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Effects of atmospheric weather and turbulence in MSK based FSO communication system for last mile users

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Abstract
In this paper, a minimum shift keying (MSK) based free space optical (FSO) communication system for the terrestrial user is modeled. In our setup 10 Gbps downlink MSK modulated signal is transmitted first over 100 km dispersion shifted fiber and then the area where deployment of fiber is not possible due to some constraints, FSO link is used to transmit the data to the last mile users. FSO link suffers from various weather conditions and atmospheric turbulence i.e. scintillation effect. Hence, both the cases are considered to transmit the data through FSO link to the end users and Gamma–Gamma fading model is used to study the scintillation effect. FSO link range is optimized to analyze the behaviour of the proposed system for six different weather conditions over weak, moderate and strong turbulence using BER curves and eye diagrams. Also, from the base station uplink data is modulated by MSK and is transmitted back to central station via same fiber and detected successfully.

Keywords Bit error rate · Eye diagram · Free space optical communication · Minimum shift keying · Scintillation effect

1 Introduction

Communication system demands high data rate with low bit error rate and also high bandwidth irrespective of the types viz wired or wireless communication system. In case of wireless communication system, the bandwidth can be increased by using optical beam from one point to another in free space. In this regard, free space optical (FSO) communication is able to catch the eyes of both industry and academic researchers in recent years. FSO is a line of sight (LOS) communication system that may be deployed in a redundant link to backup fiber in place of a second fiber link and an alternate solution to the last mile problem over a short distance [1]. FSO has the advantages of high bit rate, no health hazard, and immunity from electromagnetic interference. The deployment of such a system is easy and quick, and also low maintenance is required as a result the system is cost effective. The most significant advantage of FSO is that it does not require any license for long-range operation unlike radio communication [2,3].

The behaviour of the FSO system purely depends on atmospheric attenuation and turbulence. These two factors are the main reasons for degradation in FSO signal performance. Atmospheric scattering and absorption process causes atmospheric attenuation. This attenuation restrict the coverage of FSO communication system. Atmospheric turbulence occurs when there is variation in the refractive index because of the change in temperature inhomogeneity and pressure. As a result, it attenuates the transmitting signal [1,4]. These effects fade the received signal and the phenomenon is called as scintillation effect. Inhomogeneity causes the degradation in received signal power and in turn result in increased error. The intensity scintillation effect can be described by different models such as Gamma–Gamma, log normal, etc. [5]. In this paper, Gamma–Gamma model is chosen to cover all three i.e. weak, moderate and strong scenarios [4].

Initially, OOK modulation has been used in FSO system due to its cost effectiveness and simplicity. In this modulation, adjustment of the adaptive threshold is difficult because of the signal intensity fluctuation [1]. To overcome this in [6], pulse position modulation (PPM) technique has been used in FSO system. PPM technique has better efficiency than OOK, but compromises on bandwidth. As an alternative to OOK

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and PPM, subcarrier phase shift keying has been extensively studied in [7]. Authors in [8] have compared various weather conditions including haze and rain on FSO system and found that the system is mostly effected by heavy haze and rain. It has also been reported that the received power relies on the aperture size of the FSO. To overcome the above effects on FSO system, an optimization solution has been provided in [8] to enhance the effectiveness of the FSO system. In this regard, the aperture size and laser power have been increased up to a certain value to improve the link range and received power of the FSO system for different haze and rain conditions.

