approximated and given by [29]:

$$\sigma_{\text{rain}} = \frac{2.8}{V} \tag{2}$$

where V denotes visibility in km and its value depending on the rainfall rate is presented in Table 1.

3 Results and discussion

Here, we report the numerical simulative investigation of the proposed system for varying climate conditions. First, we investigate the proposed link performance under clear weather by computing the Quality Factor (Q Factor), bit error rate (BER) and eye diagram of the received signals for increasing link range and to determine the maximum range. In the proposed work, while performing numerical simulations, all the 32 WDM channels are transmitted simultaneously to realize a net transmission of 3.84 Tb/s information. But for the sake of convenience, we have reported Q Factor and log(BER) versus link range plots in Fig. 4 for wavelength channel 1 (193.1 THz central frequency) only since all the other channels perform similarly.

Figure 4 illustrates that for channel 1 (193.1 THz central frequency), the Q Factor under clear weather is computed as [17.36 dB, 17.46 dB, 17.44 dB] at 20 km link range, [12.12 dB, 12.27 dB, 10.94 dB] at 30 km link range, and [8.40 dB, 8.55 dB, 6.53 dB] at 40 km link range for DQPSK, PolSK, and NRZ encoded data streams, respectively. Alternatively, log(BER) of the received signal for channel 1 is computed as [− 67.27, − 68.03, − 67.84] at 20 km link range, [− 33.55, − 34.39, − 27.50] at 30 km link range, and [− 16.82, − 17.39, − 10.51] at 40 km link range for DQPSK, PolSK, and NRZ encoded data streams, respectively. Here, it can be noted that for all data streams, the signal quality degrades as the range is increased which can be attributed to the signal power loss due to atmospheric attenuation. Also, it can be noted that all three data streams have an acceptable Q Factor (~ 6 dB) and log(BER) (~ − 9) at 40 km link range. The clear eye diagrams at 40 km for DQPSK, PolSK, and NRZ encoded data streams for channel 1 as illustrated in Fig. 5 demonstrate faithful transmission at 40 km under clear weather conditions. For better reader clarity, we have reported the Q Factor and log(BER) for all 32 WDM channels at 40 km in Fig. 6 which shows that all the channels demonstrate faithful transmission to realize a 3.84 Tb/s FSO transmission system.

Furthermore, we have investigated the proposed FSO transmission system performance under varying level of rain weather conditions using numerical simulations as illustrated in Figs. 7 and 8. Here also, all 32 WDM channels are transmitted simultaneously but for the sake of convenience, the performance of channel 1 (193.1 THz central frequency) is only reported since other wavelength channels perform similarly. From the results illustrated in Figs. 7 and 8, two main observations are: (1) For all rain conditions, with increasing range, the Q Factor of the information signal decreases and log(BER) increases

