Journal of Scientific & Industrial Research
Vol. 82, June 2023, pp. 629-641
DOI: 10.56042/jsir.v82i06.1796

Performance Analysis of a DPSK-based High-Speed Spectral-Efficient FSO System under Different Weather Conditions

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Received 29 June 2022; revised 20 April 2023; accepted 21 April 2023

The Free-Space Optical (FSO) communication system has proven its capability to enhance spectral efficiency and support high data rates owing to its large available bandwidth compared to other communication techniques. However, the FSO-transmission link is highly sensitive to dynamic conditions such as atmospheric turbulence and weather conditions, therefore, channel attenuation arises and the received optical signal is degraded and distorted at the receiver end. In this paper, Dense Wavelength Division Multiplexing (DWDM) based (40 × 10) Gb/s FSO system performance is demonstrated over a maximum transmission link of 50–70 km with quality factor of Q = 16-4 in clear sky, condition whereas it is 0.1 km to 4 km in fog to rain weather conditions for the BER range of 10^{-5} to 10^{-7}. The novelty in this work is to achieve the optimum link distance with acceptable BER using a spectrally efficient (DWDM channel spacing of 0.6 nm), high speed advanced NRZ-DPSK (10 Gb/s) modulation format under very dense fog and rain weather conditions. Furthermore, an EDFA pre-amplifier with a gain of 20 dB has been incorporated at the transmitter side to mitigate the impact of atmospheric attenuation to achieve maximum transmission range of 70 km in clear sky conditions.

Keywords: Atmospheric attenuation, Bit error rate (BER), Dense wavelength division multiplexing (DWDM), Differential phase shift keying (DPSK), Quality factor (Q)

Introduction

Free-space optical (FSO) communication is a promising emerging technology for meeting the growing demand for high-speed data transmission and large bandwidth requirements in the visible to near-infrared wavelength ranges in various Line-Of-Sight (LOS) applications. It offers license-free transmission with the ease deplorability of the FSO system.[1] The performance of an FSO system is affected not only by internal system parameters such as beam divergence, antenna aperture, and signal power level, but also by external parameters such as atmospheric turbulence, multipath fading, scintillation, and, most importantly, climatic changes such as rain, fog, dust, and so on.[2] These adverse weather conditions attenuate and distort the transmitted optical signal, degrade the signal quality in terms of transmission link availability as well as high data transmission rate.[3] Signal attenuation ranges from 0.067 dB/km to 340 dB/km in clear to very dense fog weather conditions. The size of gaseous molecules and water droplets present in the air, along with the refractive index variation due to temperature changes in the atmosphere, cause the absorption and intensity fluctuations of the received signal at the receiver. The density of the fog reduces the visibility range to less than 1 km near the earth's surface, which minimizes the link range due to scattering and absorption phenomenon.[4]

The FSO system performance is evaluated by performance indicators such as the quality factor (Q), Bit Error Rate (BER), and Signal-To-Noise Ratio (SNR). To improve these performance indicators, various techniques have been reported in existing research. Research has been conducted on different parameters, such as the suitable choice of the modulation format, the polarization scheme, the appropriate optical wavelength, and the type of multiplexing. These parameters have played a critical role in improving the spectral efficiency and speed of transmission links under various weather conditions and for different transmission ranges.[5]

Literature Review

To improve the speed of the FSO system, different modulation schemes have been reported in several research papers. In comparison to the Return to Zero

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(RZ) encoding the Non-Return To Zero (NRZ) encoding format yielded the best results in cases of high data rate and long distance FSO link. The 3 km FSO link has been discussed using subcarrier intensity modulation based on OOK (SIM-OOK), Polarization Shift Keying (Pol-SK), and BPSK formats (SIM-BPSK).[6] The evaluation of a high speed FSO link using differential quadrature phase shift keying (D-QPSK) over the FSO link range of 0.8 km has been demonstrated.[7] In recent years, various orthogonal modulation formats, such as amplitude shift keying/frequency shift keying (ASK/FSK) and NRZ/DQPSK//Pol-SK have been incorporated to achieve high-speed optical links. These modulation schemes offered multi-bit/symbol transmission, and their performance has been investigated under different rainy and fog conditions.[8] In addition to selecting an appropriate modulation format, various literature surveys have discussed the selection of an appropriate transmitted optical wavelength. In different weather conditions, it has been proven that the optical wavelength near 1550 nm offers the least attenuation under the worst atmospheric conditions, hence support for increasing the transmission range in a high-speed FSO system.[9]

Different researchers have also discussed various multiplexing techniques to improve the spectral efficiency and capacity of the high-speed FSO system. Eight spatially multiplexed high-speed 10 km fibers have been combined with a 0.1 km to 1 km FSO hybrid link to provide a solution to the last-mile network with a total attenuation of 15 dB. Mode Division Multiplexing (MDM) has been incorporated to enhance the performance of the FSO link.[10,11] A transmission rate of 228 Gb/s has been made possible using direct detection Orthogonal Frequency Division Multiplexing (DD-OFDM) and found to be a good candidate in large capacity FSO systems.[12] A 100 Gb/s hybrid MDM-FSO system for a maximum link of 22 km and threshold BER of 10^{-29} under atmospheric turbulence has been proposed.[13] Wavelength Division Multiplexing (WDM) has recently emerged as a new multiplexing technique in which a large number of optical wavelengths with tight adjacent channel spacing can be multiplexed and transmitted over a turbulent atmospheric channel to achieve a spectrally efficient high speed FSO system.[14,15] An adaptive hybrid WDM, MDM, and multiband techniques have been investigated under fog conditions with a faithful 80 Gb/s transmission rate and an acceptable enhanced link range of 2 km.[16] Similarly, a 40 Gb/s dense WDM-FSO system has been reported to achieve an optimum link distance of 4 km without using any compensation techniques.[17] Furthermore, spatial multiplexing with wavelength diversity scheme has been incorporated to improve the FSO system's performance at a data rate of 40 Gb/s for a link range of 4 km. The improvement in performances has been discussed in these research papers on the basis of BER and eye pattern.[18] A hybrid, (12×2.5) Gb/s, WDM-based FSO system has been proposed to achieve a maximum link distance of 960 km. The performance of the system was investigated under different channel conditions using the Q factor and BER performance metrics.[19] An improved WDM-FSO system with Spectrum Slicing Wavelength Division Multiplexing (SS-WDM) has been focused on 4, 8, and 16 channels with a data rate of 1.56 Gb/s under wind velocity turbulence and atmospheric scintillation.[20] To enhance the received signal strength with link distance and mitigate the channel attenuation, an optical amplifier-based hybrid WDM-FSO link has been proposed under hazy and rainy weather conditions to achieve the link distance between 10 km and 27 km with a Q factor range of 5 to 11 for light and heavy rain conditions.[21]

Following a review of the literature, this study proposes a high-speed and spectrally efficient 40-channel DWDM-based FSO system, with each channel carrying 10 Gb/s non-return to zero differential phase shift keying (NRZ-DPSK) modulated data at a wavelength of 1550 nm. The 40 orthogonally modulated channels, having an adjacent channel width of 0.6 nm, are multiplexed to transmit 400 Gb/s of information over the foggy and rainy atmospheric channel, offering different attenuation levels. The ability of 0.6 nm channel width based DWDM multiplexing and NRZ-DPSK modulation to increase the spectral-efficiency of the proposed system is the driving force behind its adoption, whereas the EDFA amplifier is used to provide high gain and bandwidth to mitigate the channel attenuation. The major objective of this work is to propose a high-speed and spectrum efficient DWDM-FSO system and to analyze and compare its performance under the impact of dense fog and rain conditions having dynamic attenuation levels with existing research work.

