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ORIGINAL RESEARCH

Analysis of optical power budget in DWDM-FSO link under outdoor atmospheric channel model

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Abstract
In this paper, the effects of atmospheric turbulence on the performance of a hybrid dense wavelength division modulation (DWDM) of free space optical (FSO) communication using advanced modulations are presented. Enhancement in the capacity of transmission and bit rates of the optical networks is obtained by DWDM technology based on FSO communication systems. Proposed modulations are included Return-to-Zero Differential Phase Shift Keying (RZ-DPSK) and Non-Return-to-Zero Differential Phase Shift Keying (NRZ-DPSK) that each of them increases spectrum efficiency. Furthermore, the optical power budget of the proposed system is analytically calculated. Variation of Bit Error Rate and Max quality factor of the designed system with different path distance and input power are obtained considering outdoor atmosphere channel model. As a result, the RZ-DPSK modulation has better performance in comparison to NRZ-DPSK modulation when the atmospheric condition is considered.

Keywords Hybrid dense wavelength division modulation (DWDM) · Free space optical (FSO) communication · Atmospheric Channel

1 Introduction

In optical networks, Dense Wavelength Division Multiplexing (DWDM) systems have different applications in modern communication networks. The DWDM technology increases the bandwidth and capacity of the communication system at the same time by using several wavelength that have been transmitted on a Single Mode Fiber (SMF) without other optical fiber. Bit rate and channel spacing of DWDM systems are considered to increase the capacity and bandwidth of the optical communication systems (Kartalopoulos 1999; Marciniak 2007; Winzer and Essiambre 2006; Ali et al. Feb. 2015). Free space optical communication (FSO) can be defined as a type of optical transmission technology which transmitted signal and data through air, water or vacuum. Development of FSO technology has several advantages such as high security, simple design, high speed and low interference. FSO technology for this features is taken into

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consideration. Also, this technology can be used in several application such as inter-satellite, deep space link, last mile accesses networks and backup links. Therefore, investigation the DWDM technology with FSO communication can be increased the speed of data transmission and bandwidth in high bit rates and long distance links (Killinger Oct. 2002; Hranilovic 2005; Ciaramella et al. Dec. 2009; Li et al. 2016). In addition to the bandwidth and capacity of the networks, spectrum efficiency of transmission is one of the significant parameters in design of lightwave systems. To minimize linear and nonlinear effects over transmission, an advanced optical modulation formats are needed. A modulation format with narrow optical spectrum has capable to increase the spectrum efficiency of link. On–Off Keying (OOK) modulation is not suitable for next generation of optical networks. Intensity modulations such as Differential Phase Shift Keying (DPSK) and Quarter Phase Shift Keying (QPSK) have suitable performance for higher data rates and spectrum efficiency of DWDM systems (Kahn and Ho Jun. 2004; Haris 2008; Chen 2020; Wang and Chen 2020). These modulations formats have inherent − 3 dB better receiver sensitivity by using balanced detection (Xu 2019; Zhao 2019; Li 2018; Wang 2017). Also, atmospheric condition is fundamental problem in propagation of light at free space. So, several optimization agolrithms are proposed (Xia 2017; Shen 2016; Chen 2016; Hu 2015; Xu and H.-l.J.S.C. Chen, 2014). For example Zhang groups proposed learning algorithm (Zhang 2020; Zhang, et al. 2020a). In addition colony optimization (Zhao, et al. 2020a) and whale optimization (Tu 2021) and so are applied by research groups (Shan, et al. 2020; Yu 2021, 2020; Hu et al. 2020; Zhao 2014). Environmental effects such as pressure and atmosphere turbulence can bring variable refractive index during transmission of data. Variable refractive index makes spatial and temporal changes of beam intensity in receiver (Garg Jul. 2013). In the other words, the performance of FSO systems are affected by atmospheric conditions (Kumar and Singh 2014; Failed 2020).