In [9], authors have reported the variant of PSK i.e. DPSK for FSO system and showed that DPSK performs better in comparison to OOK. Authors also showed the effects of DPSK signal due to different weathers and turbulence. Use of MSK modulation scheme in FSO communication has not been reported in spite of having advantages in terms of spectrum, ISI effect over other modulation formats such as OOK, DPSK, etc. as reported in [10,11]. In [11], it is reported that MSK has better dispersion tolerance by 1 dB compared to RZ-DPSK and RZ-OOK and also ISI is less than these modulation formats. In [12], authors compared the performance of MSK and DPSK in WDM-PON based multicast and unicast overlay system and found that MSK performs better than DPSK. Hence, it can be understood that the performance of MSK is better than DPSK in every aspect. Therefore, we selected MSK as a modulation format in our system to analyze the effects of different weathers and atmospheric turbulence in FSO system. All the literatures available have used only one transmission medium i.e. FSO, but we have used a combination of fiber and FSO. FSO is used whenever the deployment of second fiber is not possible due to different constraints so that last mile user can also access the connectivity.

In this paper, we have analyzed the effect of six different weather conditions over three turbulence regimes on FSO after passing through 100 km DSF. Link range of FSO is optimized for all above conditions. BERs and eye diagrams are used to analyze the behaviour of the system.

2 System model

Figure 1 depicts the block diagram of the proposed MSK based FSO system for last mile users. In central station (CS) two lasers i.e Laser1 and Laser2 are used having frequency f_1 and f_2 respectively. Laser1 is used to carry the downlink data from CS to end user and Laser2 is used to carry the uplink data from base station (BS) to CS. The frequency f_1 is fed to the MSK modulator which is driven by a pseudo random bit sequence (PRBS) NRZ data. Then the MSK modulated downlink signal is coupled with the Laser2. The combined signal is then passed through a dispersion shifted fiber (DSF) to BS. Dispersion causes broadening of optical pluses while traversing through a fiber. On further transmission, through FSO the pulses start overlapping with each other and become indistinguishable. As a result identity of the data is lost. The received dispersed signal at the base station when transmitted through FSO link also got affected by atmospheric attenuation and turbulence. This further deteriorated the signal strength and quality resulting in ISI. The factors that affect FSO cannot be controlled or compensated. So, to keep the identity of the data we have considered DSF rather than SMF, so that end user will get data error free. Also, we are not using any compensation or equalization techniques to overcome the residual dispersion of the DSF as the amount is very less compared to an SMF. In BS the signal is divided into two parts. One part is amplified before transmitting via FSO link to the end user where fiber deployment is not possible due to various constraints. The other part is filtered to get the frequency f_2. Then f_2 is used to modulate the uplink PRBS data by MSK modulator and transmitted back to the CS via the same DSF. At the CS the data is demodulated and detected. At the end user, the received signal is demodulated and delivered to the user. During the propagation of the

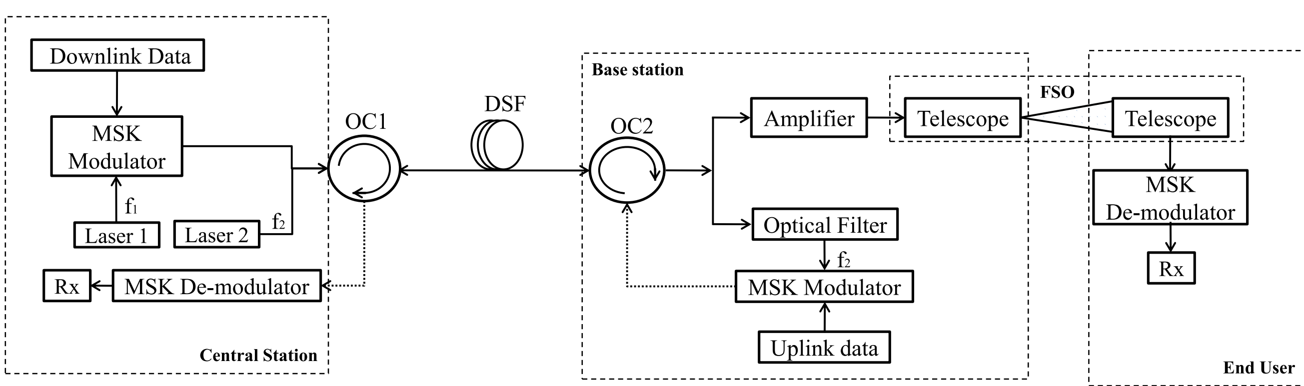

Fig. 1 Architecture of MSK based FSO system. *DSF* dispersion shifted fiber, R_x receiver, *OC* optical circulator

signal through FSO link, different factors such as weather, turbulence, etc. degrade the strength of the signal. So, in this paper, we have considered all the weather conditions and also the atmospheric turbulence to study their effect on FSO.