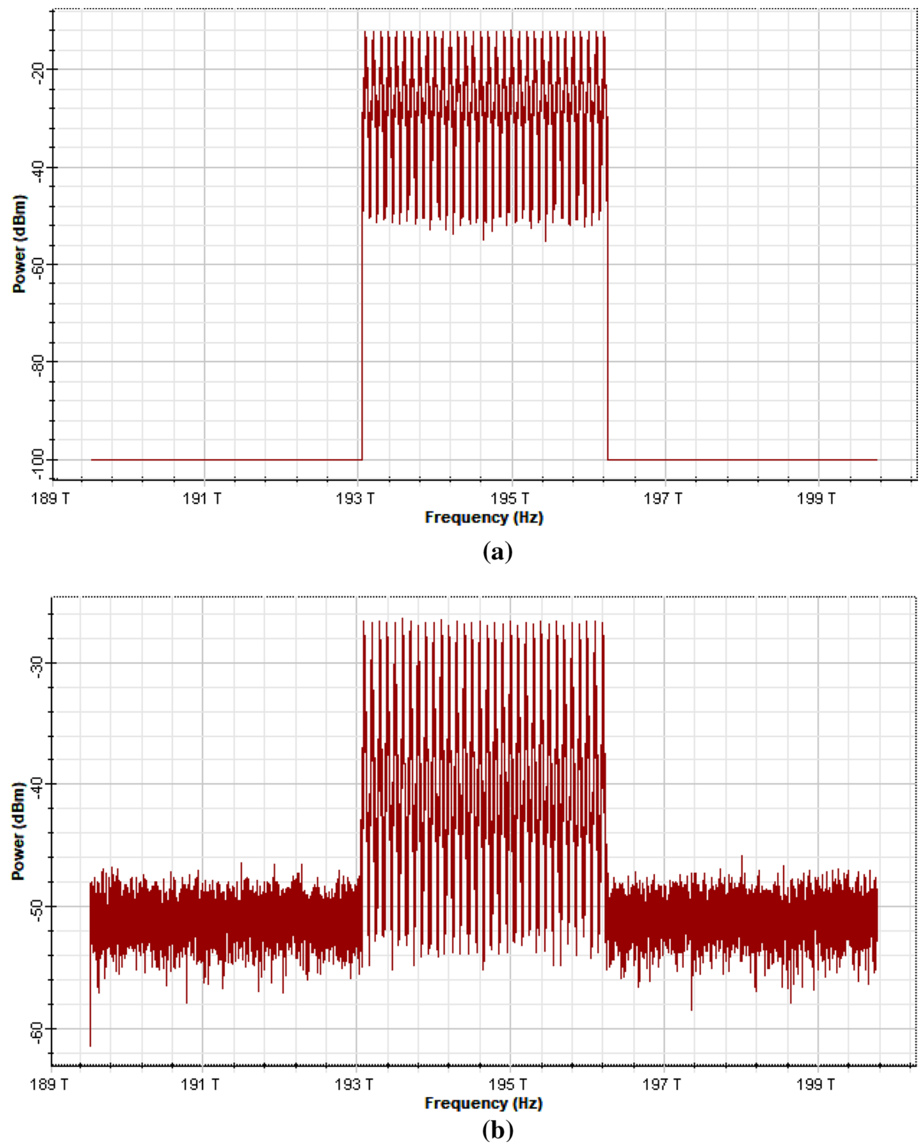


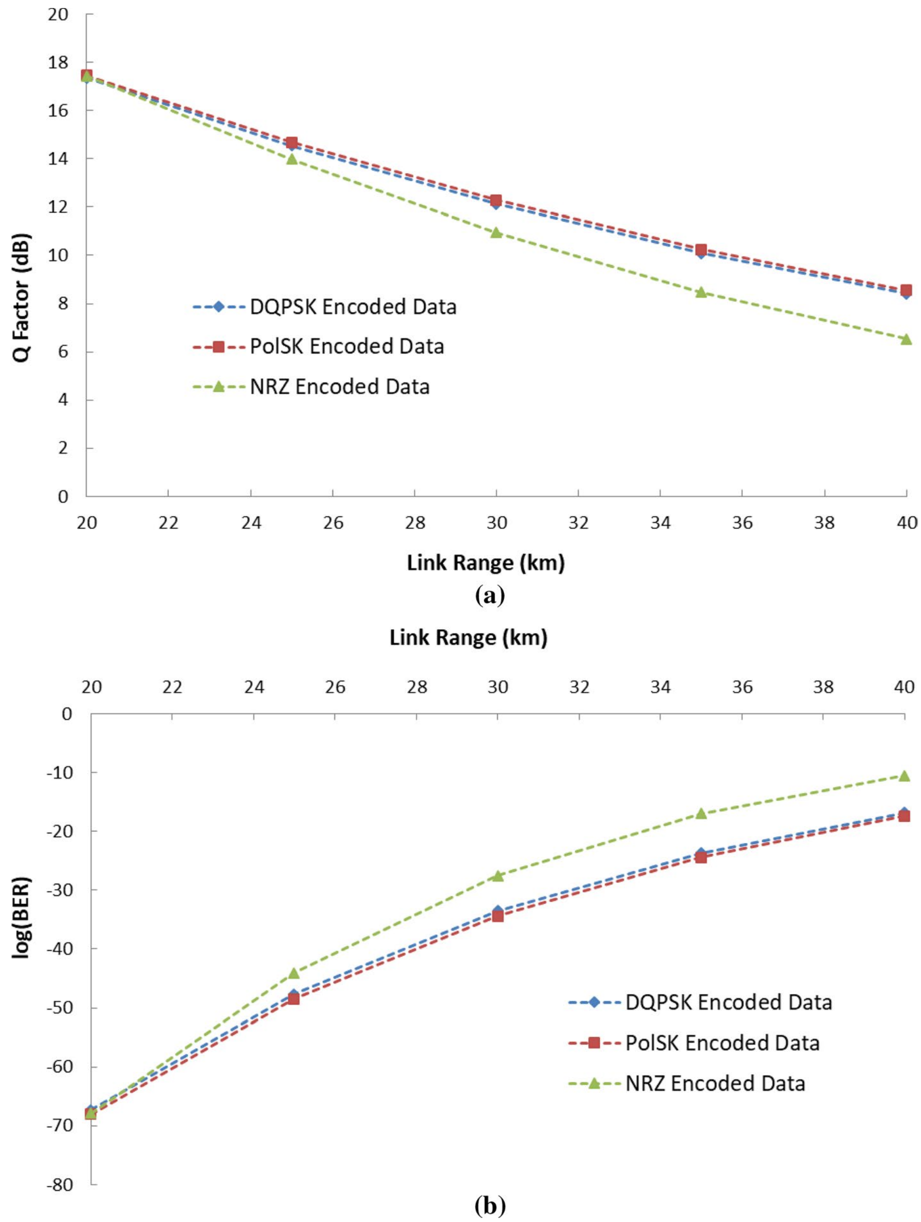
Fig. 3 Optical spectrum of the WDM signal at **a** output of MUX **b** input of DEMUX