Block and Schematic Layout of Proposed System

The block diagram of the high-speed and spectrally efficient DWDM-FSO system is shown in Fig. 1.

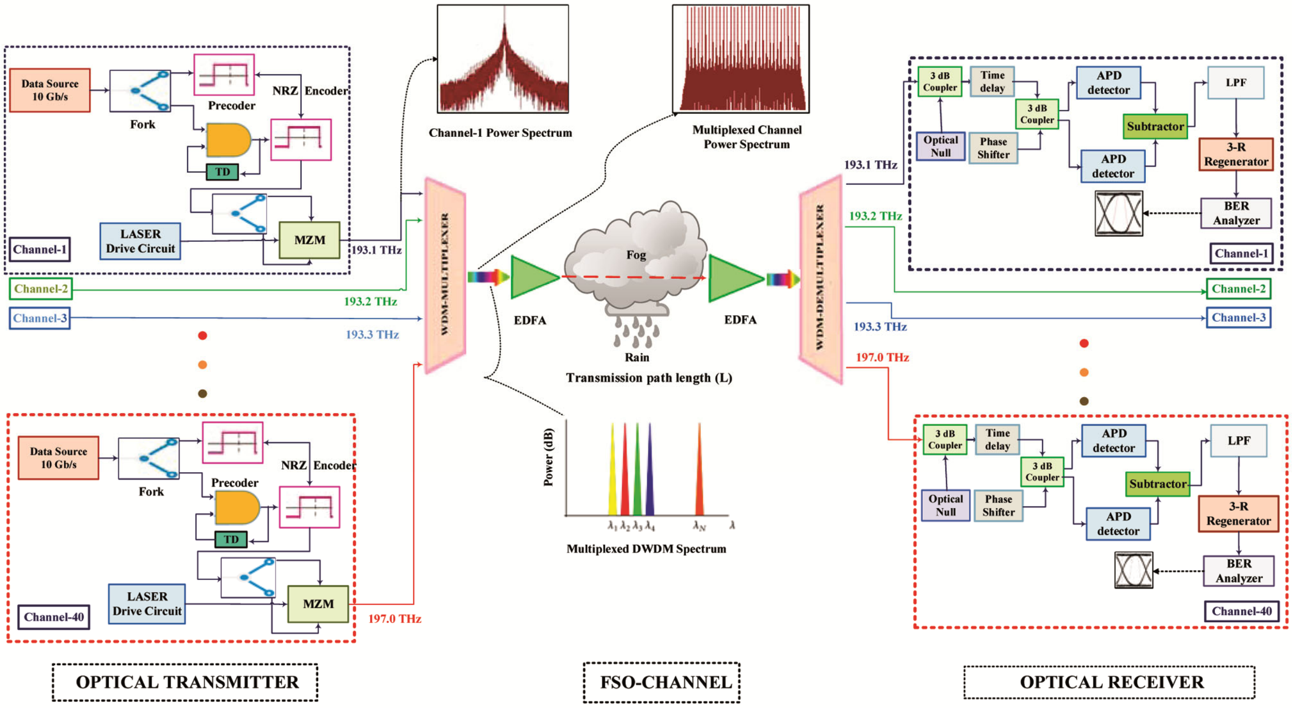

Fig. 1 — Conceptual block diagram of the proposed DWDM-FSO system

There are three sections to the proposed system: an optical transmitter, a FSO channel, and an optical receiver, respectively. An optical transmitter consists of a data sequence generator, two Fork blocks, a NRZ encoder, a pre-coder, a Mach-Zehnder Modulator (MZM), and continuous laser drive circuit blocks. The data source generates the binary information at a data rate of 10 Gb/s which is further modulated by the non-return to zero Differential Phase Shift Keying (NRZ-DPSK) orthogonal modulation scheme. A DPSK-modulated electrical signal is generated by the pre-coder block having a one-bit delay. The NRZ-DPSK requires two MZM, one for phase modulation and the other for pulse carving. This signal further drives the second MZM modulator, known as a phase modulator, and produces an optical frequency of 193.1 THz. The reason for choosing the NRZ-DPSK digital modulation scheme is to take advantage of its high data rate link capability in long distance transmission and its −3 dB better receiver sensitivity compared to other modulation schemes like an On-Off Keying (OOK) modulation. The output from such 40 modulators is multiplexed using a DWDM multiplexer block in the frequency range of 193–197 THz, near the 1550 nm wavelength. The multiplexed data is further amplified by Er^{3+} level Doped Fiber Amplifier (EDFA) with a gain of 20 dB and a noise figure of 4 dB to minimize the channel attenuation losses.[22] The amplification in this amplifier lies in the 1.5 μm band, which can be utilized directly in the 1550 nm wavelength window. The amplified optical signal is then transmitted through the free space turbulent optical channel.

The atmospheric channel is presented by the FSO channel section, with dynamic attenuation levels ranging from [9.68 to 220] dB/km, respectively. These attenuation levels represent moderate rain, heavy rain, and very dense fog, respectively. According to these weather conditions, the minimum transmission link range can be shown under very dense fog conditions. The optical receiver section has two couplers, a phase shifter, a time delay unit, two APD photo detectors, a low-pass Bessel filter, and three 3-R regenerator blocks. The attenuated optical signal is amplified before being fed into the DWDM de-multiplexer block. Using the principle of balanced detection, the de-multiplexed information is optically demodulated and converted back to an electrical signal by the Avalanche Photo Detector (APD), while unwanted noise is suppressed by the Bessel Low-Pass Filter (LPF). The APD is preferred over PIN detectors because of its capability to enhance the received signal over additive noise at the receiving end of the link. The output of the 3-R regenerator is connected to the BER analyzer, which is used to analyze the FSO channel noise effect on the proposed system in terms