In (Tripathi et al. 2020; Sharma et al. 2021), two DWDM-FSO system with considering atmospheric turbulence have been presented. the proposed system (Tripathi et al. 2020) investigated based on FSO, passive optical network (PON) and radio over free space based on DWDM configuration. By using suitable modulation, the system can transmit 12 wirless channels at 2.5 Gb/s data rate. Despite of good performance of the presented system, but the power budget of the system has not be calculated.

A FSO/fiber communication system for enhancement the operation of the proposed system based on OOK modulation formats has been designed (Elsayed and Yousif 2020). The presented communication system has good performance in the weak turbulence condition, but, in addition to the small distance, the power budget of the system has not be considerd.

Several system have been proposed for enhancement of the DWDM-FSO configuration under turbulence condition with differen modulation schems (Elsayed and Yousif 2020; Elsayed 2021a, 2021b).

In this paper a DWDM-FSO system for two different modulation schemes are presented. This paper not only investigate the proposed system under Outdoor atmospheric channel model, but also can calculate the optical power budget off the system. The novelty of the presented DWDM-FSO system is that by considering two advanced on–off keying modulation formats under modelling of free space channel, we can calculate the power budget of system analytically and optimization the parameters of the system under this issue.

The paper is organized as follows: In Sect. 2 and 3, description of modulation technique and outdoor atmospheric channel model with optical power budget are presented. The proposed system is expressed in Sect. 4. Finally simulation results and conclusion are presented in Sect. 5 and Sect. 6, respectively.

2 Description of modulation techniques

Digital modulation can be exposed by the phase of the optical carrier and referred to optical Phase Shift Keying (PSK). Figure 1a shows the configuration of Non Return to Zero Differential Phase Shift Keying (NRZ-DPSK) in lightwave systems that consist of two parts consisiting of transmitter and receiver which these parts used in transmitter and receiver of the proposed system, recpectively. In the NRZ-DPSK transmitter, is a precoder modulation which has one-bit delay composes the NRZ signal. This signal which known as DPSK electrical signal is driven to a Mach-Zehender Modulator (MZM).

The output of MZM is an NRZ-DPSK optical signal. After FSO channel and demultiplxing, we need o demodulation of inpout signals that modulated. At receiver, the signal can be detected in two ways such as direct and balanced detection. The receiver consisiting of several devices as two couplers, phas shift, time delay, two photodetector and band pass filter that coused to demodulated the oupout signal of the FSO link. This method can optimization of the signal that multiplexing in input. The The main advantage of DPSK modulation instead of OOK is − 3 dB receiver sensitivity improvement. The optical spectrum and generated bits of NRZ-DPSK modulation after MZM at 193.1

