



# Performance analysis of WDM-FSO system under adverse weather conditions

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## Abstract

Free-space optics (FSO) is a data relaying technology, which requires a direct line of sight between the transmitter and the receiver units for reliable transmission. FSO communication links have many merits such as high modulation bandwidth, high data transmission rates, low cost, and easy installation process. The performance of FSO link is affected by certain external parameters such as absorption, scintillation, and atmospheric attenuation due to different weather conditions. This paper reports the designing and simulative comparison of two wavelength division multiplexing-based FSO links under rain and snow weather conditions. The proposed system reports successful transmission of  $32 \times 10$  Gbps of data along a link distance of 16.5 and 1.07 km under rain and snow weather conditions, respectively, with acceptable performance levels ( $Q \sim 6$  dB and  $BER \leq 10^{-9}$ ).

**Keywords** Wavelength division multiplexing · Free-space optics · Link distance · Atmospheric attenuation ·  $Q$  factor · Bit error rate

## 1 Introduction

Free-space optics (FSO) also referred as wireless optical communication (WOC) technology in some literature is considered as a promising information transmitting technique for different types of networks [1–3]. It is similar to conventional optical fiber communication technology since both utilize optical signals as the information carrier; however, no expensive rooftop installations and laying of optical fiber cable are required in FSO links [4,5]. FSO links have many advantages such as high data transmission rates, availability of ample amount of license-free spectrum, no security upgrade requirement, high modulation bandwidth, immunity to electromagnetic interference, low power consumption, low cost of deployment, and easy and quick installation process [6–10]. Due to its many advantages, FSO links can be deployed for various applications such as inter-aircraft links, inter-satellite links, terrestrial links and also in military applications [11,12]. Although FSO links have many advantages, it becomes important to consider various inter-

nal parameters such as operating wavelength, transmission power level, transmission bandwidth, antenna aperture diameter, transmission rates and external parameters such as climatic conditions, atmospheric attenuation, and scintillation in order to achieve high-performance levels [13].

Line of sight (LOS) is a necessary condition for reliable information transmission in FSO links, but there are certain factors such as signal absorption, scattering, scintillations, atmospheric attenuation, multipath fading, and atmospheric turbulence which may affect the link availability and degrade the system performance [14–16]. The attenuation due to atmospheric conditions varies from 0.067 dB/km in the case of very clear weather condition to 128 dB/km in the case of dry snow conditions [17]. The absorption of the information signal is caused due to the presence of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  molecules in the propagation path of the signal [18]. Random variations in the refractive index of the air due to differential heating cause fluctuations in the intensity of the received signal [19]. The performance of the FSO system can be analyzed by determining the quality factor ( $Q$ ), bit error rate (BER), signal-to-noise ratio (SNR), and total power of the signal received at the receiver terminal [20]. The quality of the received signal and thus overall performance of FSO link are inversely proportional to BER and atmospheric attenuation factor [21,22]. Many researchers have presented different

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techniques to improve the performance of FSO links in the presence of atmospheric turbulences and also to increase the data carrying capacity of the system. Here, [23–25] present the application of an optical preamplifier to enhance the performance of FSO link. The results presented conclude that an optical preamplifier can be used to mitigate the degrading effect of atmospheric scintillations and also increase the maximum achievable link distance. The use of aperture averaging technique to enhance the performance of an FSO link under adverse weather conditions has been demonstrated in [26–28]. The results show that by increasing the size of the receiving antenna aperture diameter, the rapid fluctuations of the received signal at the receiving terminal due to atmospheric attenuation average out and thus improvement in the performance of the system. The use of a square root module of the receiving terminal to mitigate the nonlinear effect of Avalanche photodiode so as to enhance the performance of an FSO link has been discussed in [29–31]. The performance of orthogonal frequency division multiplexing (OFDM)-based FSO links under the effect of atmospheric conditions has been discussed in [32,33]. The performance comparison of OSSB- and ODSB-based OFDM-FSO links and the link enhancement using semiconductor optical amplifier have been presented in [34,35]. Here, [36] reports the simulative analysis of WDM-based FSO links in order to increase the link carrying capacity of the system under the effects of different atmospheric conditions. In [37], the use of hybrid optical amplifier stages in WDM-based FSO link to increase the maximum achievable link distance is demonstrated. Here, [38] reports the enhanced performance analysis of WDM-based FSO link using a multiple beam concept. The use of spatial diversity techniques to increase the link reliability of FSO links has been demonstrated in [39–41]. The results presented show that by using spatial diversity at the transmitter and receiver terminals, the performance of the system is considerably increased. The application of forward error correction (FEC) technique to enhance the FSO link performance is presented in [42].