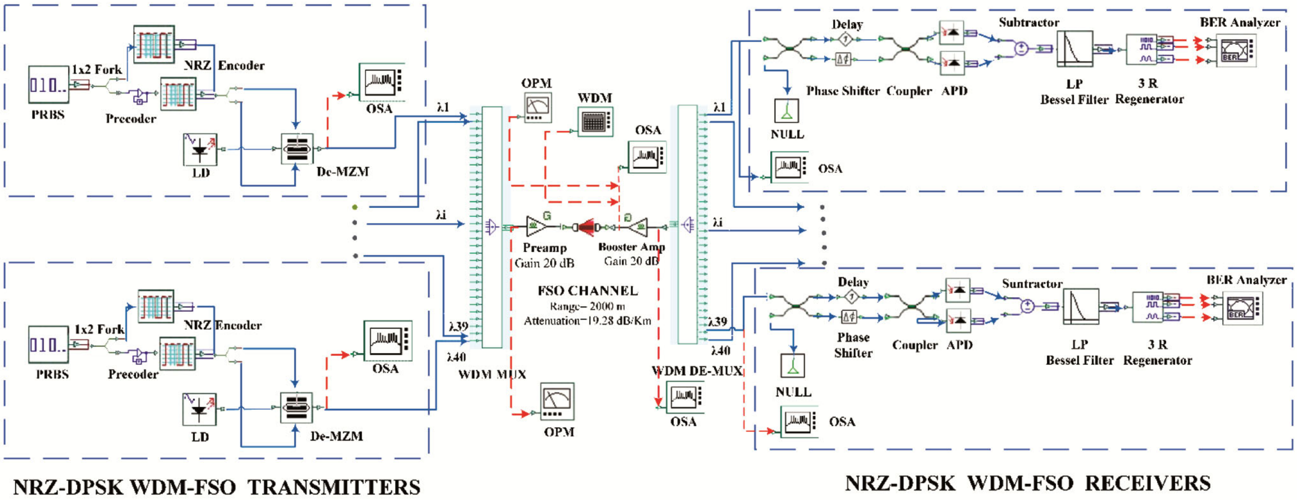

Fig. 2 — Schematic layout design of the proposed DWDM-FSO system

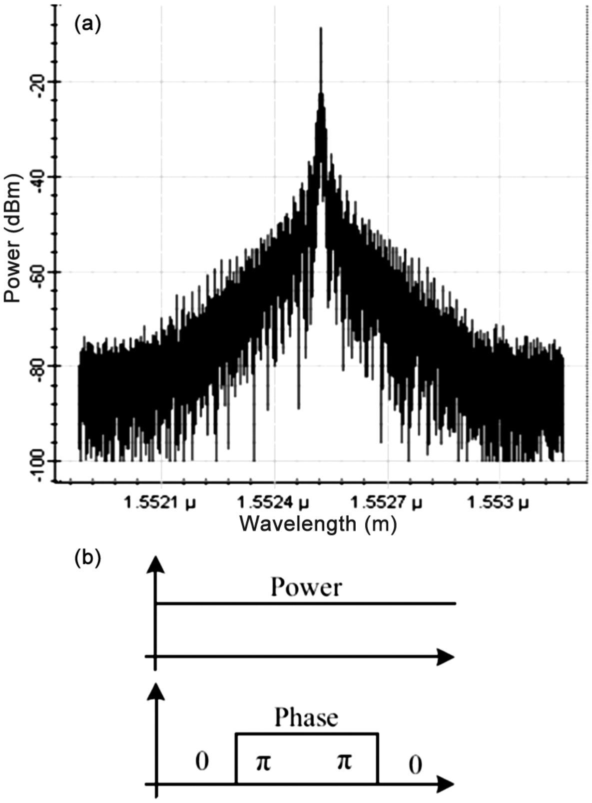

Fig. 3 — (a) Optical spectrum of NRZ-DPSK signal (b) Generated bits at channel 1 output

of the performance indicator Q factor and Bit Error Rate (BER).

The schematic layout of the proposed system is shown in Fig. 2, where binary data is produced by a Pseudo-Random Bit Sequence (PRBS) generator. This data is then duplicated without any loss of power by using 1 × 2 fork. The output of the 1 × 2 fork is connected to the input of the NRZ encoder and the input of the pre-coder. The pre-coder block generates the duo-binary signal, which is further fed to the input of the NRZ block to generate the encoded duo-binary signal. The total number of samples in this NRZ block is 8192, with 64 bits per sample. The sensitivity of the NRZ block is set to be −100 dBm. This duo-binary signal instructs the De-MZM block to generate an electrical signal with a frequency of 10 GHz. The transmitted optical laser output power is determined by the selection of the wavelength and the laser drive (LD) circuit. The continuous wave (CW) laser beam is pointed at a dual-electrode Mach-Zehnder modulator (De-MZM) with a 30 dB extinction ratio. The electrical signal that is NRZ-DPSK encoded modulates the laser beam at a wavelength of 1550 nm. All 40 wavelengths are multiplexed in a DWDM block. To further minimize the channel losses, the multiplexed optical signal is amplified by pre-amplifier gain blocks with a gain of 20 dB and a noise figure of 4 dB. An amplifier boosts the distorted received signal before feeding it to the input of the de-multiplexer at the receiver end. Then, de-multiplexed data is sent to a different part of the receiver by the selector switch, while a low-pass Bessel filter provides a sharp slope with a linear phase and hence minimum receiver noise compared to other kind of LPF. The 3-R generator block simplifies the design by eliminating the need for multiple forks. This block generates the distorted eye diagram in the BER analyzer.

The optical signal spectrum at the NRZ-DPSK modulator's output for channel 1 is presented in Fig. 3 (a), whereas Fig. 3 (b) displays the corresponding NRZ-DPSK-generated bits. The results illustrate the simulated optical spectrum, which ranges from −104.57 to −4.084 dBm for 0.02 nm resolution bandwidth near 1.55 μm optical wavelength. On the other hand, Fig. 4 illustrates the simulated optical spectrum at the output of the DWDM multiplexer. The spectrum depicts the measured maximum power of −1.69 dBm at an Optical Signal-To-Noise Ratio (OSNR) of 12.75 dB. The simulated results in Fig. 3 and Fig. 4 are taken for the link range of 2 km at an atmospheric attenuation level of 19.28 dB/km under heavy rain weather conditions.