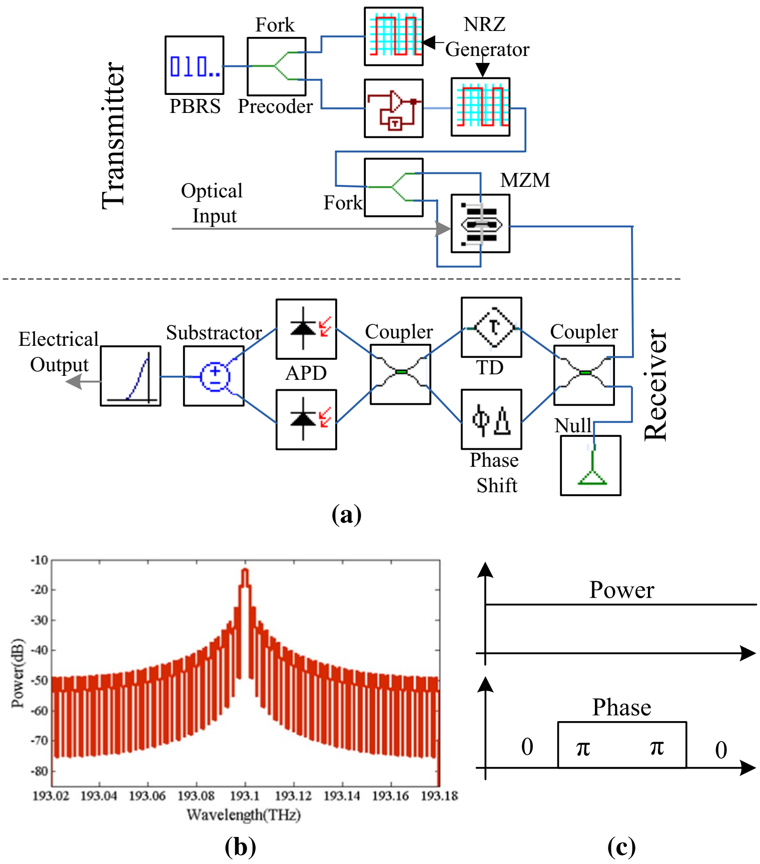


Fig. 1 **a** Configuration of NRZ-DPSK modulation, **b** its optical spectrum, and **c** generated bits

THz frequency are shown in Fig. 1b and c, respectively (Haris 2008; Elsayed 2021c; Liu and Kao 2009). It is obvious that the output power of NRZ-DPSK modulation formats is near − 10 dB.

To overtake long distance and high capacity of transmission link, Return to Zero Differential Phase Shift Keying (RZ-DPSK) modulation is proposed. Figure 2a shows the configuration of RZ-DPSK modulation. This modulation unlike the NRZ-DPSK, usually needs two MZM, one for pulse carving and the other for phase modulation. After generation of DPSK electrical signal similar to NRZ-DPSK modulation, the signal is driven to the second MZM as known as a phase modulator. The balanced detection is used in RZ-DPSK as same as NRZ-DPSK. The optical spectrum and generated bits of RZ-DPSK modulation after second MZM at 193.1 THz frequency are shown in Fig. 2b and c, respectively (Haris 2008; Elsayed 2021c; Liu and Kao 2009). As we can see from Fig. 2b, the output power of RZ-DPSK modulation is − 10 dB less than NRZ-DPSK modulation formats that affected the final DWDM-FSO system.

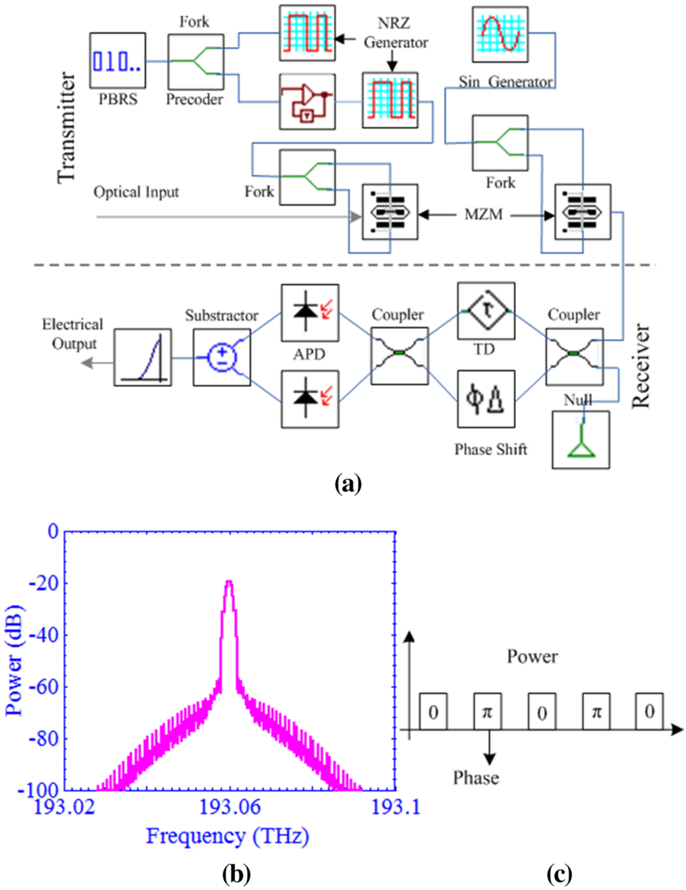


Fig. 2 **a** Configuration of RZ-DPSK modulation, **b** its optical spectrum, and **c**, generated bits