Wavelength division multiplexing (WDM) is a data transmission technology using which a number of different wavelength signals are transmitted at the same time over the same medium, thus increasing the capacity of the system [43]. WDM technique can be used to enhance the capacity of the data transmission system in order to meet the ever-increasing demand for bandwidth-hungry multimedia applications such as video conferencing and live streaming [44]. In this paper, a 32-channel WDM-based FSO link has been proposed with each channel transmitting at 10 Gbps data rate and its performance has been compared with the existing WDM-FSO system under rain and snow weather conditions. The rest of the paper is organized as follows: In Sect. 2, the design of WDM-based FSO link is presented, and the attenuation factor due to rain and snow weather con-

ditions is discussed. The results are presented and discussed in Sect. 3, and the final conclusion is drawn in Sect. 4.

## 2 System design and considerations

### 2.1 WDM-FSO system design

The FSO communication system comprises three main sections—the transmitter section, the propagation channel, and the receiver section. At the transmitter section, a pseudo-random bit sequence (PRBS) generates information in binary form which is converted into an electrical signal using non-return to zero (NRZ) pulse generator. The Mach–Zehnder modulator (MZM) modulates the electrical signal from the NRZ pulse generator with an optical signal generated by a continuous wave laser operating at 1550 nm central wavelength. The optical signal is transmitted in the free air using the transmitter antenna. At the receiving terminal, the optical signal is converted back into an electrical signal using an Avalanche photodetector (APD). A low-pass filter (LPF) is used to remove any high-frequency noise present in the information signal.

In this work, 32-channel WDM-based FSO system with each channel transmitting at 10 Gbps rate has been designed using OPTISYSTEM simulation software. The transmission power is set to be 10 dBm, and the transmitter and receiver antenna aperture diameter are taken to be 5 and 20 cm, respectively. In this paper, two systems have been designed, System 1 and System 2, as shown in Figs. 1 and 2, respectively. System 1 consists of an array of 32 continuous wave lasers at the transmitter terminal with channel spacing of 100 GHz between the adjacent channels. A WDM multiplexer and demultiplexer are used at the transmitter and the receiver terminal, respectively. The quality of the received information signal is analyzed using BER analyzer. System 2 consists of a single continuous wave laser with 10 dBm transmission power, and the output is directed toward a fork. The output of the fork has the same value as that of the previously connected component [11]. A power combiner is used at the receiver terminal, and BER analyzer is used to analyze the quality of the signal.

### 2.2 System considerations

Atmospheric attenuation is one of the most important factors which degrade the performance of an FSO link. The attenuation of an optical information signal varies with varying atmospheric conditions and can be described using Beers–Lambert law [45]:

$$P_R = P_T \exp(-\alpha z) \quad (1)$$

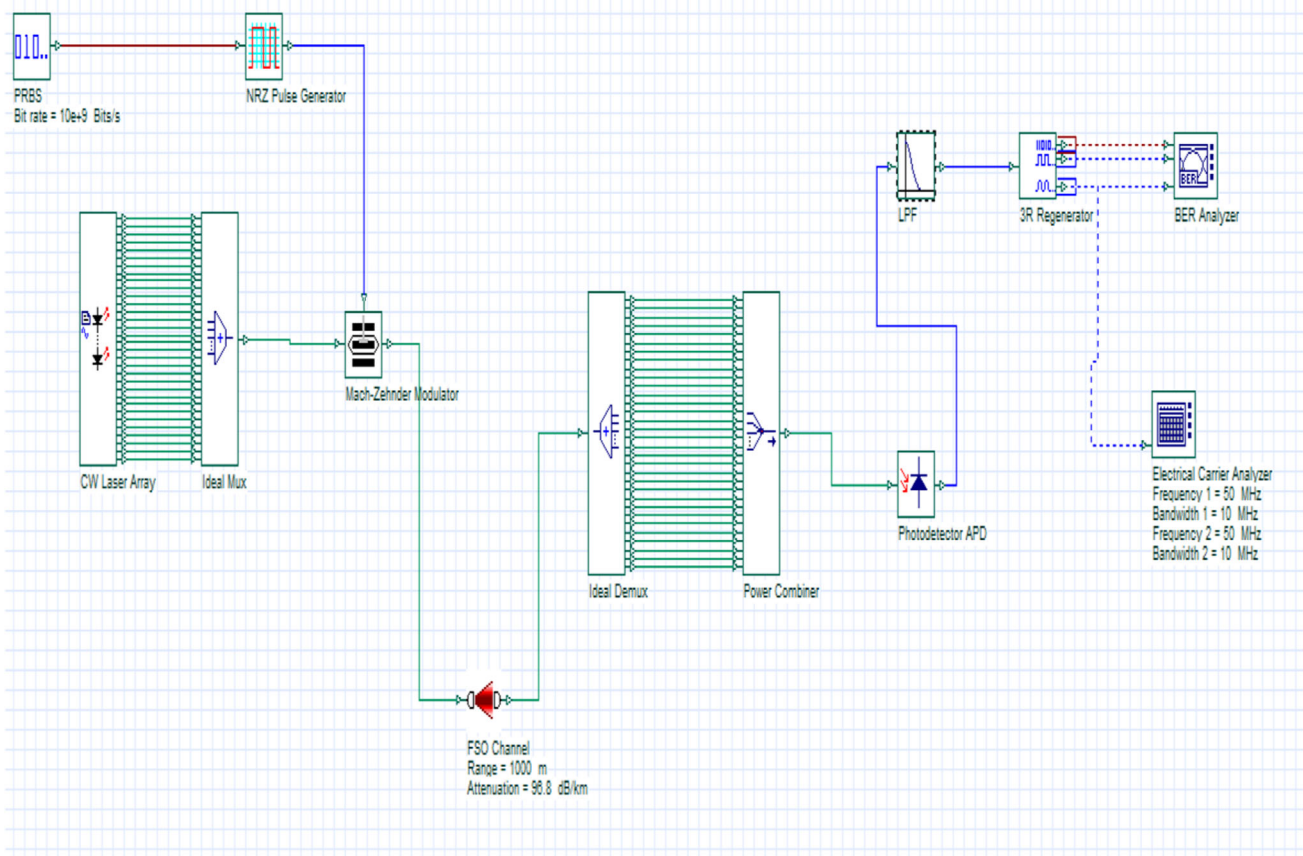


Fig. 1 Optisystem layout of System 1

where  $P_R$  and  $P_T$  denote the transmitted and the received powers, respectively,  $\alpha$  denotes the atmospheric attenuation and  $z$  is the link distance in kilometers. The atmospheric attenuation coefficient depends on different factors such as operating wavelength, link visibility, the size of particles in the atmosphere, and scattering. The signal attenuation due to snow weather is based on the link visibility range estimation and can be computed using Kim and Cruse model [15,46,47]:

$$\alpha = \left(\frac{3.91}{V}\right) \left(\frac{\lambda}{550 \text{ nm}}\right)^{-q} \tag{2}$$

where  $V$  denotes the visibility in kilometers,  $\lambda$  denotes the operating wavelength in nm, and  $q$  is the size distribution of the atmospheric particles.

The attenuation coefficient due to rain can be calculated using the equation:

$$\alpha_{\text{rain}} = \pi a^2 N_a Q_{\text{scat}} \left(\frac{a}{\lambda}\right) \tag{3}$$

where  $a$  denotes the radius of the raindrop (0.001–0.1 cm),  $N_a$  denotes the raindrop distribution,  $Q_{\text{scat}}$  denotes the scattering efficiency, and  $\lambda$  denotes the operating wavelength. The

raindrop distribution can be calculated using the equation:

$$N_a = \left(\frac{z_a}{4/3(\pi a^3)v_a}\right) \tag{4}$$

where  $z_a$  denotes the rainfall rate in cm/s and is  $7.22 \times 10^{-4}$  cm/s for the rainfall rate of 26 mm/h and  $2.22 \times 10^{-3}$  cm/s for 80 mm/h rainfall rate and  $v_a$  denotes the limit speed precipitation and is given by the equation:

$$v_a = \left(\frac{2a^2 \rho g}{9n}\right) \tag{5}$$

where  $\rho$  denotes the water density ( $0.98 \text{ g/cm}^3$ ),  $g$  is the gravitational constant ( $980 \text{ cm/s}^2$ ), and  $n$  denotes the viscosity of the air ( $1.82 \times 10^{-4} \text{ g/cm s}$ ).

Snow weather is another important factor which degrades the performance of FSO link. The attenuation due to snow weather conditions is dependent on the visibility and size of the snow particles. Depending on the liquid equivalence ratio (LER), snow can be classified as wet snow and dry snow. For wet snow, LER lies from 10:1 to 5:1, and for dry snow LER lies from 10:1 to 30:1. The specific attenuation due to snow

