Performance analysis of free space optical communication system under rain weather conditions: a case study for inland and coastal locations of India

Harjeevan Singh · Nitin Mittal

Received: 1 September 2020 / Accepted: 29 March 2021 / Published online: 9 April 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract
Free space optical communication (FSOC) has emerged as a potential candidate for providing huge bandwidth and solving the problem of spectrum congestion. But the atmospheric conditions limit the performance of FSOC link as the laser signal propagates through the atmospheric channel. This work aims to investigate the performance of FSOC link under average and heavy rainfall weather conditions of India. The meteorological data related to rainfall, over a duration of 4 years, was obtained from the Indian Meteorological Department for six different locations of India, representing the inland and coastal areas. The attenuation coefficient due to rain for all the locations has been calculated using mathematical models. The performance analysis of Wavelength Division Multiplexing based free space optical communication system has been analyzed by incorporating the attenuation due to rain for all considered locations. The inland location of Hyderabad has recorded the minimum attenuation coefficient of 1.91 dB/km due to rain and can support a link range of 5.43 km, corresponding to bit error rate of order of $10^{-9}$ under average conditions. On the other hand, the average rainfall is maximum for the coastal area of Mumbai, resulting in maximum attenuation coefficient of 4.08 dB/km. Moreover, the maximum link range for Mumbai is limited to 3.48 km, corresponding to bit error rate of order of $10^{-9}$ under average conditions of rain weather. Similarly, the inland locations of India have delivered a better link performance as compared to coastal areas under heavy rainfall weather conditions also.

Keywords Free space optical communication · WDM · Rain attenuation · Signal to noise ratio · Bit error rate · Q-factor
1 Introduction

Free space optical communication (FSOC) system uses atmosphere as an unguided media to transmit information using laser signal (Mansour et al. 2017; Aveta et al. 2020). It is a line of sight based communication and consists of transceivers at both sides to transmit data in full duplex mode (Kashif et al. 2020; Ai et al. 2020). It makes use of infrared, visible and ultraviolet band of spectrum to transmit information using optical signal (Chowdhury et al. 2018; Guiomar et al. 2020). This technology is similar to optical fiber technology as both of the technologies use optical signals to transmit information, but FSOC links does not require any digging and laying of fibers (Zhang et al. 2019). In addition to this, the cost of digging and laying down the fiber is very high and the optical fiber network cannot be relocated once it has been deployed (Lorences-riesgo et al. 2019). So FSOC links can be used as a feasible solution for last mile internet access connectivity due to easy and cost effective deployment as compared to optical fiber technology (Mohale et al. 2016; Briantcev et al. 2020; Mirza et al. 2020). The advantages of FSOC links over other technologies like Microwave and Radio Frequency (RF) communication are high data rates, less power consumption, license free transmission and high security (Kaur 2019; Tan et al. 2019; Yeh et al. 2020). Due to these advantages, FSOC links can be used to meet the increasing bandwidth requirements of applications like high speed internet, video-conferencing, high definition Television, etc. and can solve the problem of spectrum congestion (Kaushal and Kaddoum 2017). Moreover, a world record has been made by German Aerospace Centre by transmitting data at the rate of 1.72 Tbps for a range of 10.45 km by using FSOC links (Son and Mao 2017).

But despite many advantages, the performance of FSOC links is degraded by atmospheric channel conditions (Sharma and Grewal 2020). The optical signal suffers from huge attenuation due to these unfavourable atmospheric conditions. Rain attenuation is also one of the factor responsible for deteriorating the performance of FSOC link as the optical beam gets scattered after passing through the rain drops having large size (Al-Gailani et al. 2014). The heavy rainfall can lead to attenuation of optical signal upto levels of 20–30 dB/km (Ghassemlooy et al. 2013). So it becomes necessary to study the rain weather conditions of the deployment site in order to evaluate the performance of FSOC link before the installation.