3 Outdoor atmospheric channel model and optical power budget

In FSO technology, the atmospheric channel is a dynamic and wrapped environmental that affected the propagation of laser optical beam. Optical signals which propagating through atmosphere channel are tender to the atmosphere condition such as fog, rain and haze. During transmission of optical beams through FSO channel, the interaction between the photons and atmosphere molecules caused scattering and absorption of optical photons. For minimized the effect of beam scattering, a laser with very narrow band spectrum can be used. To reduce the atmospheric absorption losses, selecting a wavelength that stay on the optimal transmission windows such as visible and infrared bands is needed. For an FSO link, the receiver optical power P_r is related to optical power P_t, which defines as Eq. (1).

$$P_t = P_r \exp\left(-\tau_{od}\right) \tag{1}$$

where τ_{od} is the optical depth. Partial of transmitted power in optical communication defines as beam transmitted power. The optical depth and atmospheric transmittance are related to the atmospheric attenuation coefficient and the transmission path length L_p that explains as Eq. (2) (Cai et al. 2005; Ghassemlooy et al. 2013; Maral and Bousquet 2009).

$$T(\lambda, L) = \frac{P_r}{P_t} = \exp\left[-\gamma_t(\lambda)L_p\right] \tag{2}$$

where γ_t is total attenuation in m^{-1} and L_p is transmission path link in m. The attenuation of optical beams in atmosphere channel that generated by scattering and absorption, introduced by gases and aerosols. Also, the atmospheric attenuation coefficient can define as Eq. (3) (Gagliardi and Karp 1995).

$$\gamma_t(\lambda) = \alpha_{m1}(\lambda) + \alpha_{a1}(\lambda) + \beta_{m1}(\lambda) + \beta_{a1}(\lambda) \tag{3}$$

where α_{m1} is molecular absorption coefficient, α_{a1} is Aerosol absorption coefficient, β_{m1} is molecular scattering coefficient and β_{a1} is total scattering coefficient. Due to the experimental amount of α_{m1}, α_{a1} and β_{m1} which are insignificant, we can approximate attenuation with Eq. (4) (Willebrand and Ghuman 2002).

$$\alpha\left(\frac{\mathrm{dB}}{\mathrm{km}}\right) = \frac{13}{V}\left(\frac{\mathrm{dB}}{\mathrm{km}}\right)\left(\frac{\lambda}{550}\right)^{-\delta} \tag{4}$$

where V is visibility in km, λ is a wavelength in nm and q is dispersion distribution quantity. The value of q follows as Eq. (5) (Kruse et al. 1962).

$$\delta = \begin{cases} 1.6 & (V \geq 50\ \mathrm{km}) \\ 1.3 & (6\ \mathrm{km} \leq V \leq 50\ \mathrm{km}) \\ 0.585V^{1/3} & (V \leq 6\ \mathrm{km}) \end{cases} \tag{5}$$

The visibility and attenuation at different weather condition for different wavelengths are shown in Table 1.

To achieve high security, narrowband optical beams are used in FSO links and this is one of the advantages of them. But due to diffraction, the optical beams spread out and leads to beam divergence loss. In a system with low bit rates, the value of divergence is

Table 1 Visibility and attenuation at different weather condition for different wavelengths

Atmospheric condition	Visibility (km)	Attenuation at 780 nm (dB/km)	Attenuation at 1310 nm (dB/km)	Attenuation at 1550 nm (dB/km)
Very clear air	23–50	0.22	0.12	0.1
Clear air	18–20	0.43	0.21	0.18
Very light mist	4	2.34	1.46	1.23
Light mist	2	5	3.45	3.06
Very light fog	1–1.9	7.1	5.01	4.48
Light fog	0.77	14.01	10.14	9.8

68 mrad but in systems with high bit rates, the beam divergence is less than 2 mrad. The signal propagation loss can be expressed as Eq. (6) (Gowar 1993).