3 FSO channel model

During the downlink signal propagation through FSO link, the amplitude gets distorted due to various atmospheric interference including scattering, refraction, absorption and also due to bad weather such as thin fog, moderate fog, haze, etc. In our model, we have considered three primary factors that cause attenuation namely, atmospheric attenuation, turbulence, and geometric loss. For atmospheric attenuation, six different weather conditions are considered. For the atmospheric turbulence, Gamma–Gamma channel model is considered as it stands true for all the three turbulence i.e. weak turbulence (WT), moderate turbulence (MT) and strong turbulence (ST) conditions.

3.1 Link loss

The link loss in FSO consists of two factors, one is atmospheric attenuation and another one is a geometric loss. Geometric loss can be determined using the angle of divergence of the transmitter and the receiver aperture area. But atmospheric attenuation occurs due to scattering and absorption. The total link loss can be written as [1]

$$a_v = \frac{A}{\pi\left(\frac{\theta L}{2}\right)^2} e^{(-\beta_r L)} \tag{1}$$

where β_r denotes atmospheric extension coefficient, L denotes link distance, A denotes area of the optical receiver, θ denotes angle of divergence in radians. As per Kim's model [13] the atmospheric attenuation coefficient (σ) is given by

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

where λ denotes wavelength in nm, V denotes visibility in km, q denotes size of the distribution of the scattering particle. The value of q is taken as per Kim's model [13]. Which is reproduced as follows:

$$q = \begin{cases} 1.6 & \text{for } V \geq 50 \text{ km} \\ 1.3 & \text{for } 6 \text{ km} \leq V < 50 \text{ km} \\ 0.16\,V + 0.34 & \text{for } 1 \text{ km} \leq V < 6 \text{ km} \\ V - 0.5 & \text{for } 0.5 \text{ km} \leq V < 1 \text{ km} \\ 0 & \text{for } V < 0.5 \text{ km} \end{cases} \tag{3}$$

Then the attenuation can be written as [9]

$$A_e\left[\frac{\text{dB}}{\text{km}}\right] = \frac{17}{V[\text{km}]}\left(\frac{0.55}{\lambda[\mu\text{m}]} q \geq 0\right) \tag{4}$$

3.2 Turbulence model

When the optical signal is transmitted over an FSO, the signal suffers from atmospheric turbulence and misalignment between transmitter and receiver. The probability density function of I_a, which is the attenuation due to atmospheric turbulence can be expressed using Gamma–Gamma model as [9]

$$P(I_a) = \frac{2(\alpha\beta)^{\frac{(\alpha+\beta)}{2}}}{\Gamma(\alpha)\Gamma(\beta)} I_a^{\frac{(\alpha+\beta)}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta I_a}) \tag{5}$$

where α, β denotes effective numbers of large and small scale turbulence cell respectively, $\Gamma(.)$ denotes Gamma Function, $K_n(.)$ denotes modified Bessel function of second order. α and β are as follows: Badar and Jha [9]

$$\alpha = \left\{ e^{\left[\frac{0.49\sigma_R^2}{(1+1.11\sigma_R^{\frac{12}{5}})^{\frac{7}{6}}}\right]} - 1 \right\}^{-1},$$

$$\beta = \left\{ e^{\left[\frac{0.51\sigma_R^2}{(1+0.69\sigma_R^{\frac{12}{5}})^{\frac{5}{6}}}\right]} - 1 \right\}^{-1} \tag{6}$$

The value of Rytov variance σ_R^2 is $1.23 C_n^2 k^{7/6} L^{11/6}$. Where C_n^2 denotes refraction structure index and its value is $5 \times 10^{-17}\,\text{m}^{-2/3}$ for WT, $5 \times 10^{-15}\,\text{m}^{-2/3}$ for MT, $5 \times 10^{-13}\,\text{m}^{-2/3}$ for ST, L denotes transmission length and K denotes optical wave number [9].