According to the study conducted by Attri and Tyagi, India is a country having vast variations in the climatic conditions across its various regions and it varies from tropical in the south region to temperate in the north region of the country (Attri and Tyagi 2010). Consequently, the different locations of India experience different amount of rainfall every year. For the country as whole, the contribution of south-west monsoon (June, July, August and September) is 74.2% to the annual rainfall and the contribution of rainfall during pre-monsoon period (March, April and May) and post-monsoon period (October, November and December) to the annual rainfall is same as 11%. Due to extreme hot weather conditions during summer months, the moist winds over oceans are drawn by northern India and as a result, it receives 75% of annual rainfall during the period of south-west monsoon (June to September). On the other hand, Southern part of India receive good amount of rainfall during post-monsoon period (October–December) resulting from formation of storms in Bay of Bengal and it accounts for 35% of their annual rainfall. Hence, various locations of India receive different amount of rainfall during different months of the year. To the best of our knowledge, no consolidated study has been carried out to analyze the performance of FSOC system under rain weather conditions in potential areas of India. So this study will
focus on performance analysis of FSOC links in coastal and inland locations of India under average and heavy rainfall weather conditions. Moreover, the locations have been chosen very carefully so as to demonstrate the variation in rain weather conditions across various regions of India and analyze the impact of rain on the performance of FSOC system. In addition to this, the locations considered in this study not only represent the variation in the patterns of rainfall throughout the year but also represent the major commercial areas of the country with a great potential for deployment of FSOC links.

The structure of the paper has been defined as follows: Sect. 2 will discuss the study of the literature related to the analysis of rain weather conditions on the performance of FSOC links in other countries of the world. Section 3 will discuss about the attenuation of FSOC link due to rain and the mathematical models in order to find out the attenuation coefficient. Section 4 will discuss the simulation model of a designed FSOC system, which will be used for investigating the performance of FSOC links for different locations of India. Section 5 will include the discussion of simulation results followed by conclusion in Sect. 6.

2 Related work

The study conducted by Alkholidi and Altowij analyzed the effects of rain weather conditions of Yemen on the performance of FSOC system (Alkholidi and Altowij 2012). The meteorological data, related to rainfall of various locations across like Sana, Aden and Taiz, have been collected from Public Authority for Water Resources (PAWR) for the year 2008. The rainfall rate of Taiz is maximum as compared to Sana and Aden and hence the attenuation coefficient for Taiz is also maximum. The attenuation coefficient has been calculated for light, medium and heavy rainfall conditions. The attenuation coefficient varies from 0.036 to 0.18 dB/km for light rain, 0.24–0.37 dB/km for medium rain and 0.45–0.69 dB/km for scenario of heavy rainfall. Basahel et al. has analyzed the effects of rain on the availability of FSOC link in Malaysia (Basahel et al. 2016). The rainfall data of three years from 1st January, 2011 to 31st December, 2013 has been studied in order to investigate the link availability. Further, the cumulative distribution function (CDF) of rain rate was obtained using the rainfall data. The highest rain rate of 168 mm/h has been recorded which corresponds to exceedance probability of 0.000187% and the lowest rain rate of 12 mm/h has been recorded with the exceedance probability of 0.91989%. The attenuation corresponding to maximum rain rate of 168 mm/h is 32 dB/km, whereas the lowest rain rate of 12 mm/h has attenuation coefficient of 3 dB/km. Hence, there is an increase of attenuation level by 29 dB/km from lowest to highest rain rate which demonstrates that rain rate significantly impacts the availability of FSOC link. The study conducted by Haider et al. has studied the impact of rain on the feasibility of FSOC links in Bangladesh. Seven cities of Bangladesh namely, Dhaka, Rajshahi, Chittagong, Sylhet, Rangpur, Mymensingh and Barisal have been considered for this study (Shahiduzzaman et al. 2019). The meteorological data related to rainfall intensity of all locations from January, 2013 to June, 2016 have been collected from Bangladesh Meteorological Department. It has been found that Chittagong and Sylhet receive medium rainfall whereas Rajshahi, Rangpur, Dhaka, Mymensingh and Barisal receive light rainfall throughout the year. Under average rainfall conditions, Sylhet has recorded maximum rainfall of 11.11 mm/h with attenuation coefficient of 5.965 dB/km and Rajshahi has received minimum rainfall of 3.44 mm/h with attenuation coefficient of 0.869 dB/km. On the other hand, Chittagong
has received maximum rainfall of 50.16 mm/h with attenuation coefficient of 12.512 dB/km and Rajshahi has received minimum rainfall of 11.58 mm/h with attenuation coefficient of 6.145 dB/km under heavy rainfall conditions. In a related study by Rouissat et al., the effects of Algeria’s weather conditions on the performance of FSOC link has been investigated so as to find out the challenges related to the deployment of FSOC links in Algeria (Rouissat et al. 2012). The rainfall intensity data of four cities of Algeria namely, Algiers, Annaba, Oran and Gardaya have been analyzed in order to investigate the effects of rainfall on FSOC links. It has been observed that rainfall in Algeria decreases from East to West and from North to South. In addition to this, maximum rainfall occurs during the months of November, December and January in Algeria. It has been concluded that heavy rainfall in the north of Algeria is the major challenge for FSOC links. Twati et al. has analyzed the effects of rain weather conditions on the performance of FSOC links in Libya (Twati and Badi 2014). The meteorological data related to the intensity of rainfall of fourteen cities has been collected from Libyan National Meteorological Center (LNMC) from year 1946 to 2000. The maximum link distances for FSOC links have been computed for all cities of Libya by considering attenuation due to rainfall using Optisystem 7.0 software. The received power has been calculated and compared with the sensitivity of the receiver in order to find the maximum link distances. Under the heavy rainfall weather conditions, the maximum link distance has been found out to be 1.91 km. In a related work by Dath et al., the performance of FSOC link has been investigated under weather conditions of Snegal. The meteorological data related to intensity of rainfall for the city of Dakar has been studied from year 2003 to 2013 to investigate the performance of FSOC links (Bamba Dath et al. 2017). It has been found that rain rates less than 25 mm/h do not result in major degradation of performance of FSOC links. For rain rates greater than 25 mm/h, the probability of attenuation of 10 dB/km is equal to 35%. Similarly, the probability of attenuation of 10–15 dB/km, corresponding to varying rain rates from 25 to 50 mm/h has been found out to be 81%. In addition to this, it has been analyzed that the link range varies from 3.2 to 1 km for both wavelengths of 1300 and 1550 nm under given conditions of rainfall intensity.

