Performance Evaluation of Free Space Optical Link Under Various Weather Conditions

Monika Singh, Saloni Bhatia and Hemani Kaushal

Abstract Free space optics (FSO) is emerging as a viable complementary technology to address the need for larger bandwidth and high data rate at affordable cost. FSO communication systems face severe link availability and reliability challenges under different weather conditions, and this is a limitation for the wide-scale acceptability of the FSO technology. The main objective of this paper is to analyze the impact of fog, snow, and rain on FSO link, and hence evaluate the performance of the FSO system for various weather conditions. It is analyzed that bit error rate (BER) and link margin of FSO system are very poor for heavy fog, rain, and snow. However, decreasing the data rate for a particular weather condition can improve both these performance parameters.

Keywords Weather effects · Simulation · Link length · Bit error rate · Data rate · Link margin · Visibility · Attenuation

1 Introduction

Ever-increasing demands of the communication world for high data rates and bandwidth can easily be met by free space optics. By the virtue of inherent high optical carrier frequency (in 20–375 THz range), FSO communication system can provide highest data speeds making it suitable for first/last mile access connectivity. Due to ease of deployment and light weight systems used in FSO technology, it finds application in disaster recovery to provide ad hoc connectivity using temporary links. Moreover, being a cost-effective technology, FSO can be used to provide communication over difficult terrains where installation of conventional communication systems is a costly affair. With the advent of more mature

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optoelectronic devices, FSO communication has seen a steep rise in its growth and acceptance. A major challenge being faced by FSO communication is its sensitivity to the weather conditions and the turbulence in the atmosphere. This leads to FSO link availability and reliability issues. An insight in the performance behavior of the FSO links under various weather conditions is one of the requirements to decide FSO system design parameters prior to its deployment. Fog, rain, and snow which are most deterrent weather phenomenon lead to attenuation in the optical signal, and these attenuation can be parameterized/measured using visibility range of the optical signal in various weather conditions.

This paper has been organized as follows: Section 2 describes the characterization of snow, fog, and rain attenuation using empirical models. Section 3 enumerates the detailed aspects and schematic for simulation. In Sect. 4, performance of the FSO system under different weather conditions is analyzed, and finally conclusions of the analysis are discussed in Sect. 5.

2 Characterization of Attenuation Due to Weather Phenomenon

2.1 Fog

Fog particles are considered to be major photon scatterers since their size is comparable with the wavelength of interest in FSO communication (0.5–2 μm). It causes significant attenuation of the signal for considerable amount of time and this is deterrent for achieving high availability in FSO transmissions. The optical attenuation in case of fog droplets can be accurately predicted by applying Mie scattering theory. An approach is based on visibility range information, in which the fog attenuation is predicted using common empirical models. Visibility range is defined as the distance that a parallel luminous beam travels in the atmosphere until its intensity drops 2 % of its original value. The wavelength of 550 nm is usually taken as the visibility range reference wavelength. Equation 1 defines the attenuation coefficient given by common empirical models for Mie scattering [1]:

$$\beta_{\mathrm{fog}} = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-p} \tag{1}$$

where V (km) stands for visibility range, λ (nm) is the operating wavelength, and p is the size distribution coefficient of scattering.

According to Kim model [2] p is given as

$$p = \begin{cases} 1.6 & V > 50 \\ 1.3 & 6 < V < 50 \\ 0.16V + 0.34 & 1 < V < 6 \\ V - 0.5 & 0.5 < V < 1 \\ 0 & V < 0.5 \end{cases} \quad (2)$$

According to Kruse model [3], p is given as

$$p = \begin{cases} 1.6 & V > 50 \\ 1.3 & 6 < V < 50 \\ 0.585V^{\frac{1}{3}} & V < 6 \end{cases} \quad (3)$$

Different weather conditions can be specified based on their visibility range values. Table 1 summarizes the visibility range for different weather conditions [4].