4 Simulation setup

Figure 2 depicts the simulation setup of our MSK based FSO system. In CS two continuous wave (CW) lasers i.e. CW1 and CW2 are used having frequency 193.1 and 193.2 THz respectively. The carrier generated by CW1 is used to carry the downlink data from CS to end user and the carrier generated by CW2 is used to carry the uplink data from BS to CS. Here, CW2 is used in CS instead of BS to reduce the cost and complexity of the BS part of the system. In CS the CW1 laser is fed to the MSK modulator, which is driven by a $2^{10} - 1$, 10 Gbps pseudo random bit sequence (PRBS) non return to zero (NRZ) data. Then the MSK modulated downlink signal is coupled with another carrier generated from CW2 laser. The combined signal at the output of the coupler is first fed to an optical circulator (OC1) before being sent through a

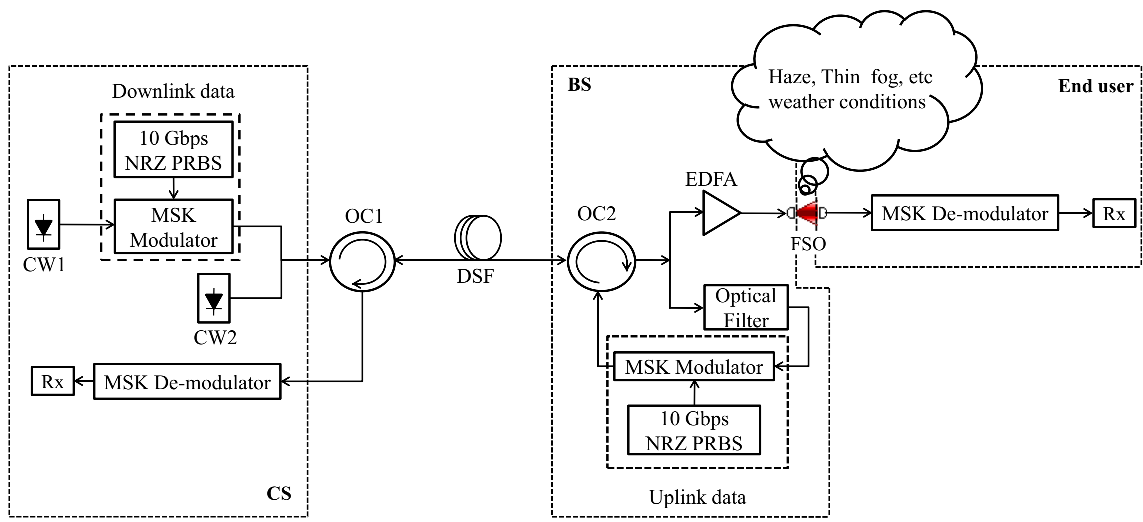

Fig. 2 Simulation setup. *CS* central station, *DSF* dispersion shifted fiber, *BS* base station, R_x receiver, *CW* continuous wave, *OC* optical circulator, *EDFA* erbium-doped fiber amplifier