Table 1 Visibility and attenuation coefficient depending on rainfall rate [29, 30]

Rainfall type	Rainfall rate in mm/hr	Visibility in km	Attenuation (dB/km)
Light rain	0.25	18–20	6.27
Moderate rain	12.5	2.8–4	9.64
Heavy rain	25	1.9–2	19.28

which is because of the increasing signal power loss due to atmospheric attenuation as the optical signal propagates through free space medium and (2) As the climate conditions move from light rain to heavy rain, the achievable range decreases which can be attributed to the fact that with increasing rainfall rate, the atmospheric attenuation increases as illustrated in Table 1. The Q Factor for channel 1 under light rain conditions at 4000 m is computed as 8.21 dB, 8.36 dB, and 6.31 dB; under moderate rain at 2800 m is computed as 8.96 dB, 9.11 dB, and 7.15 dB; and under heavy rain at 1600 m is computed as 8.65 dB, 8.80 dB, and 6.80 dB for DQPSK, PolSK, and NRZ encoded data streams, respectively. Alternatively, the log(BER) for channel 1 under light rain conditions at 4000 m is computed as − 16.12, − 16.67, and − 9.91; under moderate rain at 2800 m is computed as − 18.95, − 19.58, and − 12.42; and under heavy rain at 1600 m is computed as − 17.75, − 18.34, and − 11.33 for DQPSK, PolSK, and NRZ encoded data streams, respectively. The reported simulation results in Figs. 7 and 8 demonstrate a faithful transmission at a link distance of 4000 m under light rain, 2800 m under moderate rain, and 1600 m under heavy rain with acceptable performance.

Fig. 4 **a** Q Factor **b** log(BER) versus FSO link range under clear weather

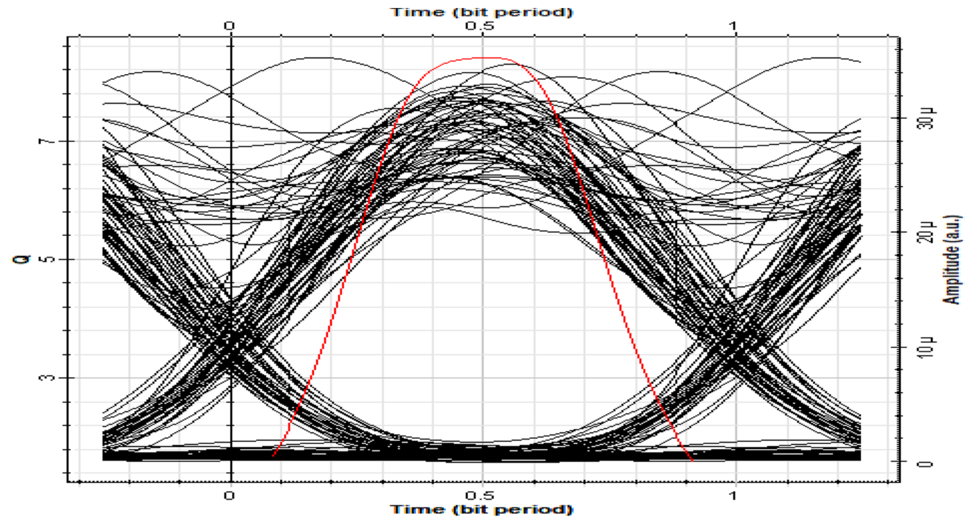


Also, we have compared the proposed FSO system performance with other reported systems in previous works as illustrated in Table 2 to highlight the performance enhancement using the proposed technique. Here, it can be noted that the proposed FSO system achieves the highest transmission capacity of the link as compared to the other reported systems. The higher achieved link range in the case of Ref. [19] and [20] is because the authors have used high power laser with an input power of 30 dBm and 25 dBm, respectively, as compared to low-power laser with 0 dBm input power used in this work.