$$P_L = \left(\frac{\lambda}{4\pi L_P}\right)^2 \tag{6}$$

where λ is wavelength in nm. The performance of FSO link is degraded when the optical beam interaction with atmosphere turbulence causes the scintillation of optical beam. Atmosphere turbulence is an irregular random motion which caused change in refractive index of atmosphere channel. We used the Hufnagel-Valley (HV) method to model the refractive index structure of atmospheric channel. This method that is widely used in optical communication systems is described as Eq. (7) (Wang et al. Jun 2013).

$$C_n(L_p) = 0.00549\left(\frac{v}{27}\right)\left(\frac{10^{-5}}{L_p}\right)^{10} \exp\left(\frac{-L_p}{1000}\right) + 2.7\times10^{-16}\exp\left(\frac{-L_p}{1000}\right) + A\exp\left(\frac{-L_p}{100}\right) \tag{7}$$

where A is min value of C_n (0) at the ground in $m^{-2/3}$, and v is rms of wind speed in m/s, that for our proposed system is almost 3.4×10^{-25}. For optical communication systems, the power budget can be calculated as the Eq. (8).

$$Optical\,power\,budget = Max\,transmit\,power - received\,power \tag{8}$$

The received power includes the splitter, splice loss, connector loss, attenuation loss and FSO loss. The free space loss is given by Eq. (9) (Couch 2013).

$$\left(L_{fs}\right)_{dB} = 20\log\left(\frac{4\pi L_p}{\lambda}\right)_{dB} \tag{9}$$

Should bear in mind that, number of a splice in (L) km is L-1. Thus, the splice loss is 1×0.2 dB $=0.2$ dB. Table 2 shows the typical link budget for 10 Gbps bit rate and 2 km path link.

Table 2 Optical power budget for DWDM-FSO system

Parameters	Values
Free space loss	24.3 dB
Splice loss	0.2 dB
Attenuation loss	0.36 dB
Number of ONU	16
Connector loss	4.8 dB
Receiver power	29.66 dB
Max transmit power	10 dB
Power budget	39.66 dB

4 Proposed system

Figure 3 shows the configuration of our proposed FSO-DWDM system with 16 channels by 2 km path link. The proposed system is simulated at 10 Gbps bit rate with two modulation formats consist of RZ-DPSK and NRZ-DPSK. This system is similar to the other communication systems, consist of transmitter block, FSO channel and receiver block.

Transmitter block is consist of three main parts such as 1: a transmitter that used 16 channels with 200 GHz frequency spacing and 10 dB input power in 193.1 THz center frequency, 2: subsystem 1 until subsystem 16 that consists of RZ-DPSK and NRZ-DPSK modulations and 3: an optical Ideal Mux. In transmission link, we modeled communication channel by FSO channel with 2 km path link. Receiver block is consist of 1: an optical Ideal Demux and 2: receivers 1 up to 16 use balanced detector for detection of the signals. We analyzed the performance of output results by BER analyzer. The simulation parameters of the proposed system and FSO channel are presented in Table 3.

5 Simulation results

The proposed system in the clear weather condition was simulated. In Fig. 4a and b, the eye diagram of NRZ with direct detection and NRZ-DPSK with balanced detection for proposed system are shown. The system is simulated at 10 Gbps and 2 km path link.

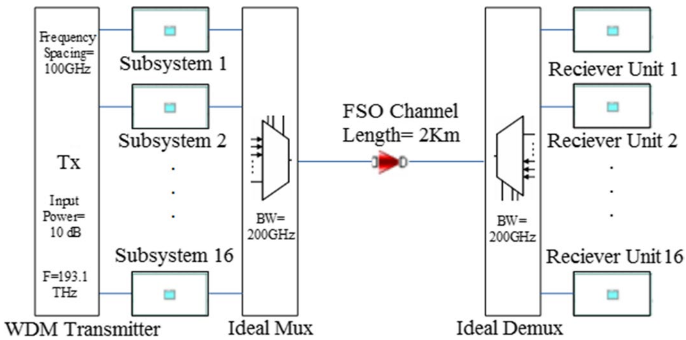


Fig. 3 The configuration of the proposed 16-channel DWDM-FSO system

Table 3 Comparison of the results for different bit rate

Parameters	Values
Bitrate	10 Gbps
Sequence length	512
Samples/bit	64
DWDM channel spacing	100 GHz
Capacity	16-Channel
Rang of OWC	2 km
Input power	10 dB
Center frequency	193.1 THz