Attenuation Models for FSO Channel

Depending on the size and density of the rain and fog particles, the transmitted signal through the atmospheric link has to deal with absorption and scattering losses. Here, the geometrical losses due to transmitter and receiver apertures are assumed to be negligible for the proposed system. Hence the total atmospheric losses are given by

Attenuation (dB/km) = absorption losses + scattering losses ... (1)

When the optical signal is transmitted through the atmosphere, the photons will interact with the gaseous particles and cause absorption and scattering of the photons. A very narrow optical band spectrum is preferred to minimize optical signal scattering. The attenuation level present in the FSO link leads to a reduction in the performance of the proposed system. The presence of atmospheric attenuation in FSO link is mainly due to the different particle dimensions and their concentrations present in the air, which vary with time and local weather conditions. Due to the presence of rain and fog particles in the atmosphere for a longer period of time, the visibility of the link is affected.[23] In general, if the optical power transmitted is P_T, the optical power received P_R at the receiver can be expressed by Eq. (2)

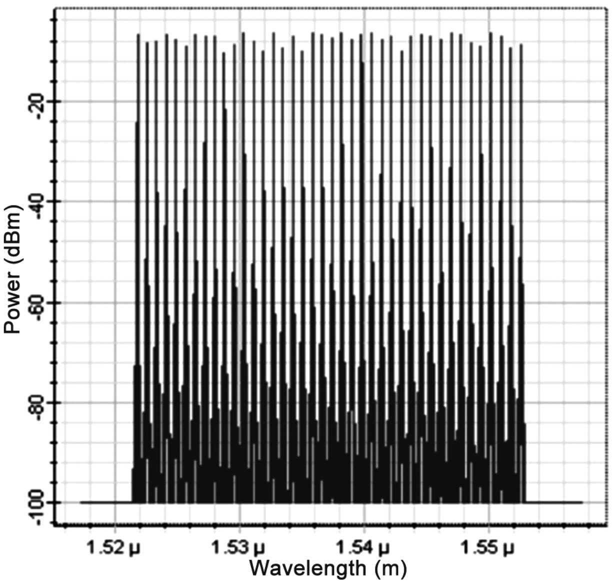

Fig. 4 — Optical spectrum at DWDM-Mux output

$$P_R = P_T e^{(-\tau_d)} \qquad \ldots (2)$$

The optical depth (τ_d) can be rearranged in terms of the total attenuation coefficient $\alpha_T(\lambda)$ and free space loss (L_{FS}), so Eq. (1) can be further modified and given by

$$P_R = P_T e^{[-\alpha_T(\lambda) L_{FS}]} \qquad \ldots (3)$$

The gases and aerosols present in the link are primarily responsible for the optical signal attenuation caused by scattering and absorption, which is explained by

$$\alpha_T(\lambda) = \alpha_m(\lambda) + \alpha_a(\lambda) + \beta_m(\lambda) + \beta_a(\lambda) \qquad \ldots (4)$$

where, α_m and α_a are the molecular and aerosol absorption coefficient, whereas $\beta_m$and β_a are the molecular and aerosol scattering coefficient. The first three attenuation coefficient in Eq. (4) are experimentally insignificant, so the aerosol scattering coefficient is equal to the total attenuation coefficient.[24] Hence the Eq. (4) is approximated to Eq.(5).[25]

$$\alpha_T(\lambda) = \frac{13}{v}\left(\frac{\lambda}{550nm}\right)^{-q} \qquad \ldots (5)$$

The visibility range constant v, and the dispersion distribution (DD) parameter q are summarized in Table 1 for different weather conditions. At optical wavelength of λ = 1550 nm, the standard value of α_T chosen for our proposed system is shown in Table 2.[26] The system experiences strongest attenuation under very dense fog conditions.

Rain Distribution Model

Rain consists of droplets of different radii, from 1 mm and beyond. It is formed at different times and in different atmospheric regions by the water vapour present in the atmosphere. Non-selective scattering occurs as a result of the rainfall of droplets of varying sizes with radii ranging from 10^2 to 10^3 m. These droplets radius is larger than the transmitted

Table 1 — Attenuation in different weather conditions[21]

Weather	q	v (Km)	α_T(dB/Km)
Moderate Rain	0.585 $v^{1/3}$	2.4-3.8	9.68
Heavy Rain	1.3	1.8-2.0	19.28
Very dense Fog	1.6	0.05-0.08	320

Table 2 — Simulation Parameters of the proposed system

Parameters	Values
Data rate/channel	10 Gb/s
Transmitted Power	1 dBm
Modulation scheme	NRZ-DPSK
Channel spacing	0.6 nm
Laser line width	10 MHz
Laser noise threshold	−100 dB
Apertures diameter	0.1m
Average Atmosphere Temperature	25℃
Refractive index structure constant	5×10^{-13} $m^{-2/3}$
Rytov Parameters	0.8
Maximum link distance	70 km
Dark Current	10 nA
MZI insertion Loss (Extinction Ratio)	30 dB
EDFA Amplifier and Gain	20 dB
Beam divergence	0.25 mrad
Refractive index structure	$5x10^{-3}$ $m^{-2/3}$
Photodiode responsivity	0.9 A/m
Ionization current	0.9 A
LPF cutoff frequency	0.75 × bit rate
LPF sensitivity	−100 dBm

wavelength, so the optical signal is easily able to pass through the raindrop with less scattering loss. Rain attenuates less than haze particles due to their larger size, and thus they stay in the atmosphere for a shorter period of time. The rain scattering coefficient for a raindrop of radius r (cm) and scattering efficiency q_{scat} is shown in following expression.[27]

$$R_{Scat} = \pi r^2 N_a q_{scat} \left[\frac{r}{\lambda}\right] \quad \dots (6)$$

Raindrop distribution N_a(cm^{-3}) and speed precipitation V_r for the rainfall rate R (cm/s) are given by

$$N_a = \frac{R}{1.33\pi r^3 V_r} \text{ and } V_r = \frac{2r^2 \rho g}{9\eta} \quad \dots (7)$$

where, ρ (1gm/cm^3), and g (980 cm/sec^2) are the water density and gravitational constant, respectively, while the constant η have the value of 1.8×10^{-4} g cm^{-1}.sec^{-1}. The rain attenuation β_{rain} can be expressed by the below equation

$$\beta_{rain} = e^{(-R_{Scat} L_p)} \quad \dots (8)$$

Fog Distribution Model

The major challenge in designing the FSO link is fog channel modelling, which is considered the worst case scenario, reducing visibility range to a few meters. Water droplets and ice particles suspended in the atmosphere are the main components of fog. At 100% saturation, these particles scatter the transmitted optical beam, reducing link visibility to less than 1 km. The fog is explained using particle size, water content, ambient temperature, and humidity. In general, fog particle size is comparable to the transmitted optical wavelength, resulting in significant attenuation when compared to rain attenuation. Under very dense fog, this signal attenuation reaches a maximum of 480 dB/km. Fog is a random process that changes with season, location, and time, and it is best understood using a probabilistic model that is dependent on visibility data. Using Koschmieder law, the fog attenuation[26] is expressed as the following expression for the meteorological visual range v

$$v = -10\frac{\log_{10}(T_{th})}{\beta_\lambda} \quad \dots (9)$$

$$\beta_\lambda = 10\frac{\log_{10} T_{th}}{v(Km)}\left(\frac{\lambda_o}{\lambda}\right)^q \quad \dots (10)$$

where, the visual threshold T_{th} is chosen 2% of the original transmitted power for the solar band spectrum at $\lambda_0 = 550$.