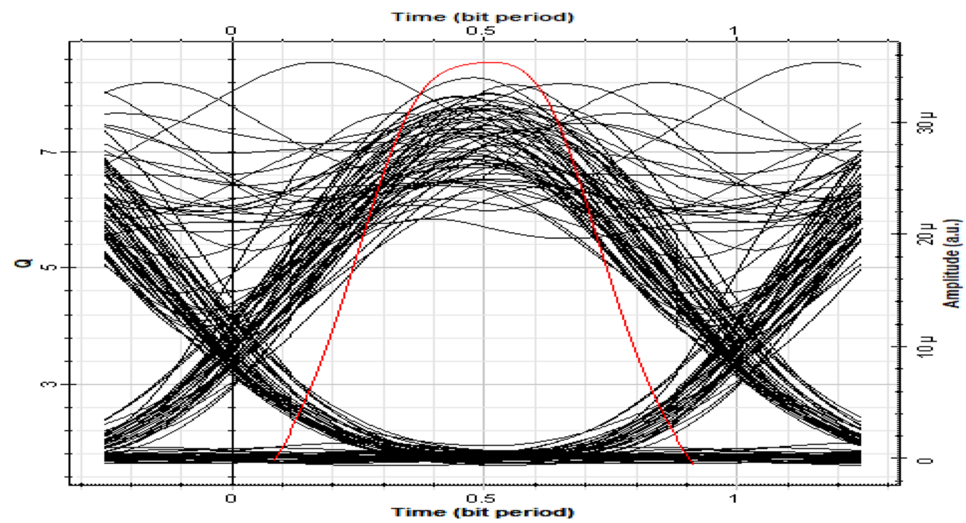
4 Conclusion

A novel high-capacity bandwidth-efficient NRZ-DQPSK-PolSK modulation scheme has been proposed to transmit simultaneously three independent 40 Gb/s data signals on a single optical carrier beam to realize 120 Gb/s transmission capacity per channel. The proposed modulation scheme is incorporated in a 32 channel WDM-FSO system with 0.1 THz channel spacing. Using numerical simulations, we investigate the transmission performance of

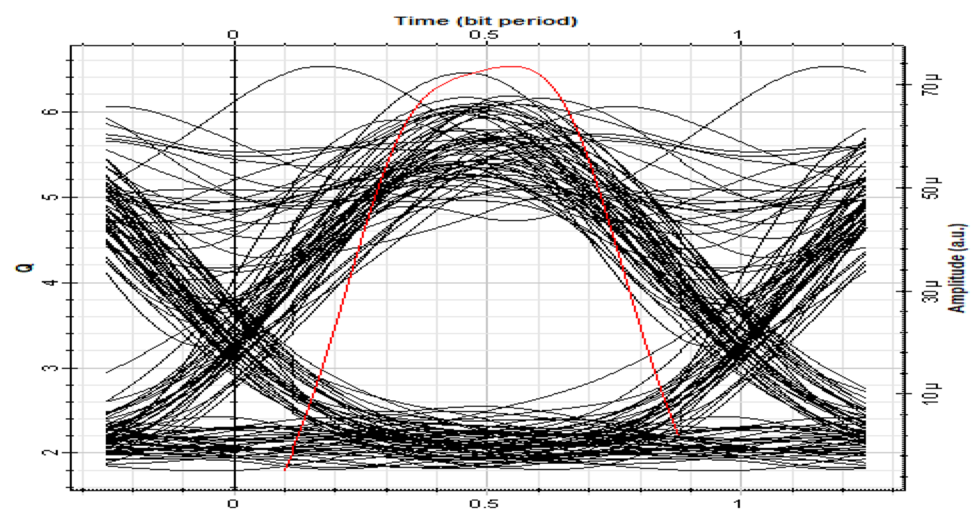
Fig. 5 Eye diagram at 40 km link range for channel 1 (193.1 THz) **a** DQPSK-encoded data **b** PolSK encoded data **c** NRZ encoded data under clear weather



(a)



(b)



(c)