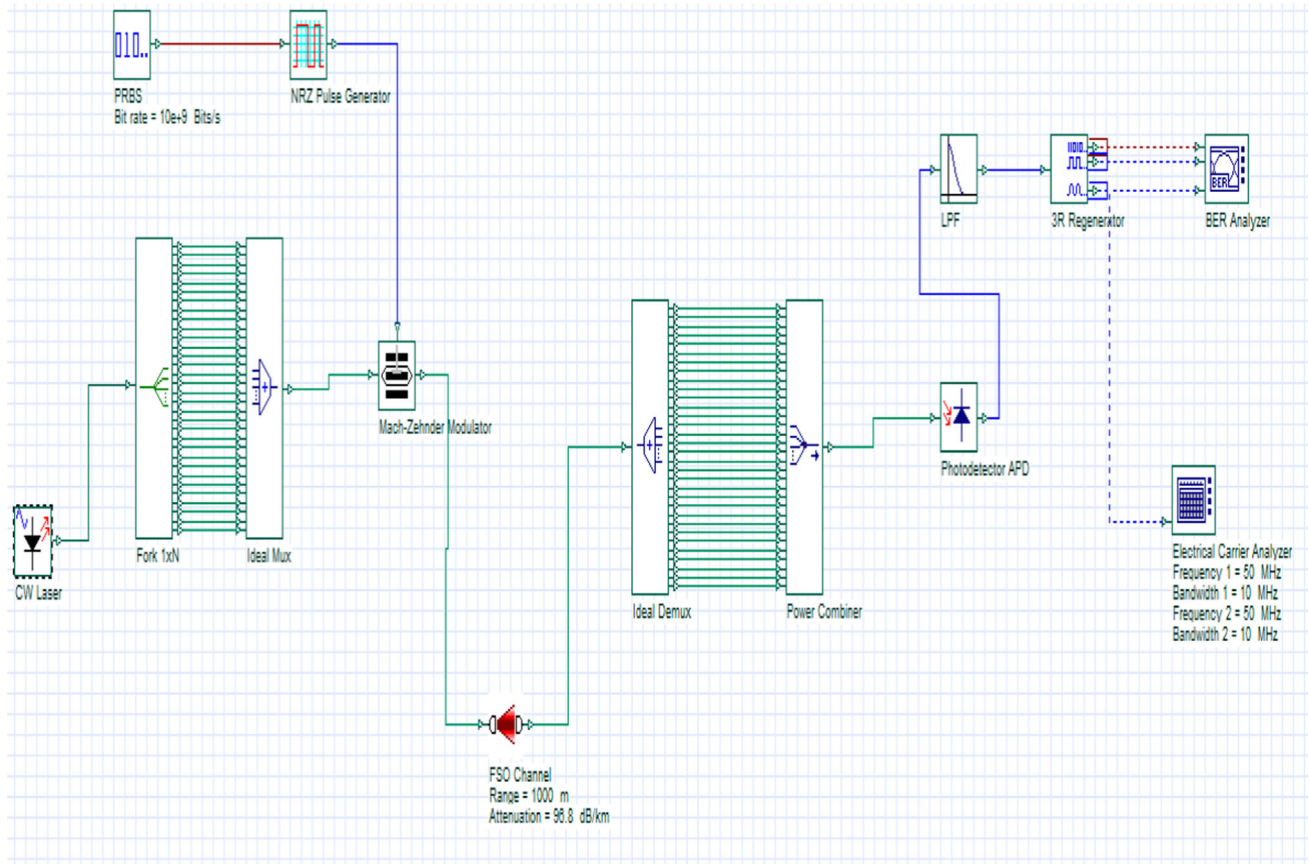


Fig. 2 Optisystem layout of System 2

can be calculated from the equation:

$$\alpha_{\text{snow}} = a \cdot S^b \tag{6}$$

where  $S$  is the snow rate in mm/h and  $a$  and  $b$  for dry snow are calculated as:

$$a = 5.42 \times 10^{-5} \times \lambda + 5.4958776, b = 1.38;$$

And for wet snow are calculated as:

$$a = 1.023 \times 10^{-4} \times \lambda + 3.7855466, b = 0.72$$

The attenuation factors due to rain and snow weather conditions at 1550 nm operating wavelength are calculated using Eqs. (2–6) and are presented in Table 1.

### 3 Results and discussion

#### 3.1 Performance analysis of WDM-FSO system

In this paper, simulative analysis of two WDM-based FSO links under rain and snow weather conditions has been per-