For the proposed system, the fog attenuation of 320 dB/Km is chosen as shown in Table 1. The best estimation model which accurately predict the fog attenuation for the proposed visibility range less than 1 Km is given below[28]

$$\beta_\lambda = 10\ln\left[\frac{0.11478\lambda + 3.8367}{v(Km)}\right] \quad \dots (11)$$

Results and Discussion

This section provides a thorough discussion and analysis of the simulation results obtained for the proposed system under moderate and, heavy rain and very dense fog conditions. The optimal system parameters used for the simulation are presented in Table 2, while Table 3 compares the simulation results obtained with the current research work. The Eq. (12) defines the relationship between spectral efficiency and data rate for the proposed NRZ-DPSK modulated DWDM-FSO system. To achieve a high spectral efficiency in the DWDM-FSO system, the multiplex channel spacing f_s must be reduced while the modulation alphabet size M must be increased. This increases the symbol rate (R_s) and the data rate of the proposed FSO system. The relation between these parameters is given by Eq. (12).

$$S = \frac{\log_2(M)R_s}{f_s} \qquad \dots (12)$$

The wavelength channel spacing of 0.6 nm and the constant refractive index structure parameter of 5×10^{-13} $m^{-2/3}$ are chosen considering the moderately turbulent conditions under Gamma-Gamma distribution. The proposed system performance is analyzed by different performance indicators, such as the Q, BER, eye diagram, and the link distance.

For the clear visibility and the atmospheric attenuation level of 0.01 dB/km, the quality factor (Q) and the log bit error rate (BER) vs. optical link range (L) are shown in Figs 5(a) and (b), respectively. As shown in Fig. 5(a), the maximum Q factor of 16 is observed at a link distance of 50 km, which further decreases exponentially up to a minimum value of 4.2 for a link distance of 70 km. The visibility range obtained from the simulation validates the visibility range shown in Table 1 for clear sky conditions. The BER curve increases exponentially from −24.96 dB for 50 km and attains the maximum value of −2.97 dB at 70 km, as depicted in Fig. 5(b). The BER value of 10^{-6} is attained with the addition of an EDFA amplifier at a 70 km link distance for the corresponding factor of 4.52 whereas, without using an amplifier, the same BER is obtained for the link range of 25 km. The results in Fig. 5(a) show that as the 1 km link distance increases, the quality factor decreases by factor of 0.58. However, the BER increases from −24.96 dB to −2.13 dB and almost reaches saturation at 0 dB after a 70 km link range. The simulation results clearly predict that the proposed system will achieve the link distance of 70 km with a data rate of 400 Gb/s and a satisfactory BER of 10^{-6}. The results also show that the quality factor falls below the acceptable Q value of 6. At this Q value, the BER analyzer calculates a BER of −3.63 dB for a 66 km FSO link. The results conclude that the proposed system offers the best performance below link distance at 50 km with a favorable BER of less than 10^{-6}.

The correlation between the Q factor and log BER for moderate rain, heavy rain, and very dense fog is depicted in Figs. 6(a) and 6(b), respectively. In all climatic conditions, the results show that as transmission range increases, the Q factor decreases

Table 3 — Comparison of the proposed work with existing reported work at λ = 1550 nm

References	Ref.16	Ref.17	Ref.18	Ref.19	Ref.20	Ref.21	Proposed Work
Data rate (Gb/s)	80	40	40	30	24	12 Gb/s	400
Channels	4	8	4	12	16	03	40
Modulation scheme	QAM-4	RZ	NRZ	NA	NRZ	NRZ	NRZ-DPSK
Multiplexing	WDM, MDM	DWDM	WDM	DWDM	SS-WDM	NA	DWDM
Weather Conditions	fog	rain	rain	rain	fog	rain, haze	rain, dense fog
Attenuation(dB/km)	19.28	3.5	25	19.28	30	3–20	9.68–320
Link Range (km)	2	4	2	3	10	57	0.1–70
Q Factor	2.3	8.46	5.68	3.41	3.42	12.0564	4–16
BER	NA	1.70×10^{-15}	9.14×10^{-26}	10^{-7}	10^{-19}	NA	10^{-12}–10^{-19}

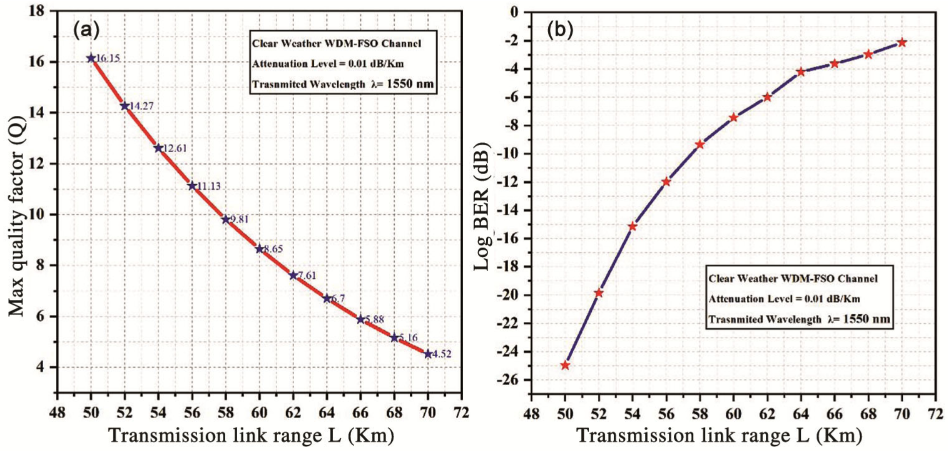

Fig. 5 (a) — Quality factor and (b) BER vs. transmission range under clear sky condition while the log BER increases. For the moderate rain rate, the Q factor decreases exponentially from value 39.75 to 6.2 for the link range from 2.3 km to 2.7 km. This means the quality factor decays by a factor of 83.76 km, and so the proposed system works satisfactorily up to a 2.7 km range. On the other hand, the log BER increases in an exponential manner from −21.16 to 0 dB for the transmission range of 0.4 km to 0.5 km. Under conditions of heavy precipitation, the quality factor decreases from 58.2 to 26.2 (106 times/km) is observed for the link transmission range of 1.1 km to 1.4 km whereas the log BER increases from −41.17 dB to −2.27 dB. In Fig. 6(b), the BER rapidly increases from −41.17 dB to 0 dB for the link range of 1.9 km to −2.5 Km. This clearly predicts the poor performance of the proposed system under heavy rain conditions as compared to moderate rain weather conditions. The simulation results for the foggy climate condition present the worst scenario for the transmission link range greater than 0.3 km. In Fig. 6(a), the Q factor decreases from 127.2 to 52 by 376 times per km for the transmission range from 0.1 to 0.3 km. So for a very small change in link distance, the signal strength attenuates very fast. Under very dense fog conditions, the proposed system performs satisfactorily only for a small link range of 0.2 km. The received signal strength falls below the threshold value of 0 dB due to a change in the small link distance of around 0.8 km. These results clearly indicate that, due to the low visibility in a foggy climate, the received optical power is very small compared to moderate and heavy rain conditions. The results also infer that BER approaches 0 dB under foggy and heavy rain conditions for the link ranges of 0.5 km and 2.5 km, respectively. However, 0 dB BER can be achieved even beyond 4 km. The numerical results obtained prove that the dense fog conditions are the worst scenario for the proposed system compared to the two other scenarios.