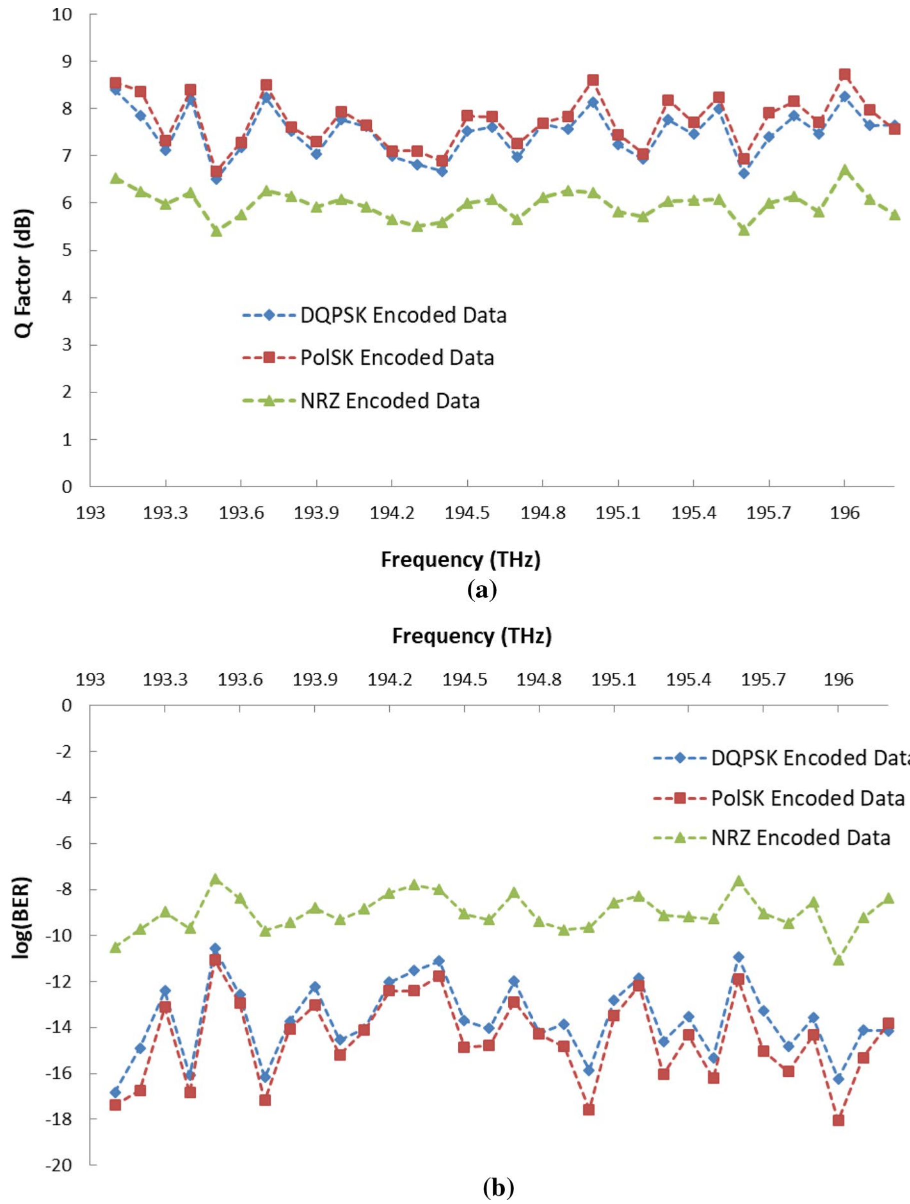


Fig. 6 **a** Q Factor **b** log(BER) for all WDM channels (193.1–196.2 THz) at 40 km link range under clear weather

the proposed 3.84 Tb/s WDM-FSO system for clear and varying rainfall conditions. The numerical results demonstrate faithful transmission at 40 km under clear conditions whereas the maximum link range limits to 4 km, 2.8 km, and 1.6 km under light, moderate, and heavy rain conditions, respectively. The proposed work can be implemented to realize a high-capacity FSO transmission system under adverse climate affairs.