100 km DSF having dispersion 2 ps nm^{-1} km^{-1}, dispersion slope 0.075 ps^{-1} nm^{-2} k^{-1}, effective area 80 μm^2 and non-linearity index (n_2) 26×10^{-21} m^2 W^{-1}. In BS, the received signal is split into two parts after passing through another optical circulator (OC2). One part is amplified so that the signal strength of the received signal remains high for further transmission. Another part is fed to a bandpass optical filter having bandwidth 0.01 nm to separate the second carrier generated from CW2 so that it can be used for uplink transmission. The uplink carrier is fed to another MSK modulator which is driven by a $2^{10} - 1$, 10 Gbps PRBS NRZ data and the MSK modulated uplink signal is transmitted to CS via a combination of OC2, 100 km DSF and OC1. At the CS the received uplink signal is demodulated using MSK demodulator and detected error free. The amplified signal at the BS is sent through an FSO channel so that the transmitted signal can be delivered to the last mile user where deployment of fiber is not feasible due to some geographical constraints such as hill area, dense forest etc. At the user end, the signal received from the FSO transmitter is sent to an MSK demodulator and detected successfully. During the propagation of the signal through FSO link, different factors such as weather, turbulence, etc. degrade the strength of the signal. So here, we have analyzed the effect of six different weather conditions on the FSO link under all three turbulence regimes. The MSK modulator and demodulator are designed as per [10].

Table 1 shows the simulation parameter used in our setup. The values of visibility and attenuation for different weather conditions as per IVC are taken from [14].

Table 1 Simulation parameter

Simulation parameter	Value
FSO link range	Optimized
Geometrical loss	Considered
Additional loss	1 dB
Transmitter aperture diameter	5 cm
Receiver aperture diameter	20 cm
Beam divergence	2 mrad
Transmitter loss	1 dB
Scintillation model	Gamma–Gamma

5 Result and discussion

Performance of the designed system in presence of different weather conditions and atmospheric turbulence is analyzed using different curves.

Figure 3 shows the curve of link range v/s bit rate for all weather conditions under moderate turbulence. It can be seen that with increase in bit rate the link range of the FSO system decreases for all the weather conditions. Due to increase in dispersion of the fiber with increase in bit rate, the signal pulses get broaden. When these broadened pulses again passed through the FSO link the strength of the pulses further degraded due to the atmospheric attenuation and scintillation effect in FSO. So, these factors effect the coverage of FSO when bit rate is increased. Since our aim is to transmit high bit rate error free to reasonable distance over FSO, so we have considered 10 Gbps bit rate in our system.

We have optimized the link range to find the exact value of FSO link where BER becomes 10^{-9}. The optimized link

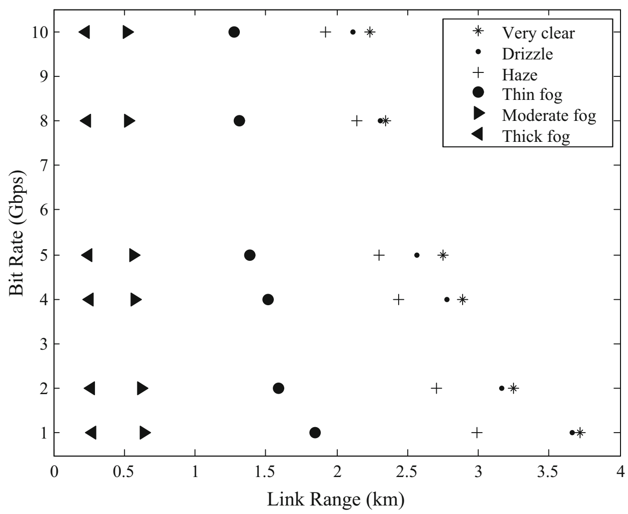

Fig. 3 Link range (km) v/s Bit rate (Gbps) under moderate turbulence

Table 2 Optimized link ranges for BER 10^{-9}

Atmosphere	Attenuation [14]	WT	MT	ST
Very clear	0.0647	2.421	2.231	1.703
Drizzle	0.2208	2.304	2.112	1.684
Haze	0.7360	2.079	1.925	1.632
Thin fog	4.2850	1.330	1.272	1.129
Moderate fog	25.516	0.521	0.516	0.468
Thick fog	85.000	0.231	0.230	0.223