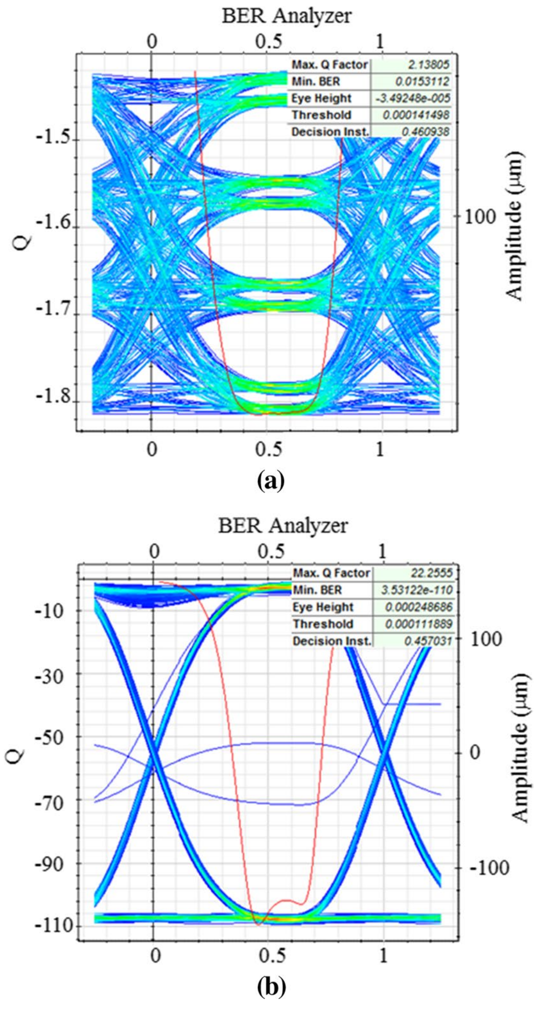


Fig. 4 Eye diagram and *Q*-factor of **a** RZ and **b** NRZ-DPSK at 10 Gbps

The maximum quality factor $Q = 2.13$ and 22.25 is obtained for NRZ and NRZ-DPSK modulation at 10 Gbps bit rate, respectively. Also, the minimum BER is 1.5×10^{-2} and 2.53×10^{-110} for NRZ and NRZ-DPSK modulation.

Similarly, for RZ with direct detection and RZ-DPSK with balanced detection, the maximum quality factor Q is 2.17 and 21.28. Also, the minimum BER is 1.39×10^{-2} and 5.36×10^{-101}, respectively. Figure 5a and b shows the eye diagram for RZ and NRZ-DPSK modulations. Results show RZ and NRZ modulations with direct detection are not suitable for the proposed system. It is obvious that when eye diagram is in best condition (for example Fig. 4b), so the Q and BER are in good condition. For example the NRZ-DPSK modulation has good condition than RZ-DPSK, so exactly the Q and BER parameters have very good operation that it is very obvious.

To study the performance of the proposed system under the influence of different atmospheric condition, attenuation of the different condition is applied to the proposed system. Figure 6a and b shows the diagram of a maximum quality factor versus time for NRZ-DPSK and RZ-DPSK at 10 Gbps, respectively. Results for two modulations show suitable