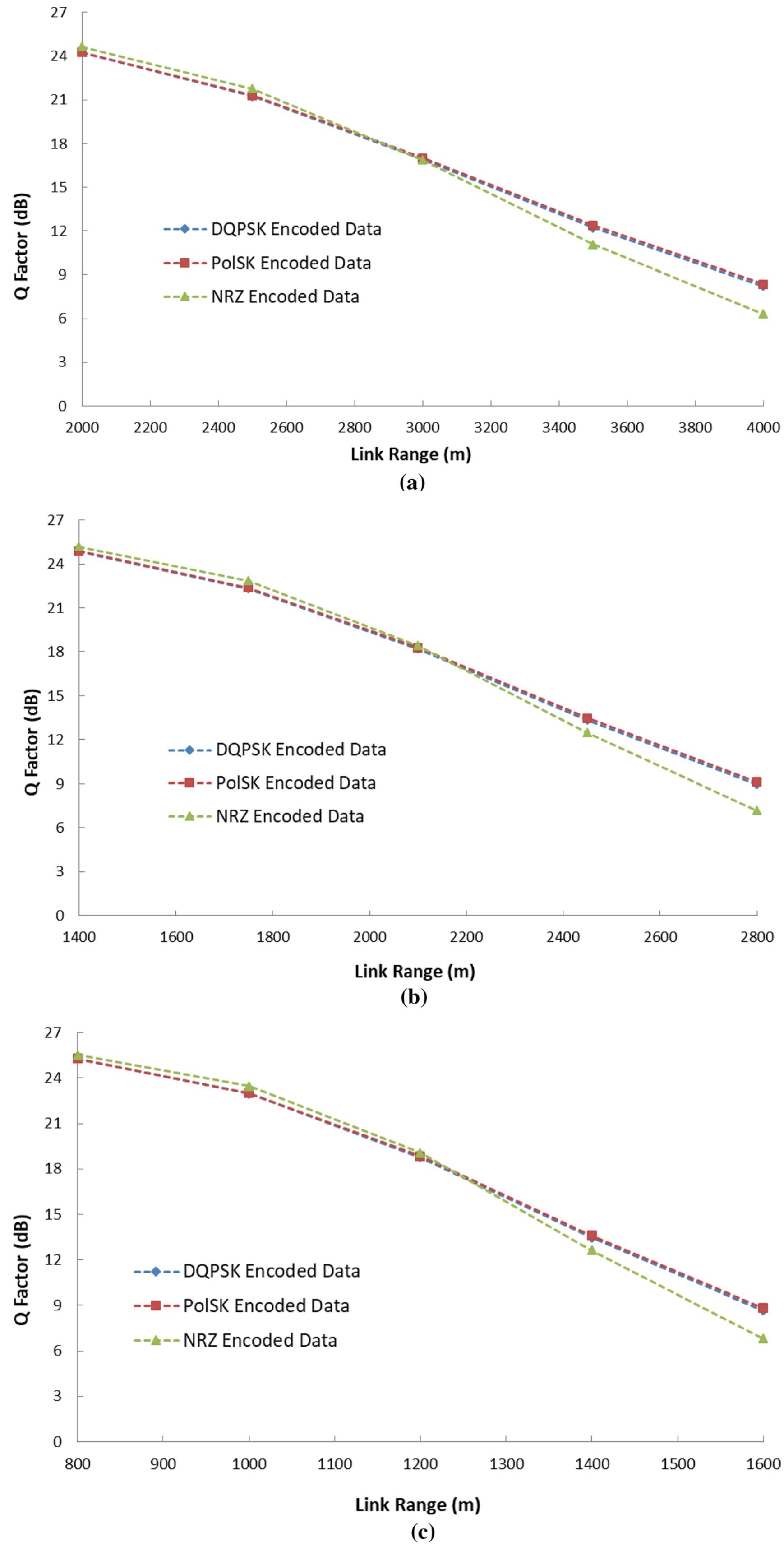


Fig. 7 Q Factor versus link range under **a** light rain **b** moderate rain **c** heavy rain