Table 1 Atmospheric attenuation values for rain and snow weather condition

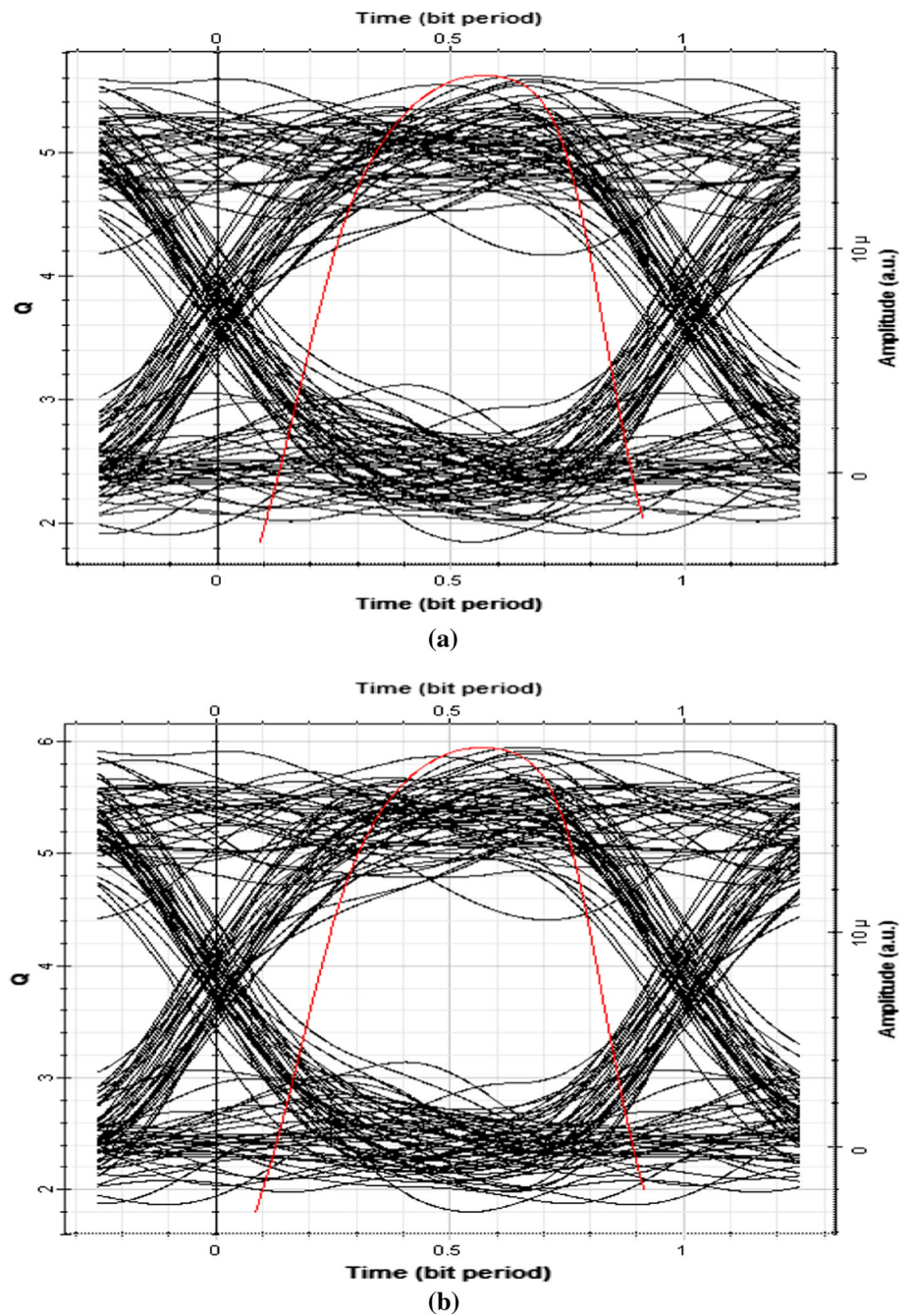
Weather condition	Rate (mm/h)	Attenuation (dB/km)
Light rain	26	6.27
Heavy rain	80	19.28
Wet snow	6	13.73
Dry snow	8	96.8

formed and their performance has been compared on the basis of  $Q$  Factor, BER, SNR, received power and eye diagrams of the received signal. System 1 deploys an array of 32 lasers at the transmitting terminal. The performance analysis of System 1 under rain and snow weather conditions is presented in Table 2, and BER plots are analyzed in Fig. 3. From the results presented in Table 2, it can be seen that with the increase in the attenuation values for different atmospheric conditions, the performance of the WDM-FSO system degrades and the maximum link distance with acceptable performance levels reduces. The maximum link distance in the case of light rain is 14.1 km which limits to 4.6 km in the case of heavy rain. Similarly, the maximum link distance in the case of the wet

**Table 2** Performance analysis of System 1 under different weather conditions

Weather condition	Attenuation (dB/km)	Maximum link distance (km)	$Q$ factor (dB)	BER	Eye height
Light rain	6.27	14.1	5.61	$9.58e^{-009}$	$6.79e^{-006}$
Heavy rain	119.28	4.6	5.99	$1.01e^{-009}$	$7.80e^{-006}$
Wet snow	13.73	6.4	5.94	$1.35e^{-009}$	$7.67e^{-006}$
Dry snow	96.8	0.91	5.65	$7.81e^{-009}$	$6.89e^{-006}$