According to the discussed literature, it has become apparent that the analysis of atmospheric conditions of deployment site is mandatory before the installation of FSOC links and it helps in deciding the system parameters of FSOC system in order to get the desired link performance. Due to variation in the amount of rainfall intensity across various regions of India, the performance of FSOC links will also vary according to the locations. So this motivates to analyze the rain weather conditions of India in order to investigate the performance of FSOC system in different parts of the country.

### 3 Rain attenuation model

Rain is formed due to presence of water droplets in the atmosphere. These water droplets have variable form and number in space and time. As the form of water droplets depends on their size, they are spherical in shape up to radius of 1 mm and become oblate spheroids beyond the radius of 1 mm (Alkholidi and Altowij 2014). Rain is one of the factors responsible for degrading the performance of FSOC link. Moreover, heavy rainfall can lead to unavailability of FSOC links also. The scattering caused by rainfall is called non-selective scattering and it is independent of wavelength as radius of rain drops (100–1000 µm) is more than the wavelength used for FSOC links (Basahel et al. 2017). Systems operating
at frequencies below than 10 GHz are not attenuated by atmospheric weather conditions. However, systems operating at frequencies higher than 10 GHz, as in case of FSOC system, undergo attenuation due to weather conditions like rainfall (Suriza et al. 2013). In order to analyze the effect of rain on the performance of FSOC link, the drop size distribution of rain along with rate of rainfall are required. Rain attenuation coefficient can be calculated by integrating all rain drop sizes as follows (Basahel et al. 2017):

$$\alpha_{\text{rain}} = 4.343 \int_0^\infty Q(D, \lambda, m)N(D)dD$$

(1)

where \(Q\) represents the extinction cross section (\(\text{mm}^2\)) and it is a function of diameter (\(D\)) of drop, wavelength (\(\text{mm}\)) and complex refractive index of water (\(m\)), \(N(D)\) represents the drop size distribution function. But the parameters defined in Eq. (1) are not easily available and it becomes difficult to calculate the attenuation due to rain. So an empirical formula involving specific rain attenuation and rain rate has been derived as follows (Olsen et al. 1978):

$$\alpha_{\text{rain}}(\text{dB/km}) = kR^\alpha$$

(2)

where \(R\) represents the intensity of rainfall (\(\text{mm/h}\)), \(k\) and \(\alpha\) represents the power law parameters whose values depend upon the size of rain drop and temperature of rain. The values of \(k\) and \(\alpha\) are taken as 1.076 and 0.67 respectively and the empirical formula for calculating the rain attenuation is given by (Rashed and El-Halawany 2013; Dayal et al. 2017; Kaushal et al. 2017; Ghassemlooy et al. 2019):

$$\alpha_{\text{rain}}(\text{dB/km}) = 1.076R^{0.67}$$

(3)