2.2 *Effect of Snow*

Snow attenuation can vary depending upon the snowflake size and snowfall rate. Since snowflakes are larger in size than rain drops, hence, they produce deeper fades in the signal as compared to the rain drops. Snowflake size can be as large as 20 mm which can completely block the path of the optical signal depending upon the beam width of the signal. For snow, FSO attenuation can be classified into dry and wet snow attenuation. The dry snow affects at the low snow rate, whereas wet snow affects at high snow rate. Specific attenuation is a fundamental factor used to determine attenuation at a defined distance and it is measured in dB/km. The specific attenuation for snow rate S in mm/h is given by [5]

$$\beta_{snow} = aS^b \quad (4)$$

For an operating wavelength λ, values of parameters a and b in dry and wet snow are $a = 5.42 * 10^{-5} + 5.4958776;\ b = 1.38$ and $a = 1.023 * 10^{-5} + 3.7855466;$

Table 1 Visibility range values corresponding to weather conditions

Weather conditions	Visibility range (km)
Heavy fog	0.2
Moderate fog	0.5
Light fog	0.770–1
Thin fog	1.9–2
Haze	2.8–40
Clear	18–20
Very clear	23–50

$b = 0.72$, respectively. The snow attenuation based on visibility range can be approximated by the empirical model [5] given as

$$\alpha_{\text{snow}} = \frac{58}{V} \quad (5)$$

2.3 Effect of Rain

The optical signal is randomly attenuated by rain and fog droplets. Although the main factor for attenuation is fog, the sizeable rain droplets can also cause wavelength-independent scattering. The attenuation produced by rainfall increases linearly with rainfall rate. The specific attenuation [6] against rain rate of R (mm/h) for a FSO link is given as

$$\beta_{\text{rain}} = 1.067R^{0.67} \quad (6)$$

The rain attenuation for FSO link can be reasonably well approximated by empirical formula [7] given as

$$\alpha_{\text{rain}} = \frac{2.8}{V} \quad (7)$$

where V is the visibility range in km and its values based on rainfall rates [1] are summarized in Table 2.

2.4 Visibility Calculation for Cloud

The cloud attenuation can be evaluated using the visibility condition, which is given by

$$V = a(LWC)^b \quad (8)$$

In the above expression, LWC stands for liquid water content. For a daylight-level illumination, values of the empirical constants 'a' and 'b' are given by $65 \leq a \leq 178$

Table 2 Rainfall rates and their visibility ranges

Rainfall type	Rainfall rate (mm/h)	Visibility range (km)
Heavy rain	25	1.9–2
Medium rain	12.5	2.8–40
Light rain/drizzle	0.25	18–20

Table 3 Visibility range values for different cloud types

Cloud type	LWC (g/m^{-3})	Visibility range (m)
Cumulus	1.0	65–178
Stratus	0.29	29.8–54.2
Stratocumulus	0.15	19.7–28.8

and $0.63 \leq b \leq 0.96$. Table 3 shows LWC which is taken from modified gamma distribution [7].

Once the visibility range is estimated, the cloud attenuation can be predicted using the visibility range-dependent Kruse [3] empirical model given by Eq. (3). Even though there are more cloud types present in the atmosphere, only three types of clouds (Stratus, Cumulus, and Stratocumulus) have been considered in this paper since these clouds are present at a lower height which is below 1 km, whereas the height of the buildings is only in meters.

3 Simulation

In this paper, numerical simulations using MATLAB have been carried out for various weather conditions based on which the performance of the FSO communication system has been analyzed. Furthermore, a FSO communication system with (On–Off keying Non-return to zero) OOK NRZ modulation scheme has been simulated using simulation software OptiSystem 12.0 to verify the results obtained in the numerical simulation. The simulation block diagram of the FSO communication system is shown in Fig. 1.

The transmitter block consists of laser diode as optical source, a modulating data source, and an external modulator (Mach–Zehnder modulator). OOK is the most

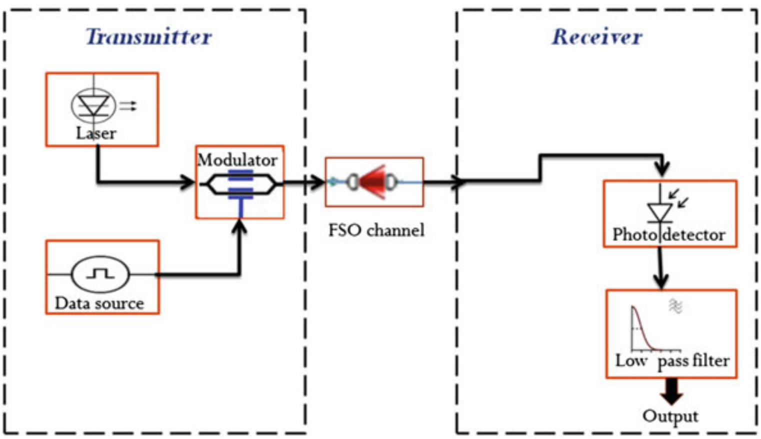


Fig. 1 Block diagram of FSO communication system with OOK modulation

commonly used modulation scheme in terrestrial FSO communication systems, primarily due to its simple implementation and resilience to laser nonlinearity.