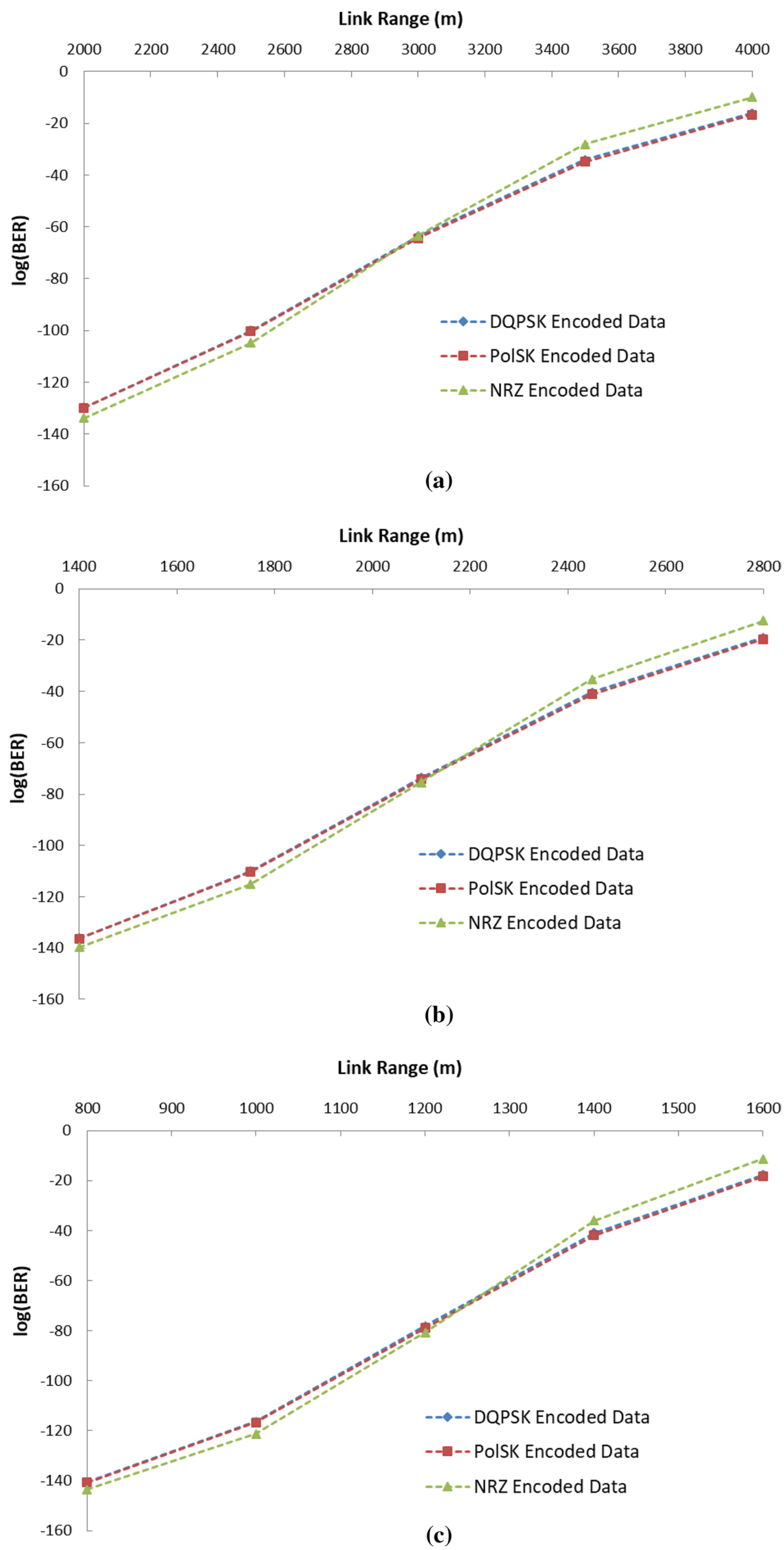


Fig. 8 log(BER) versus link range under **a** light rain **b** moderate rain **c** heavy rain

Table 2 Performance comparison of the proposed FSO system with other reported systems

References	Reported FSO system technique	Transmission capacity (Gb/s)	Climate condition	Achieved link range (km)
Ref. [12]	MDM-based FSO system	8×5	Light Rain	1.7
			Moderate Rain	1.15
			Heavy Rain	0.65
Ref. [18]	SAC-OCDMA-based FSO system with DDW code	5	Light Rain	2.5
			Moderate Rain	2
			Heavy Rain	1
Ref. [19]	WDM-FSO system with NRZ modulation	32×2.5	Light Rain	16
			Moderate Rain	10
			Heavy Rain	5
Ref. [20]	SS-WDM-FSO system with NRZ modulation	4×1.56	Light Rain	8.3
			Moderate Rain	5.7
			Heavy Rain	3.14
Proposed work	WDM-FSO system with orthogonal modulation scheme	32×120	Light Rain	4
			Moderate Rain	2.4
			Heavy Rain	1.6

References

1. Khalighi, M.A., Uysal, M.: Survey on free space optical communication: a communication theory perspective. IEEE Commun. Surv. Tutorials **16**(4), 2231–2258 (2014)
2. Ramezani, A., Noroozi, M.R., Aghababaee, M.: Analyzing free space optical communication performance. Int. J. Eng. Adv. Technol. **4**(1), 46–51 (2014)
3. Singh, J., Kumar, N.: performance analysis of different modulation format on free space optical communication system. Optik Int. J. Light Electron Opt. **124**(20), 4651–4654 (2013)
4. Ren, Y., et al.: 400-Gbit/s free space optical communications link over 120-meter using multiplexing of 4 collocated orbital angular- momentum beams. Opt. Fiber Commun. Conf. **1**, 15 (2015)
5. Shah, D., Kothari, D.: Optimization of 2.5 Gbps WDM-FSO link range under different rain conditions in Ahmedabad. In: 2014 Annual IEEE India Conference (INDICON), Pune (2014), pp. 1–4. Doi: https://doi.org/10.1109/INDICON.2014.7030643
6. Singh, M., Malhotra, J.: Performance comparison of M-QAM and DQPSK modulation schemes in a 2×20 Gbit/s-40 GHz hybrid MDM-OFDM-based radio over FSO transmission system. Photon. Netw. Commun. **38**, 378–389 (2019)
7. Singh, M., Malhotra, J.: Performance comparison of high-speed long-reach mode division multiplexing-based radio over free space optics transmission system using different modulation formats under the effect of atmospheric turbulence. Opt. Eng. SPIE **58**(4), 046112 (2019)
8. Singh, M., Malhotra, J.: Long-reach high-capacity hybrid MDM-OFDM-FSO transmission link under the effect of atmospheric turbulence. Wirel Personal Commun **107**, 1549–1571 (2019)
9. Amphawan, A., Chaudhary, S., Ghassemlooy, Z., et al.: 2 × 2-channel mode-wavelength division multiplexing in Ro-FSO system with PCF mode group demultiplexers and equalizers. Opt Commun (2020). https://doi.org/10.1016/j.optcom.2020.125539
10. Kishore Upadhyay, K., Kumar Shukla, N., Chaudhary, S.: A high speed 100 Gbps MDM-SAC-OCDMA multimode transmission system for short haul communication. Optik (2019). https://doi.org/10.1016/j.ijleo.2019.163665
11. Singh, M., Malhotra, J.: Performance comparison of 2 × 20 Gbit/s-40 GHz OFDM based RoFSO transmission link incorporating MDM of Hermite Gaussian modes with different modulation schemes. Wirel Personal Commun **110**, 699–711 (2020)
12. Al-Dawoodi, A., et al.: Investigation of 8 × 5 Gb/s mode division multiplexing-FSO system under different weather conditions. J. Eng. Sci. Technol. **14**(2), 674–681 (2019)
13. Singh, M., Malhotra, J.: Enhanced performance of 40 Gbit/s-80 GHz OFDM based radio over FSO transmission link incorporating mode division multiplexing under strong atmospheric turbulence. Optoelectron. Adv. Mater. Rapid Commun. **13**(7–8), 437–447 (2019)
14. Ritu, G., Tara, S.K., Preeti, S.: Performance of OFDM:FSO communication system with hybrid channel codes during weak turbulence. J. Comput. Netw. Commun. **130**, 6491 (2019). https://doi.org/10.1155/2019/1306491
15. Dabiri, M.T., Saber, M.J., Sadough, S.M.S.: BER performance of OFDM-based wireless services over radio-on-FSO links in the presence of turbulence and pointing errors. In: 2016 8th International Symposium on Telecommunications (IST), Tehran, pp. 30–33. (2016)
16. Chaudhary, S., Choudhary, S., Tang, X., Wei, X.: Empirical evaluation of high-speed cost-effective Ro-FSO system by incorporating OCDMA-PDM scheme under the presence of fog. J Opt Commun (2020). https://doi.org/10.1515/joc-2019-0277
17. Kaur, G., Srivastava, D., Singh, P., Parasher, Y.: Development of a novel hybrid PDM/OFDM technique for FSO system and its performance analysis. Opt. Laser Technol. **109**, 256–262 (2019). https://doi.org/10.1016/j.optlastec.2018.08.008
18. Kaur, G., Bal, G.S.: Performance analysis of SAC-OCDMA in free space optical medium using DDW code. Optik (Stuttg). **133**, 36–42 (2017). https://doi.org/10.1016/j.ijleo.2016.12.057
19. Malik, A., Kumar, S., Singh, P., Kaur, P.: Performance enhancement of point-to-point FSO system under rain weather conditions. Intell. Commun. Control Devices (2018). https://doi.org/10.1007/978-981-10-5903-2_63