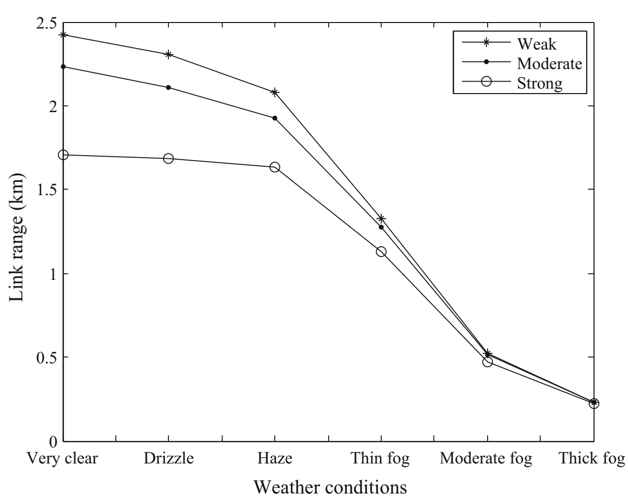

Fig. 4 Weather conditions v/s link range (km) at optimized BER = 10^{-9}

ranges for all six weather conditions with attenuation under three turbulence are shown in Table 2 for comparison.

The graphical representation of Table 2 (approximated up to 3 decimal points) is shown in Fig. 4. From the figure, it can be seen that the optimized range for each weather condition is decreasing with increase in turbulence i.e. weak–moderate–strong. The decrease in range occurs due to the increase in refraction structure index from weak–moderate–strong. Also, when weather changes from very clear to thick fog, the attenuation in atmosphere also increases along with the change in weather from good to bad as can be seen from Table 2. In [14], it has been reported that visibility decreases with increase in attenuation from very clear to thick fog. A similar trend can be found in Fig. 4 and Table 2, that optimized link range in each turbulence decreases due to increase in attenuation when weather changes from very clear to thick fog.

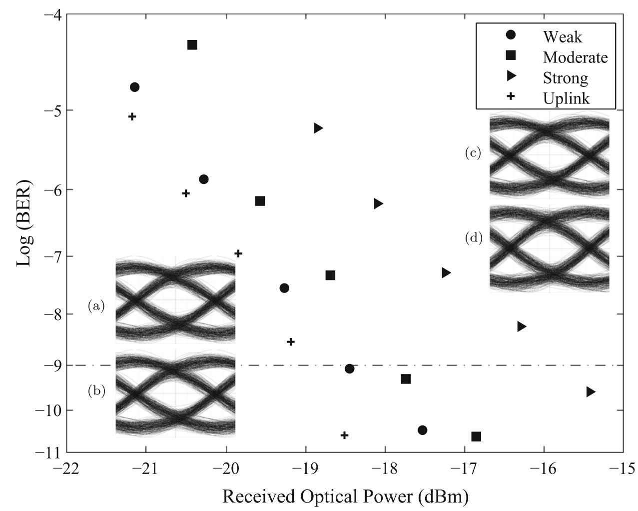

Fig. 5 ER v/s received optical power for very clear with optimized link ranges. Inset: eye diagram of (a) WT, (b) MT, (c) ST, (d) uplink