Atmospheric channel has been used as FSO communication channel in the analysis. To analyze the effects of various weather conditions on FSO link, the attenuation of the channel has been kept variable. By varying the link range of the channel, a good approximation of the system performance under different visibility ranges can be measured. Figure 2 shows the simulation schematic of the FSO system with OOK modulation. All the simulations have been carried out at 1550 nm wavelength for the obvious reasons: its compatibility with third window wavelength division multiplexing networks, eye safety, and reduced scattering in light haze/fog. The simulation parameters are given in Table 4.

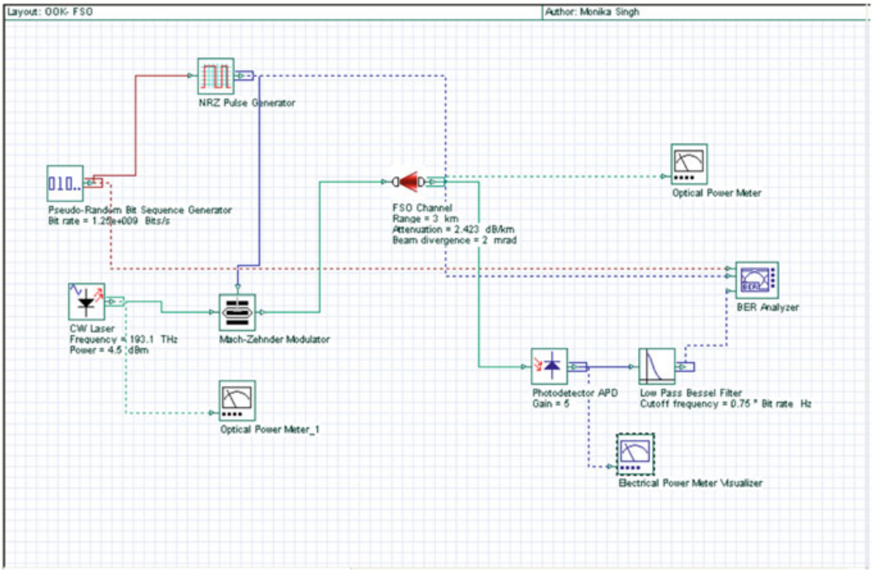


Fig. 2 OptiSystem simulation schematic of the FSO communication system

Table 4 System parameters used in FSO link analysis

Parameter	Symbol	Value
Transmitter optical power	P_t	5 mW
Divergence angle	θ	2 mrad
Receiver aperture diameter	D_R	15 cm
Transmitter efficiency	ψ_t	0.5
Receiver efficiency	τ_T	0.5
Laser wavelength	λ	1550 nm
Receiver sensitivity	N_b	−20 dBm

4 Results and Analysis

4.1 Attenuation Versus Visibility

Variation of attenuation with visibility for heavy and light fog is shown in Figs. 3 and 4, respectively. For a low-visibility weather condition, i.e., heavy fog, operating wavelength has a negligible effect on the specific attenuation, whereas for light fog when the visibility range is high (≥6 km), attenuation is quite less for an operating wavelength of 1550 nm as compared to 850 and 950 nm. Dependency of the attenuation on wavelength decreases when visibility increases beyond 20 km (clear weather).