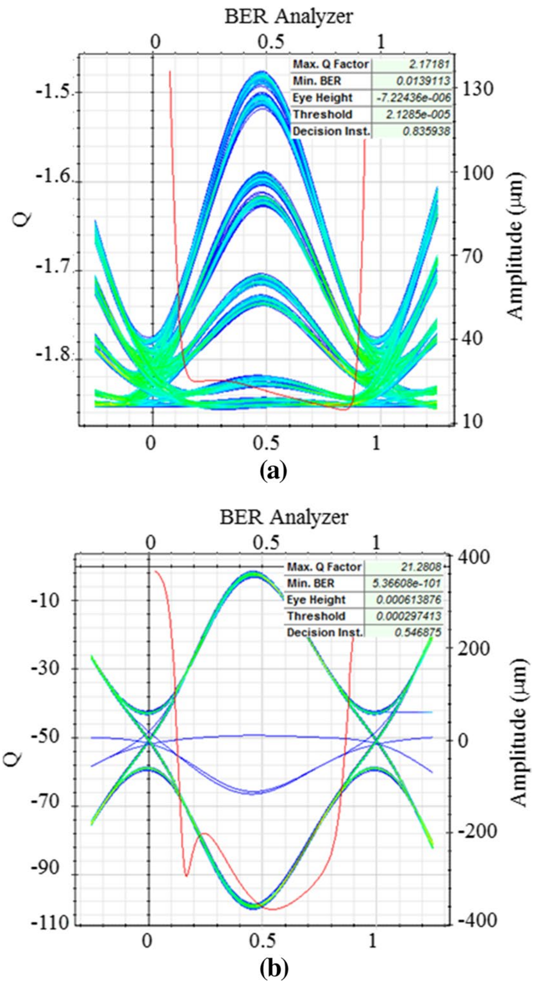


Fig. 5 The Eye diagram and Q-factor of **a** RZ and **b** NRZ-DPSK at 10 Gbps

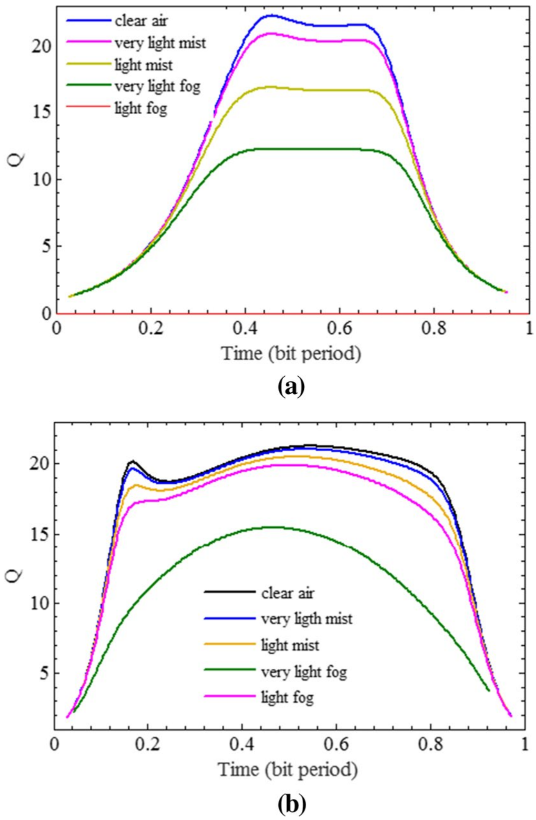


Fig. 6 Maximum quality factor versus time for **a** NRZ-DPSK and **b** RZ-DPSK at 10 Gbps

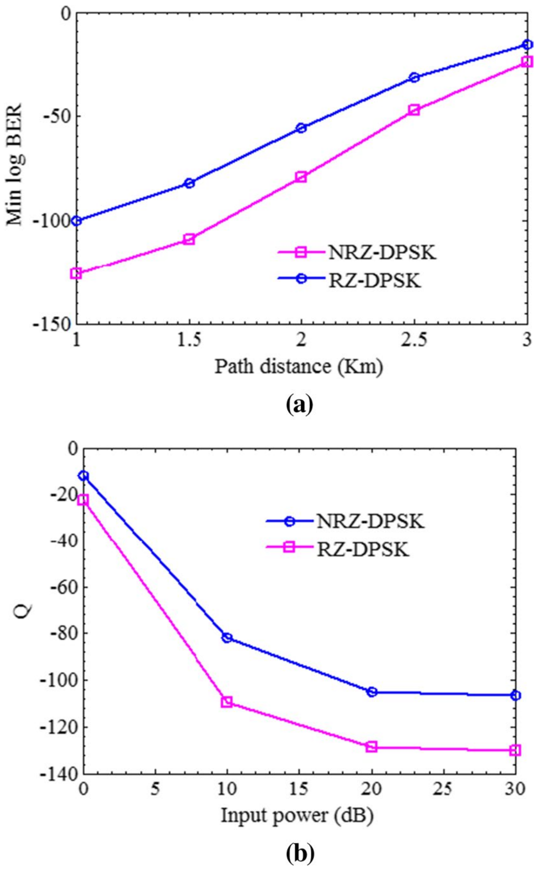
performance for the proposed system. However, the NRZ-DPSK modulation for clear air has a higher maximum quality factor and the RZ-DPSK modulation shows better performance at the unclear atmospheric condition. Also, Table 4 shows the maximum quality factor and minimum BER for the different atmospheric condition at 10 Gbps. It is obvious, because the eye diagram of NRZ-DPSK has good condition, so Q and BER have very good operation in compare with RZ-DPSK modulation format.