The characteristics of the transmitted optical frequencies under the three weather conditions are plotted in Fig. 7 in terms of quality factor and BER. For the link range at 2.3 km shown in Fig. 7(a), comparing moderate and heavy rain, the maximum Q value of 17.7 is found at 196.7 THz for moderate rain, while the minimum Q value of 12.15 is found at 196.6

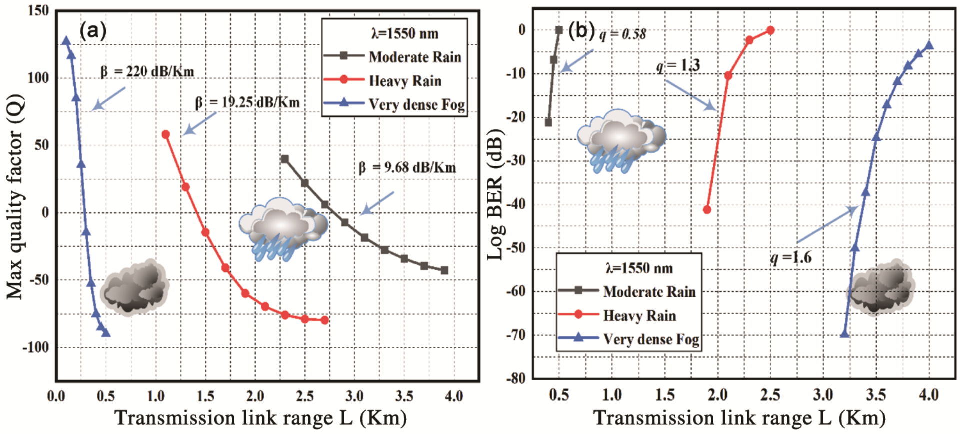

Fig. 6 — (a) Quality factor and (b) BER v/s link distance under different weather conditions

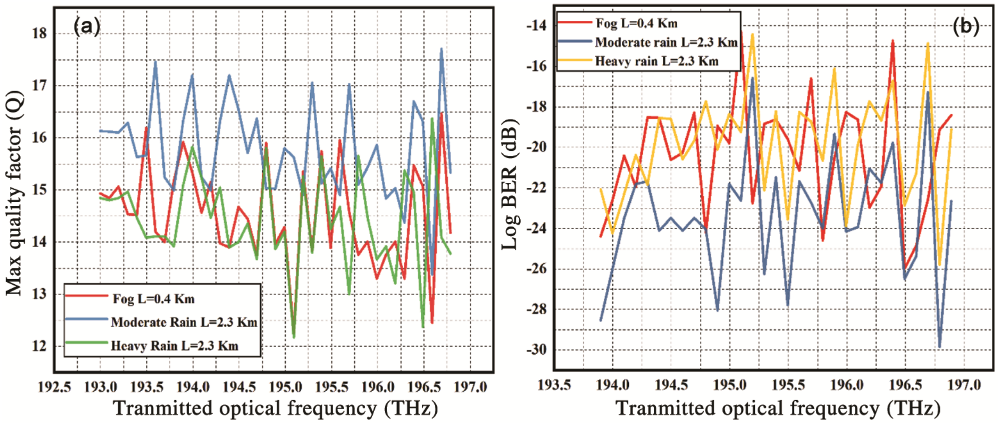

Fig. 7 — (a) Quality factor v/s link range (b) BER v/s transmitted optical frequencies

THz for heavy rain. This clearly indicates that at a 2.3 km link distance, the 196.7 THz transmitted frequency is least attenuated, while the 196.6 THz frequency is most attenuated in both the moderate and heavy rain conditions. For foggy conditions, 196.7 THz is the least attenuated and 196.6 THz is the maximum attenuated frequency component during the transmission. In Fig. 7(b) the variations in received power strengths for various transmitted frequencies under three different climatic conditions are depicted. For moderate rain at a link distance of 2.3 km, the 196.8 THz frequency components provide the lowest BER of 29.9 dB, while the 195.2 THz frequency components provide the highest BER of 16.6 dB. In heavy rain, the 195 THz optical frequency offers a minimum BER of −19.82 dB, while the 195.2 THz optical frequency offers a maximum BER of −14.27 dB. At L = 2.3 km, the transmitted signal is completely attenuated due to the dense fog conditions. However, the 195.0 THz frequency performs best in terms of BER near a 0.4 km link distance. We can conclude that increasing the transmitted power improves link performance in all cases for fixed link ranges. We can conclude that frequencies near 196.5 THz perform best in all weather conditions and over a wide range of link distances.

The transmitted optical spectrum of the DWDM multiplexed channels at the output of the EDFA amplifier is presented in Fig. 8(a). The maximum and minimum power contained by the optical wavelengths is 19.3036 dBm and −105.681 dBm, respectively, whereas the transmitter-side components contribute a total noise level of −66 dBm. This DWDM-FSO signal is transmitted through the FSO channel under moderate rain climatic conditions, which provides a total attenuation level of 9.68 dB/km at a link distance of 2.3 km. The corresponding optical spectrum at the input of the DWDM de-mux is also portrayed in Fig. 8(b). The maximum and minimum power levels found at this condition are −0.489 and −104.739 dBm, respectively, along with a total noise level of −59.982 dBm. The channel spectrum of the received optical signal is illustrated in Figs 8(c) and 8(d) at the input of the DWDM de-mux under heavy rain and dense