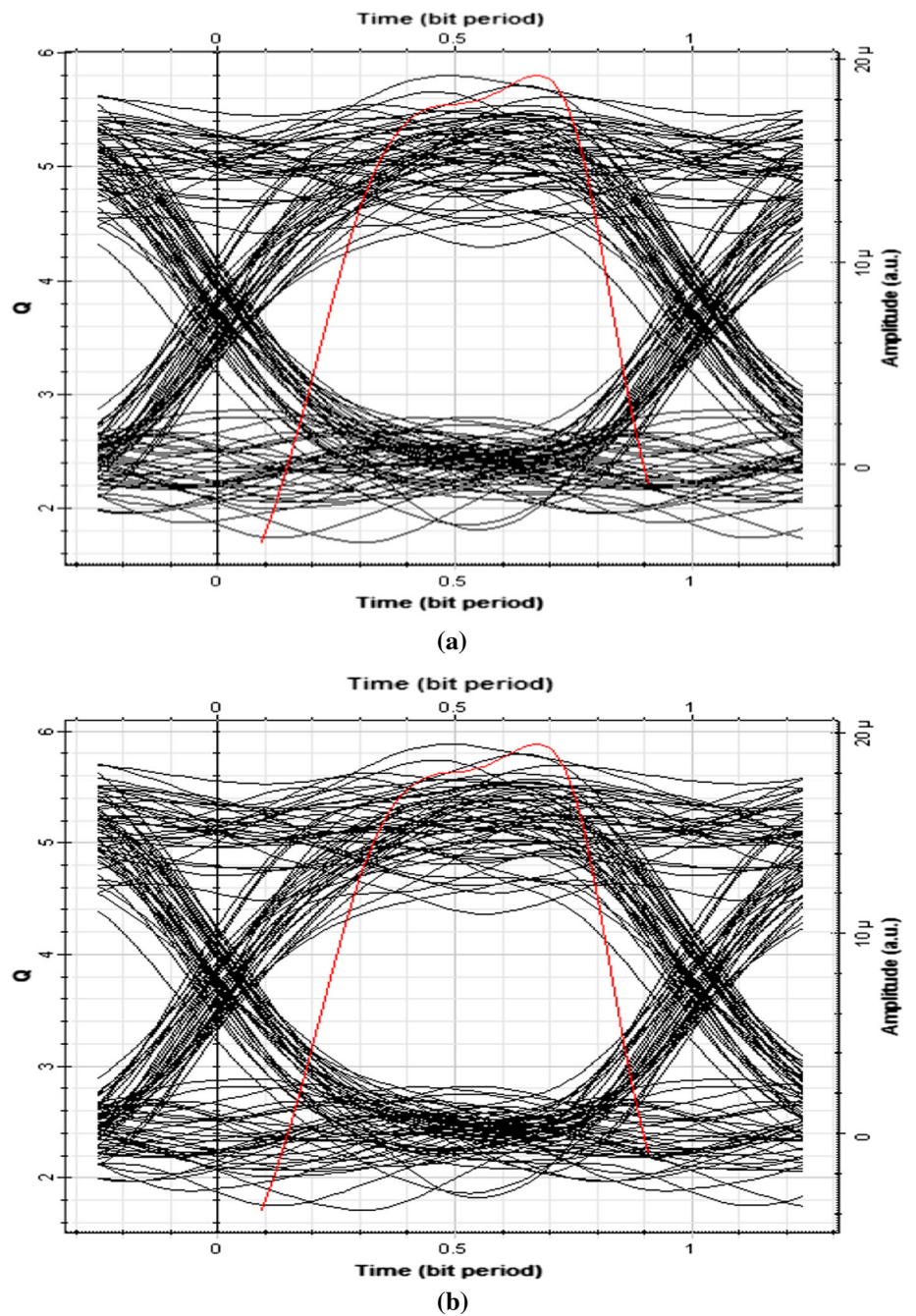
**Fig. 3** Eye diagram of the received signal using System 1 under **a** Light rain condition at a link distance of 14.1 km, **b** dry snow condition at a link distance of 0.91 km



**Table 3** Performance analysis of System 2 under different weather conditions

Weather condition	Attenuation (dB/km)	Maximum link distance	$Q$ factor (dB)	BER	Eye height
Light rain	6.27	16.5	5.79	$3.18e^{-009}$	$7.41e^{-006}$
Heavy rain	119.28	5.4	5.93	$1.39e^{-009}$	$7.78e^{-006}$
Wet snow	13.73	7.6	5.77	$3.64e^{-009}$	$7.34e^{-006}$
Dry snow	96.8	1.07	5.88	$1.92e^{-009}$	$7.64e^{-006}$

**Fig. 4** Eye diagram of the received signal using System 2 under **a** light rain condition at a link distance of 16.5 km, **b** dry snow condition at a link distance of 1.07 km



snow is 6.4 km which limits to 0.91 km in the case of dry snow. The eye diagrams of the received signals under light rain and dry snow at a link distance of 14.1 and 0.91 km, respectively, are presented in Fig. 3. The results presented show that the amount of BER and the eye opening for light rain weather at 14.1 km link distance is same as dry snow weather at a link distance of 0.91 km.