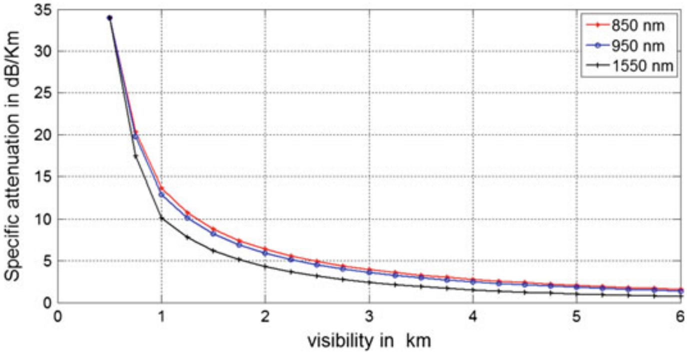


Fig. 3 Attenuation versus visibility plot for heavy fog

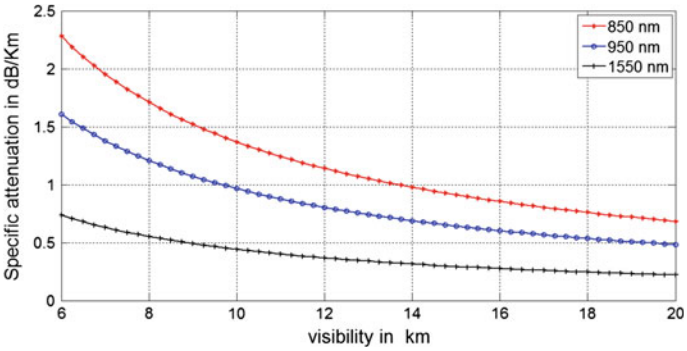


Fig. 4 Attenuation versus visibility plot for light fog

4.2 Attenuation Due to Weather at 1550 nm

The attenuation for different weather conditions, i.e., heavy fog and cloud, light fog, and haze at 1550 nm, are shown in Figs. 5 and 6, respectively, and are tabulated in Table 5. These values of attenuation at 1550 nm are used to characterize different weather conditions in further simulations.

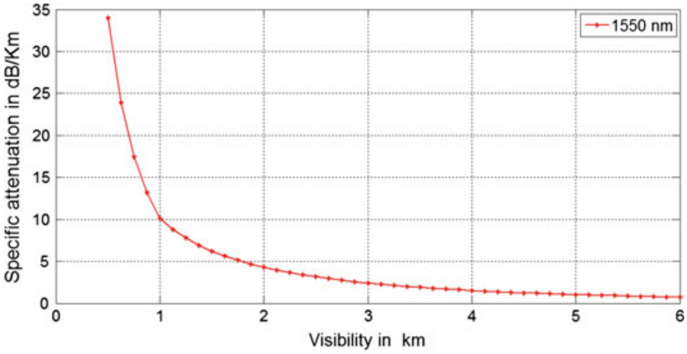


Fig. 5 Attenuation for heavy fog and cloud at 1550 nm

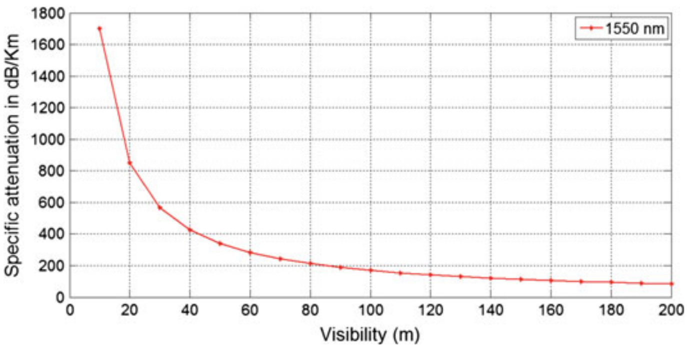


Fig. 6 Attenuation for light fog and haze at 1550 nm

Table 5 Attenuation at 1550 nm

Weather conditions	Visibility range (m)	Attenuation (dB/km)
Haze	3000	2.423
Light fog	875	13.17
Heavy fog	100	170
Cloud	30	566.7

4.3 Comparison of Attenuation for Fog, Snow, and Rain

Scattering in different fog conditions gives significantly high attenuation because the size of fog particles is comparable to the optical transmission wavelengths. It can be observed from Fig. 7 that attenuation is maximum for snow and less for rain as compared to fog. In case of fog, there is a sudden increase in attenuation for visibility range less than 150 m which exactly matches with the data provided in Table 1 (i.e., visibility range <200 m corresponds to heavy fog) for an operating wavelength of 1550 nm.