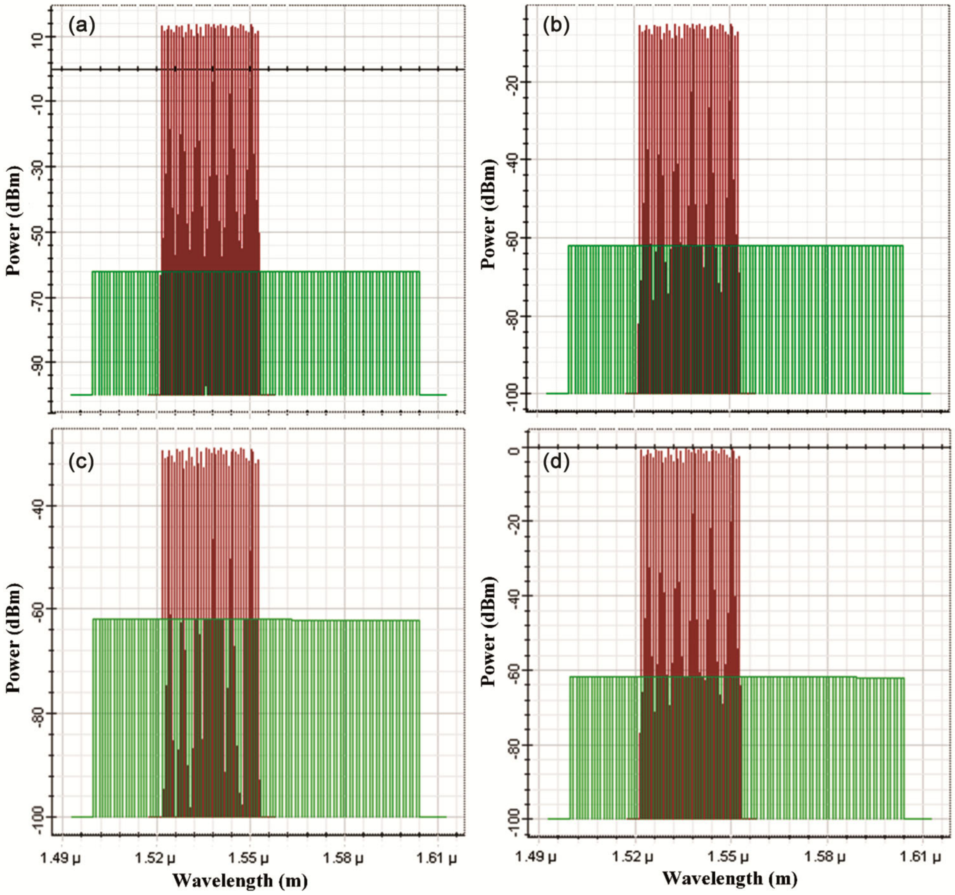

Fig. 8 — Channel spectrum of (a) transmitted DWDM-FSO signal (b) received signal under moderate rain at L = 2.3 km, DWDM channel Spectrum for (c) heavy rain at L = 2.3 km and (d) dense fog at L = 0.1 km

fog climatic conditions for a link distances of 2.3 Km and 0.1 km, respectively. The attenuation levels for moderate weather conditions are assumed to be 19.68. Under heavy rain conditions, the maximum and minimum received power is −25.36 dBm and −103.34 dBm respectively, with −59.9 dBm. A very dense fog condition with an attenuation level of 320 dB/km is shown in Fig. 8 (d). The maximum and minimum power levels are 4.66 dBm and −104.98 dBm, respectively, with an added noise level of −59.89 dBm. From the results obtained from the simulation, it has been found that the maximum link distance of a 0.15 km is achieved for the received signal threshold level. Below this level, the optical receiver is not capable to detect the signal. So beyond this transmission range, the BER is maximum and the performance of the proposed system iw worst.

The eye diagram comparison of the proposed system is demonstrated in Fig. 9. The results depict the differences in the received signal quality of the DWDM-FSO system under different weather conditions. The received signal quality is shown in Figs. 9(a) and 9(b) for two different link distances under a moderate rain scenario with a constant attenuation level of 9.28 dB/km. The received signal quality decreases by an amount of 28.8 for every 0.3 km link change with almost no change in BER, as shown in Fig. 9(b). This proves that the proposed system performance is better than less than 2.0 km link distance. The signal quality further decreases as the attenuation level changes to 19.68 dB/km under the heavy rain scenario presented in Figs. 9(c) and 9(d). For the same amount of change in link distance, the quality factor further decreases by an amount of 8.1, and the corresponding BER changes from 10^{-9} to 10^{-30}. This concludes that for the same link range, the eye height is higher in Figs. 9(a) and 9(b) compared to 9(c) and 9(d). This huge difference highlights the better performance of the proposed system under moderate rain conditions. Further, in the dense fog scenario shown in Figs. 9(e) and 9(f), the proposed system performs better at a link distance of 0.1 km. When this link range increases to 0.25 km, the Q factor decreases quickly from 188.4 to 6.37, keeping the same BER. So the final result predicts that the proposed system will achieve a maximum link distance of 0.1 km. The above discussion is based on when an EDFA amplifier is added to the proposed system in all weather conditions. Simulation results justify the fact that, without using an optical amplifier, the visibility range under dense fog conditions further decreases to less than 50 m. Hence, the EDFA amplifier improves the link range for the proposed system up to 0.1 km for the same BER.

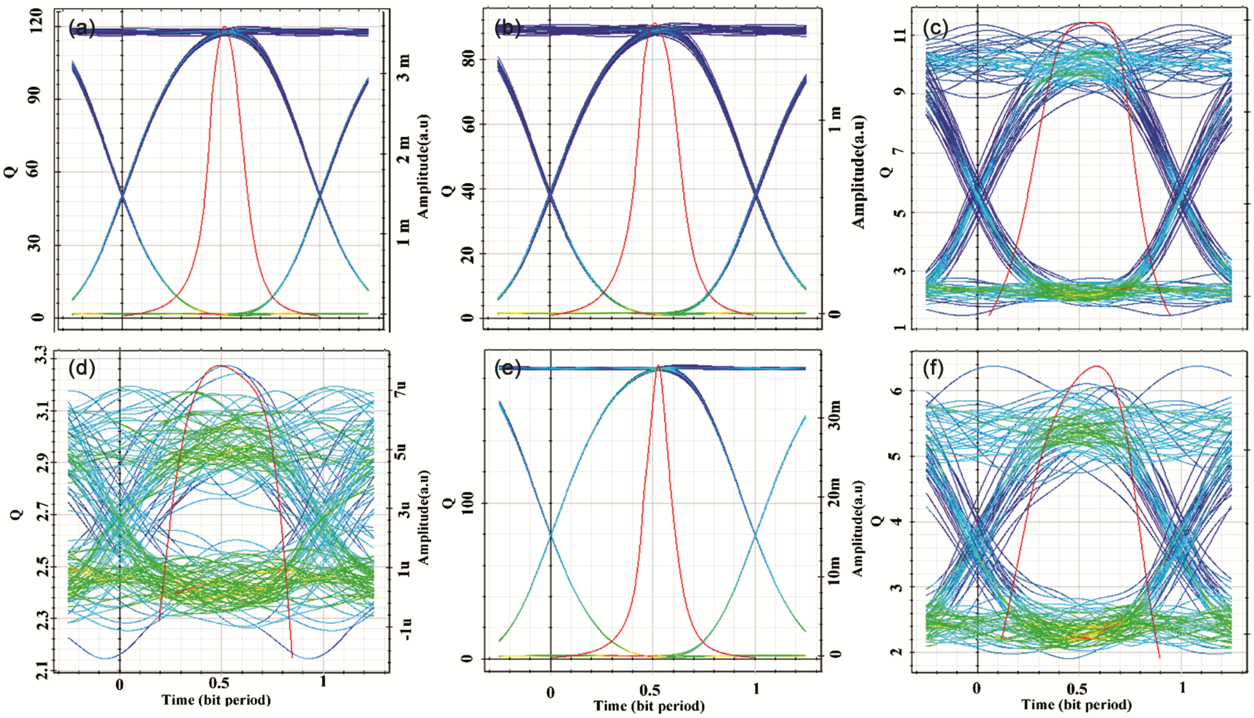

Fig. 9 — Eye diagram under moderate rain condition at (a) L = 2.0 km and (b) L = 2.3 km, Eye diagram under heavy rain at (c) L = 2.0 km and (d) L = 2.30 km, Eye diagram under dense fog at (e) L = 0.1 km and (f) L = 0.25 km