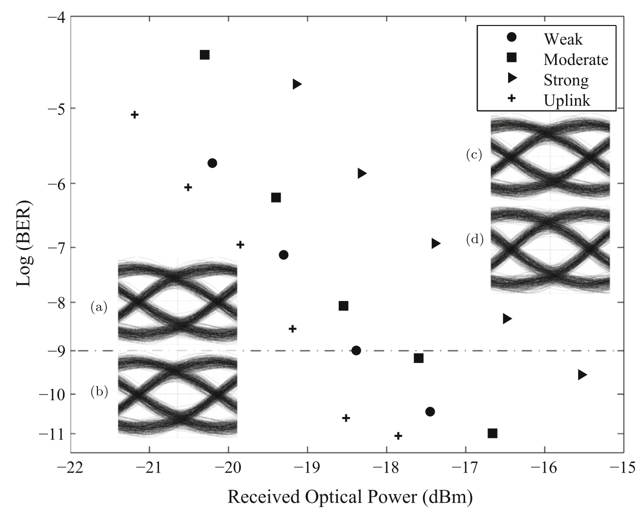

Fig. 6 BER v/s received optical power for drizzle with optimized link ranges. Inset: eye diagram of (a) WT, (b) MT, (c) ST, (d) uplink

Figures 5, 6, 7, 8, 9, and 10 shows the BER v/s received optical power for very clear, drizzle, haze, thin fog, moderate fog and thick fog under weak, moderate and strong turbulence respectively. The BER curves of different weath-

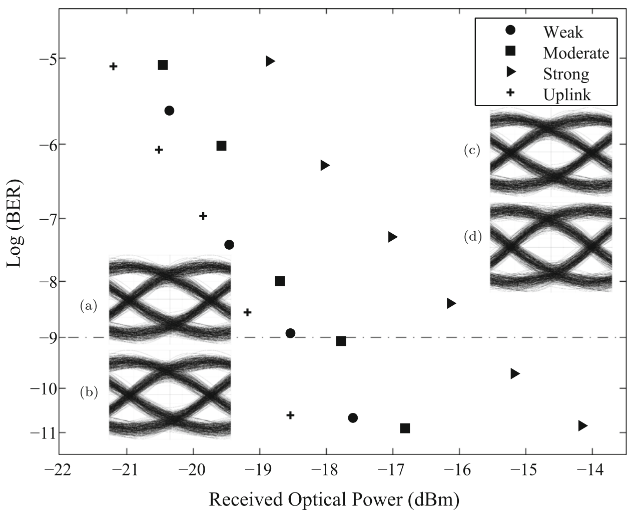

Fig. 7 BER v/s received optical power for haze with optimized link ranges. Inset: eye diagram of (a) WT, (b) MT, (c) ST, (d) uplink

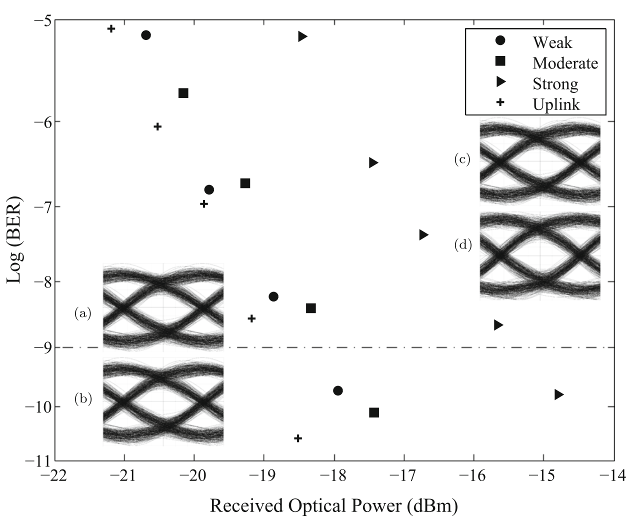

Fig. 8 BER v/s received optical power for thin fog with optimized link ranges. Inset: eye diagram of (a) WT, (b) MT, (c) ST, (d) uplink