The proposed System 2 deploys a single continuous wave laser at the transmitter terminal which reduces the complexity of the transmitter. The performance analysis of System 2 under rain and snow weather conditions is presented in Table 3, and BER plots are analyzed in Fig. 4. The maximum link distance in the case of light rain is 16.5 km which limits to 5.4 km in the case of heavy rain. Similarly, the maximum link distance in the case of the wet snow is 7.6 km which limits to 1.07 km in the case of dry snow. The eye diagrams of the received signals under light rain and dry snow at a link distance of 16.5 and 1.07 km, respectively, for System 2 are presented in Fig. 4. The results presented show that the amount of BER and the eye opening for light rain weather at 16.5 km link distance are same as dry snow weather at a link distance of 1.07 km.

### 3.2 Performance comparison of System 1 and System 2

The SNR value of the received signal is one of the most important parameters that determine the overall performance of a communication system as the decrease in the power of the received signal causes the SNR value to decrease and thus results in the increase in BER of the information signal [22]. Figure 5a–d depicts the SNR plots for the received signal under a light rain, heavy rain, wet snow, and the dry snow, respectively, for System 1 and System 2 at varying link distances. Similarly, Fig. 6a–d depicts the total power plots for the received signal under a light rain, heavy rain, wet snow, and the dry snow, respectively, for System 1 and System 2 at varying link distances.

From the results presented in Fig. 5, it can be seen that the SNR value of the received signal reduces from [62, 33] to [38, 7] dB for System 2 and System 1, respectively, and for link distances varying from 12.5 to 15.5 km under the light rain weather. Similarly, the SNR value reduces from [63, 35] to [28, 0] dB for link distances varying from 4 to 5 km under the heavy rain weather, from [55, 25] to [27, 0] dB for link distances varying from 6 to 7 km under the wet snow weather and from [63, 35] to [26, 0] dB for link distances varying from 800 to 1000 m under dry snow weather for System 2 and System 1, respectively.

From the results presented in Fig. 6, it can be seen that the total power of the received signal reduces from [−19, −50] to [−43, −76] dBm for System 2 and System 1, respectively, and for link distances varying from 12.5 to 15.5 km under the