The performance of the proposed system is compared with existing research and summarized in Table 3. The data rate, attenuation level, and number of multiplexed channels for the proposed system are on the higher side as compared to the existing research work. The proposed system performance is tested under three different weather conditions to achieve the transmission range of 0.2 km to 4 km using the same system specification and performance metrics like Q factor and BER, while the system simulation parameters are the same as described in existing research work shown in Table 3. The proposed DWDM-FSO system is a high-speed (400 Gb/s) and more spectrally efficient system (40 channels) as compared to the FSO system presented by Balasaraswathi *et al.*[16] in which the maximum link distance of 2 km is achieved with a Q factor of 2.3 and data transmission rate of 80 Gb/s under fog weather conditions with a moderate attenuation level of 19.28 dB/km. Most of the FSO system summarized in Table 3 is investigated for a single weather condition with a light or moderate attenuation level. The maximum channel attenuation level chosen for the proposed system is 320 dB km, which maps to very dense fog conditions. The proposed system performs excellently in terms of all the performance metrics compared to other FSO systems proposed in Table 3. The simulated eye-diagrams for the moderate and heavy rain scenarios presented in Fig. 10(a) and 10(b) validate these statements. The simulation results obtained for quality factor (Q = 2.3) by Balasaraswathi *et al.*[16] are very low as compared to those shown by Modalavalasa *et al.*[18] for the same transmission link range, even at higher attenuation levels and higher BER of 10^{-26}. However, the proposed system is showing better Q, BER, and link range performance under even higher attenuation levels (320 dB/km) for very dense fog conditions. On comparing the simulation results obtained for Q (8.46) and BER of 10^{-15} by Prakash *et al.*[17] and the proposed system offers better BER performance even at weather condition with higher attenuation levels.

The BER result illustrated in Figs. 11(a) and 11(b) for the proposed system is analyzed under dense fog

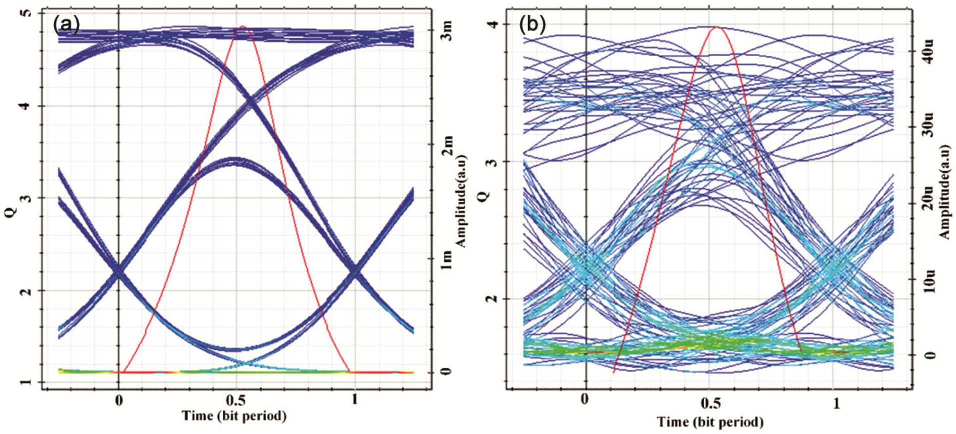

Fig 10 — Eye diagram for (a) moderate rain (b) heavy rain conditions at L = 3 km

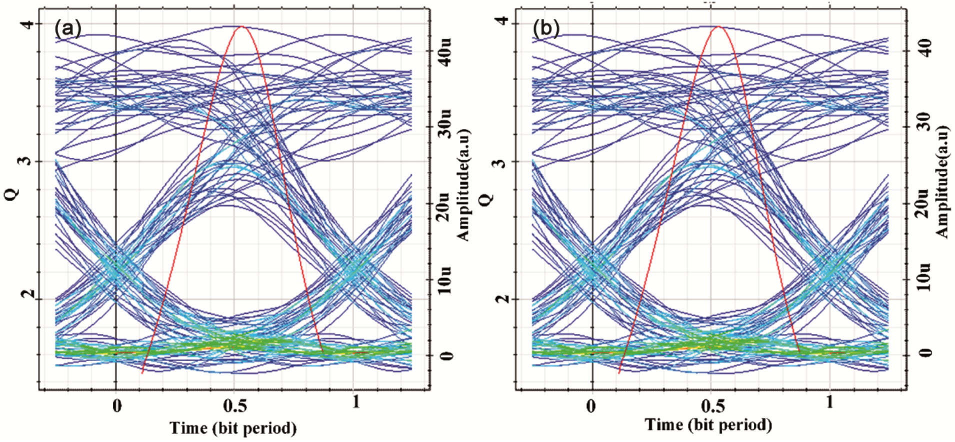

Fig 11 — Eye diagram for (a) L = 2 km (b) L = 3 km under dense fog conditions

conditions, keeping attenuation level and link range the same as those considered by Balasaraswathi *et al.*[16] and Harjeevan *et al.*[20], i.e., 19.28 dB/km and [2–3] km, respectively. The improved quality factor (3.98) and BER of $10^{-5}$are obtained from the simulation compared to the previous work shown in Table 3. The simulation results show that an improved spectral efficiency and data rate (400 Gb/s) with almost the same quality factor, minimum BER with maximum 4 km link distance under moderate rain conditions is achieved for the proposed system when we compare it with the existing research work.

Conclusions

In this paper, a spectrally efficient, advanced modulated (NRZ-DPSK) DWDM-FSO system has been proposed to transmit simultaneously (40×10) Gb/s multiplexed independent optical signals over the attenuated channel representing very clear, moderate rain, heavy rain and very dense fog weather conditions. The numerical results demonstrate successfully transmission of the multiplexed signal upto maximum 70 km under clear sky using EDFA amplifier whereas the maximum link distance limits to 2.3 km and 0.125 km for heavy rain, and very dense fog weather conditions corresponding to the acceptable BER of 10^{-19} and 10^{-12}, respectively. The reason for the drastic change in link range for rainy and dense fog conditions is the high value of the attenuation levels. The impact of attenuation level on different transmitted frequencies are also analyzed under different weather conditions and observed that frequency components are highly affected under fog conditions and achieve maximum 0.4 km link distance. The simulation results are compared in terms of transmission range, quality factor, and BER, and so the proposed system is found to be a better choice for implementing future generation high-speed optical wireless networks.

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