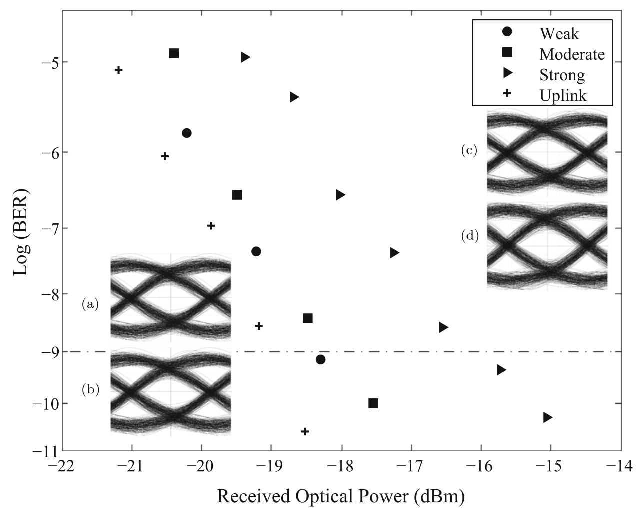

Fig. 9 BER v/s received optical power for moderate fog with optimized link ranges. Inset: eye diagram of (a) WT, (b) MT, (c) ST, (d) uplink

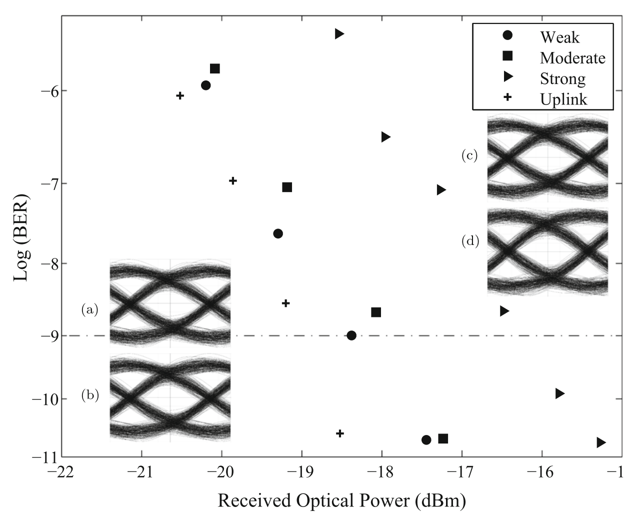

Fig. 10 BER v/s received optical power for thick fog with optimized link ranges. Inset: eye diagram of (a) WT, (b) MT, (c) ST, (d) uplink

ers are drawn by considering the optical link range as shown in Table 2. From each curve, it can be observed that the received optical power decreases from weak to moderate to strong. Since refraction structure index increases from weak to strong, the signal strength propagating through FSO under moderate and strong turbulence is degraded more than weak turbulence. Hence, a decrease in received power can be observed for moderate and strong turbulence than weak turbulence. Eye diagrams of different weathers under all turbulence are included in respective BER curves. Also from eye diagrams, it can be seen that at optimized link range the eyes are open enough. Thus, we can conclude that the signal can be transmitted to the optimized link ranges and detected error free. Uplink BER curve and eye diagram are also inserted in Figs. 5, 6, 7, 8, 9, and 10. From the BERs and eye diagrams of uplink signal, we can infer that uplink signal is also transmitted error free through the same fiber.

6 Conclusion

Effects of atmospheric turbulence and different weather conditions on MSK based FSO system for last mile users are successfully studied and analyzed. In our simulation setup, 10 Gbps downlink MSK modulated data is first sent through a 100 km DSF and then again transmitted through FSO to the end user. Also, the uplink data from the BS is modulated by MSK modulator and transmitted back via the same fiber to CS and recovered successfully. The effect of increase in bit rate on FSO link for all weather conditions under different turbulence is analyzed and found that the link range decreases with increase in bit rate. The link ranges of FSO for each weather over weak, moderate and strong turbulence are optimized. It is found that the value of the optimized link range decreases with increase in attenuation due to weather as well as increase in turbulence. The BER curves and eye diagrams of all the weathers for all turbulence and uplink signal are analyzed. From BER curves and eye diagrams, it can be confirmed that the performance of FSO system in weak turbulence is better than that of moderate and strong. In summary, at optimized range error free transmission is achieved under different weather and turbulence conditions.

Compliance with ethical standards

Conflict of interest Both authors declare that they have no conflict of interests.

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