20. Prabu, K., Charanya, S., Jain, M., Guha, D.: BER analysis of SS-WDM based FSO system for Vellore weather conditions. Opt. Commun. **403**, 73–80 (2017). https://doi.org/10.1016/j.optcom.2017.07.012
21. Lach, E., Idler, W.: Modulation formats for 100G and beyond. Opt. Fiber Technol. **17**, 377–386 (2011)
22. Chow, C.W., Wong, C.S., Tsang, H.K.: Optical packet labeling based on simultaneous polarization shift keying and amplitude shift keying. Opt. Lett. **29**, 1861–1863 (2004)
23. Zhang, Y., Deng, N., Chan, C., Chen, L.: A Multicast WDM-PON Architecture Using DPSK/NRZ Orthogonal Modulation. IEEE Photon. Technol. Lett. **20**(17), 1479–1481 (2008)
24. Ohm, M., Speidel, J.: Quaternary optical ASK-DPSK and receivers with direct detection. IEEE Photon. Technol. Lett. **15**(1), 159–161 (2003)
25. Wang, X., He, Z., Liu, H., et al.: Improved optical coding method for orthogonal ASK/DPSK modulation format Front. Optoelectron. China **1**, 14 (2008)
26. Dai, B., Gao, Z., Wang, X., Kataoka, N., Wada, N.: A Novel Optical Orthogonal Modulation Format Based on Differential Phase-Shift Keying and Code-Shift Keying. IEEE Photon. Technol. Lett. **23**(17), 1210–1212 (2011)
27. Zhang, J., Shao, Y., Fang, W., Huang, Bo., Tao, Li., Zhu, J., Chi, N.: Novel orthogonal modulation format DRZ-FSK/DPSK for high-speed long-haul optical communication. Chin. Opt. Lett. **8**, 852–855 (2010)
28. Kaur, D., Chaudhary, S.: 4 x 10 GBPS cost effective hybrid OADM-MDM short haul interconnects. Microwave Opt. Technol. Lett. **58**, 1613–1617 (2016). https://doi.org/10.1002/mop.29869
29. Ghassemlooy, Z., Popoola, W.O.: Terrestrial free space optical communications. In: S.A Fares, F. Adachi (eds.) Mobile and Wireless Communication Network Layer and Circuit Level Design, (InTech, 2010)
30. Aditi, M., Preeti, S.: Free space optics: current applications and future challenges. Int. J. Opt. (2015). https://doi.org/10.1155/2015/945483

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