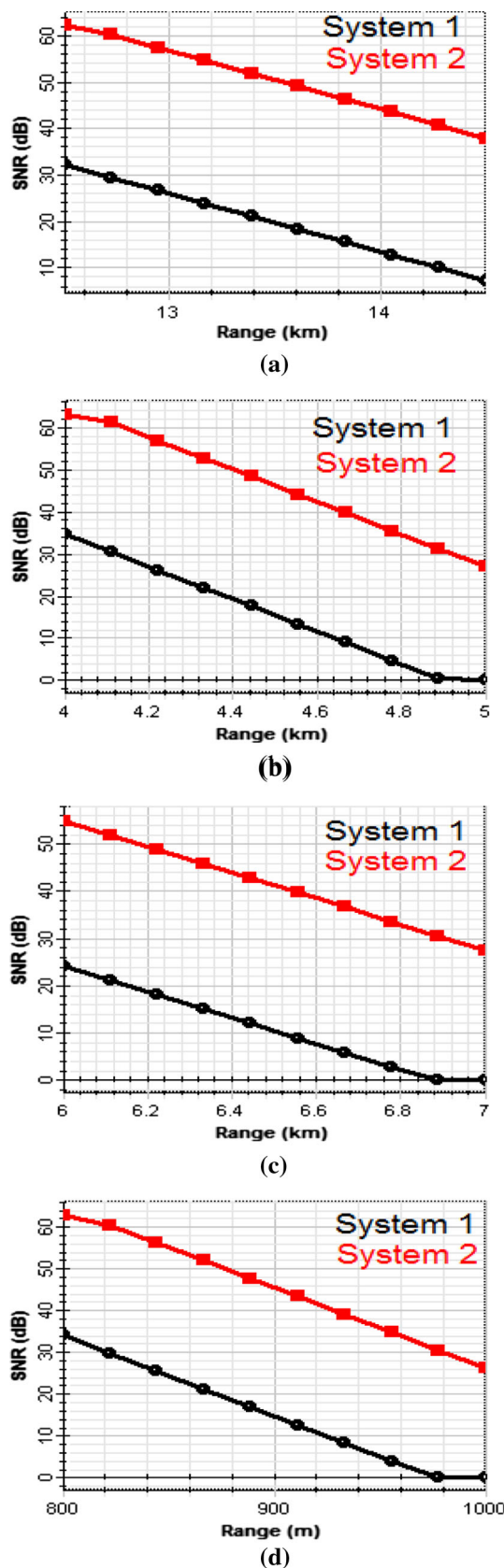
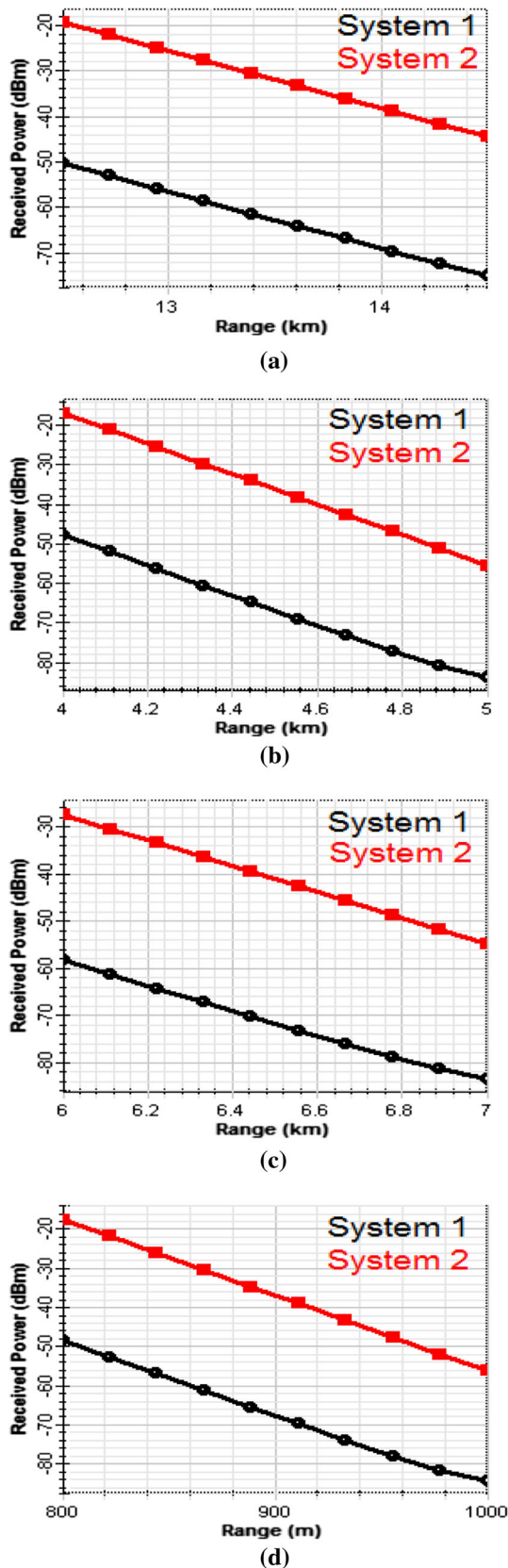


Fig. 5 SNR versus link distance for System 1 and System 2 under a light rain, b heavy rain, c wet snow, d dry snow



**Fig. 6** Received power versus link distance for System 1 and System 2 under **a** light rain, **b** heavy rain, **c** wet snow, **d** dry snow

light rain weather. Similarly, received power reduces from  $[-17, -47]$  to  $[-58, -42]$  dBm for link distances varying from 4 to 5 km under the heavy rain weather, from  $[-28, -58]$  to  $[-55, -83]$  dBm for link distances varying from 6 to 7 km under the wet snow weather and from  $[-18, -49]$  to  $[-56, -83]$  dBm for link distances varying from 800 to 1000 m under dry snow weather for System 2 and System 1, respectively. From the results presented in Figs. 5 and 6, it can be seen that the proposed System 2 supports longer link distance with acceptable performance levels ( $\text{SNR} \geq 20$  dB and received power  $\geq -60$  dBm) under all weather conditions as compared to System 1.

## 4 Conclusion

In this paper, two WDM-based FSO systems are proposed and their performance is compared on the basis of  $Q$  Factor, BER, eye opening, SNR values, the total power of the received signal and eye diagrams with respect to varying link distances under rain and snow weather conditions. The attenuation values under rain and snow weather conditions are determined for 1550 nm operating wavelength. The results show that System 2 outperforms System 1 under all weather conditions. For a transmission rate of 10 Gbps, the proposed System 2 supports link distance up to 16.5 km in light rain and 5.4 km under heavy rain. Also, the proposed system is capable of achieving link distance of 7.6 km under wet snow and 1.07 km under dry snow conditions with acceptable performance levels. Thus, the proposed WDM-FSO system can provide an effective solution to the last mile problems and can meet the ever-increasing demand for channel capacity and spectrum.

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