4.4 Received Power for FSO System

Consider a laser source L_s transmitting power P_T at a wavelength of 1550 nm. The received signal power P_R [3] can be obtained as

$$P_R = P_T \frac{D_R^2}{\theta^2 L^2} 10^{-\gamma L/10} \tau_t \tau_r \tag{9}$$

where D_R is the receiver aperture diameter, θ is the beam divergence, L is the link length, γ is the atmospheric attenuation factor, τ_r and τ_t are receiver and transmitter optical efficiencies, respectively. For a receiver sensitivity of −20 dBm, achievable transmission distances for cloudy, heavy fog, light fog, and haze are 45, 105, 435, and 691 m, respectively. These observations are made based on the graph shown in Fig. 8. Similar observations have been made using OptiSystem and it has been shown in Fig. 9.

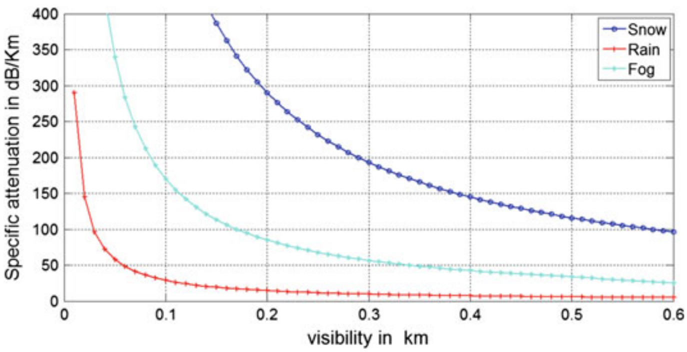


Fig. 7 Attenuation for fog, snow, and rain

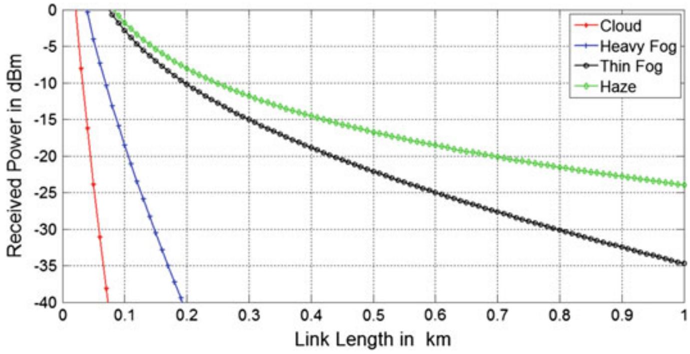
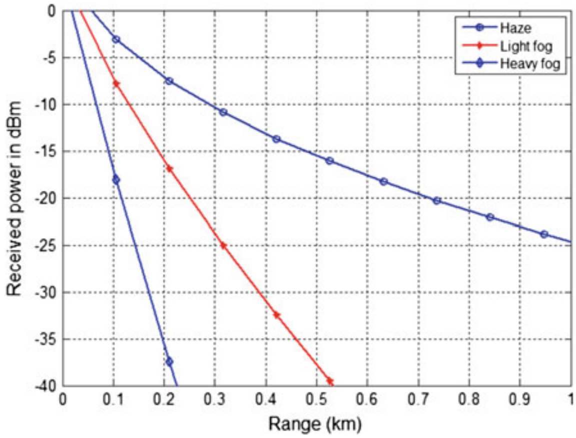


Fig. 8 Output power versus link length

Fig. 9 Output power versus link length (software simulated)



4.5 Data Rate for FSO System

For a given receiver sensitivity (in this case, it is −20 dBm equivalent to 327,000 photons/bit), the achievable data rate R [8] is given by

$$R = \frac{P_T D_R^2 10^{-\gamma L/10} \tau_t \tau_r}{\pi \left(\frac{\theta}{2}\right)^2 L^2 E N_b} \tag{10}$$

where $E = hc/\lambda$ *is* the photon energy at wavelength λ and N_b is the receiver sensitivity in photons/bit, h is the Planck's constant, and c is the velocity of light. Data rate of 1 Gbps is obtained at a link distance of 20 m for cloudy weather, 80 m for heavy fog, and 111 m for haze as shown in Fig. 10.