To demonstrate the performance of the proposed system, Fig. 7 has been brought. Figure 7a and b show the Min log BER versus of path distance and input power.

Table 4 Maximum quality factor and minimum BER for the different atmospheric condition

Atmospheric condition	NRZ-DPSK		RZ-DPSK	
	Max Q	Min BER	Max Q	Min BER
Very clear air	23.23	5.7×10^{-112}	21.28	5.3×10^{-103}
Clear air	22.25	3.53×10^{-110}	21.26	7.3×10^{-101}
Very light mist	20.88	2.63×10^{-97}	21.04	8.25×10^{-99}
Light mist	16.81	8.9×10^{-64}	20.5	6.9×10^{-94}
Very light fog	12.23	9.1×10^{-35}	19.9	1.35×10^{-88}
Light fog	0	1	15.4	3.6×10^{-54}

Fig. 7 Min log BER versus **a** path distance and **b** input power at 10 Gbps



Results demonstrate that by increasing the value of path distance, the Min BER is increased (Yeh et al. 2019). In the other hand increment the input power reduces the Min BER but enhances the insertion loss of the system. Finally, it can be shown the obtained results for free space optical communication can be used in WDM (Zuo et al. 2017), and advanced applications (Zuo et al. 2015; Zhang et al. 2020b; Zhang et al. 2020c; Zhang et al. 2019a; Liu et al. 2020; Niu et al. 2020; Niu et al. 1998), such as transceiver front end (Liu et al. 2020), multicarrier communication systems (Niu et al. 2020), mmWave UAV Communications (Zhao et al. 2020b), chaotic systems (Wang and Chen 2019), micro-Doppler signatures (Yang et al. 2019), wideband-tunable opto-electronic oscillator (Zhang et al. 2021), fast sliding-mode speed controller (Qu et al. 2021), quantum key distribution (Wang 2021), MBR performance (Sun et al. 2021), and also several materials can be used such as Organic Dye (Zhang et al. 2020d), NaClO (Zhang et al. 2019b), membrane (Sun et al. 2019), graphite (Dai, et al. 2021), carbon based material (Li et al. 2020; Yang et al. 2020; Liu et al. 2021a; Yan et al. 2021) and so on (Liu et al. 2021b; Hou et al. 2021).

6 Conclusion

In this paper, the performance of DWDM-FSO system under outdoor atmospheric channel model is presented. The proposed system is simulated at 10 Gbps bit rate and 2 km path link with different modulation type, NRZ-DPSK and RZ-DPSK. The mathematical model to study the attenuation loss, atmospheric loss and refractive index structure are used to model the outdoor atmospheric channel. Also, the optical power budget was calculated for the proposed system. Results show that the NRZ-DPSK and RZ-DPSK modulations for clear air condition have same and suitable performance, and Min BER for two modulations is less than 10^{-100}. But, in unclear atmospheric weather condition the RZ-DPSK modulation has better performance in comparison to NRZ-DPSK modulation.

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Data availability All data included in this paper are available upon request by contact with the contact corresponding author.

Declarations

Conflict of interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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