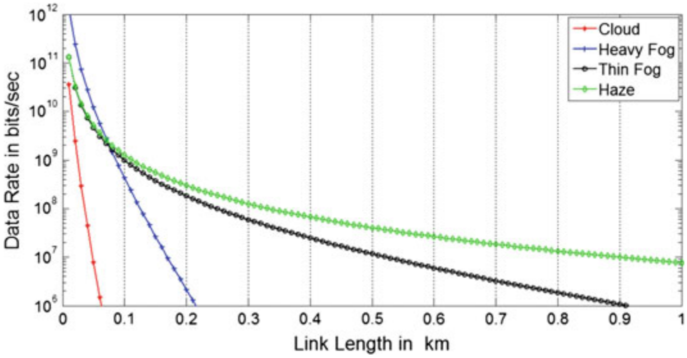


Fig. 10 Data rate versus link length

4.6 Link Margin for FSO System

The link margin is included in the link budget equation in order to compensate for scattering, absorption, and scintillation losses at a given range. Link margin [8] is defined as the ratio of the available power at the receiver to the power required for achieving a specified BER at a given data rate and it can be expressed as

$$L_M = \left[\frac{P_T \lambda}{N_b R h c}\right] * \left[\frac{a l D^2}{\theta^2 L^2}\right] * 10^{-\gamma L/10} \tau_r \tau_t \quad (11)$$

Link margin has been analyzed for different weather conditions as well as for different data rates in case of haze.

For a fixed link range, link margin decreases with increase in bit rate. For a link range of 100 m in haze, link margin at data rates 5 Mbps, 1.25 Gbps, 2.5 Gbps, and 5 Gbps are 15, 11, 10, and 8 dB, respectively. This is shown in Fig. 11. It is

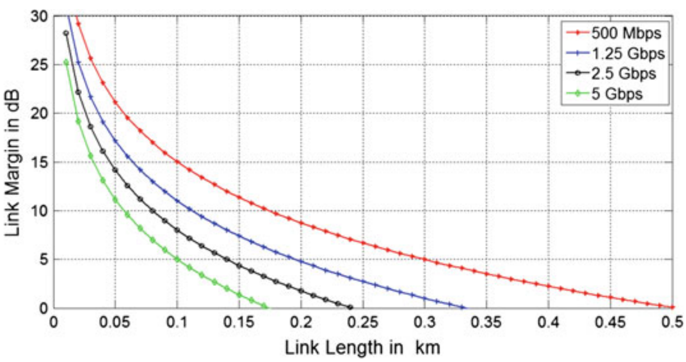


Fig. 11 Link margin for different data rates

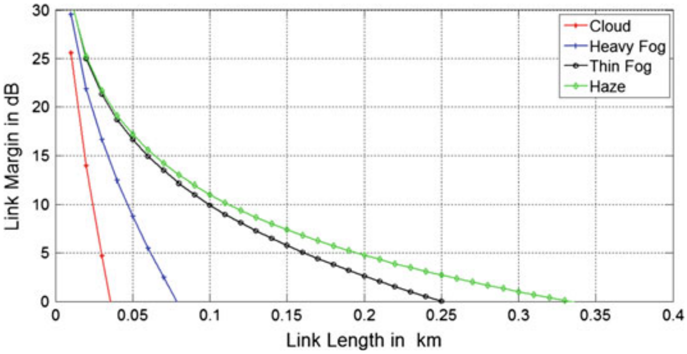


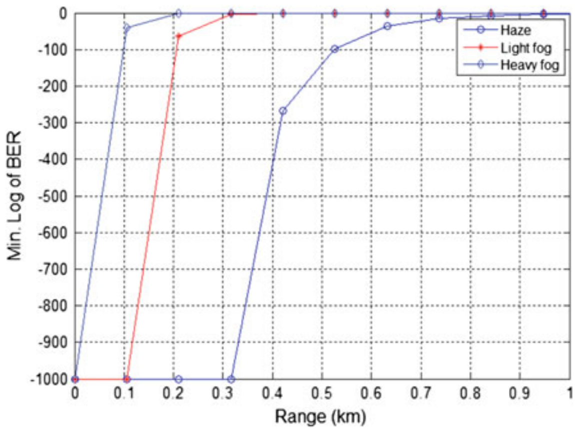
Fig. 12 Link margin for different weather conditions

apparent from Fig. 12 that link margin of 10 dB is obtained for link lengths of 24, 46, and 112 m in case of cloudy, heavy fog, and haze weather conditions, respectively.

4.7 *Bit Error Rate*

Bit error rate is the probability of an incorrect identification of a bit by the decision circuit of a receiver. For communication systems, criteria used are that the BER $\leq 10^{-9}$. The BER results for different weather conditions show that BER is very poor for heavy fog and snow as shown in Fig. 13. Using the simulation results in Fig. 14, we can infer that BER performance of the FSO system degrades with

Fig. 13 BER versus link range for different weather conditions



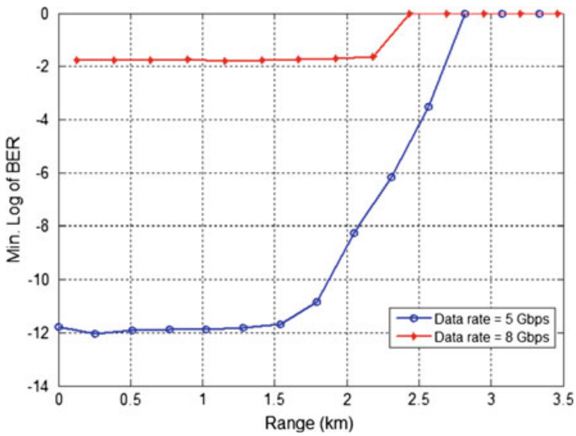


Fig. 14 BER versus link range for different data rates

increase in data rate. For a link range of 1.5 km, the FSO system degrades with increase in data rate. For a link range of 1.5 km, the FSO system with lower data rate say 5 Gbps gives BER of 10^{-12}.

5 Conclusions

Despite its major advantages, FSO access technology suffers from severe availability and reliability challenges mainly due to different weather effects like fog, rain, snow, and clouds in the earth atmosphere. Following are the conclusions made on the basis of the above simulation and analysis:

1. For a OOK-modulated FSO system, the simulation results show that attenuation due to absorption and scattering is minimum at 1550 nm, and thus using 1550 nm optical wavelength for transmission in an FSO system is a better choice.
2. Due to sudden increase in specific attenuation in case of heavy fog, there is a substantial degradation in the performance FSO communication link.
3. It was also observed that a link margin of 10 dB is obtained for longer link lengths in haze as compared to cloud and heavy fog, which shows that an FSO system's performance would be less affected by haze as compared to cloudy and heavy fog weather.
4. There is a tradeoff between the data rate and link margin. For a particular weather condition, higher link margins can be obtained by decreasing the data rate and vice versa.
5. BER decreases with increasing data rates. Also, BER performance is very poor in heavy fog and snowy weather.

6. On increasing the link length, the achievable data rate drops down significantly for heavy fog and cloudy weather which can severely affect the communication by leading to complete link outage.

Future work can focus on performance analysis of the FSO systems with modulation schemes like PPM, DPPM, and DPIM under various weather conditions.

References

1. Ghassemlooy, Z., Popoola, W.: Terrestial free-space optical communications. In: Fares, S.A., Adachi, F. (eds.) Intech, ISBN 978– 953-307-042 (2010)
2. Kim, I.I., McArthur, B., McArthur, A.E.K.B., Korevaar, E.: Comparison of laser beam propagation at 785 and 1550 nm in fog and haze for optical wireless communications (2001)
3. Kruse, P.W., McGlauchlin, L.D., McQuistan, R.B.: Elements of infrared technology: generation, transmission and detection. Wiley, New York (1962)
4. Farukh, N., Kvicera, V., Awan, M., Leitgeb, E., Muhammad, S., Kandus, G.: Weather effects on hybrid fso/rf communication link (2009)
5. OŠBrien, H.W.: Visibility and light attenuation in falling snow, vol. 9, pp. 671–683 (1970)
6. Atlas, D.: Shorter contribution optical extinction by rainfall, vol. 10, pp. 486–488 (1953)
7. Rammprasath, K., Prince, S.: Analyzing the cloud attenuation on the performance of free space optical communication, pp. 3–5, April 2013
8. Guo-yong, H., Chang-ying, C., Zhen-qiang, C.: Free-space optical communication using visible light (2006)