4 Simulation design

FSOC system mainly comprises of three sections namely, transmitter, propagating channel and receiver. The simulation model has been designed using Optisystem 13.0 software. The transmitter section comprises of Pseudo-Random bit sequence (PRBS) generator, Non-return-to-zero (NRZ) pulse generator, Mach–Zehnder modulator (MZM) and a continuous wave laser. PRBS generator generates signal in the binary format and this binary signal from PRBS generator is converted into an electrical signal by NRZ pulse generator. Further, the optical signal produced by the laser source is modulated by Mach–Zehnder modulator with respect to electrical output produced by NRZ pulse generator. The modulated optical beam is transmitted through free space towards the receiver end. At receiver, Avalanche Photodetector (APD) converts the optical beam into an electrical signal. The low pass filter (LPF) is further used to filter out any high frequency noise component present in the signal and the desired output can be observed on bit error rate (BER) analyzer.

In this work, 32-channel Wavelength Division Multiplexing (WDM) based FSOC system, having transmission rate of 10 Gbps for each channel, has been designed. Wavelength Division Multiplexing is a technique which transmits a number of signals having different wavelengths simultaneously over the same medium (Nam et al. 2017). WDM technology can also be used for high bandwidth demanding multimedia services like live streaming of videos and video conferencing (Qin et al. 2004). WDM based FSOC links have been used to increase the capacity of FSOC system under various atmospheric conditions (Robinson and Jasmine 2016). Hybrid optical amplifiers have been used for WDM based FSOC
system in order to increase the maximum achievable link range (Dayal et al. 2017). Multi-beam WDM based FSOC system has been demonstrated to mitigate the effects of haze weather conditions on the performance of system (Grover et al. 2017). Four channel WDM based FSOC system integrated with optical fiber network has been experimentally demonstrated to support upstream and downstream traffic with data rate of 10 Gbps for each channel (Yeh et al. 2019). As shown in Fig. 1, the transmitter of WDM based FSOC system consists of 32 lasers and the spacing between each channel is 100 GHz. The operating power has been set to 10 dBm, ensuring the safety of human eye (Brien and Katz 2005). A WDM multiplexer and a demultiplexer has been employed at the transmitter and receiver section respectively. The output of the designed system has been observed on BER analyzer at the receiver section. The atmospheric attenuation due to rain for various locations has been incorporated into the designed WDM-FSOC system in order to analyze the performance of system in terms of received power, signal to noise Ratio (SNR), Q-Factor and bit error rate (BER). The simulation parameters of designed WDM-FSOC system are given in Table 1 (Mikołajczyk et al. 2017; Kakati and Arya 2019).

5 Results and discussion

In order to determine the attenuation due to rain intensity, the meteorological data related to rain intensity of various locations have been collected from Indian Meteorological Department for the duration of 4 years from 2014 to 2017. The locations considered in this study (Chandigarh, Mumbai, Pune, Kolkata, Hyderabad and Chennai) are widely spread across the country and represent major commercial areas of the country. Mumbai and Chennai are located on the western coast and south-eastern coast of India respectively and represent the proper coastal locations of India whereas Kolkata is located in the eastern part of India at a distance of around 170 km from the coastal line of India. Similarly, Pune is located in the western part of India at a distance of around 150 km from the coastal line of India. On
the other hand, Hyderabad and Chandigarh are situated far away from the coastal line of India in the south-central and north-west interior part of India respectively and represent the typical inland locations of the country. The performance analysis has been done for the average and heavy rainfall weather conditions in India.

5.1 Performance analysis of WDM-FSOC system under average rainfall weather conditions

In order to evaluate the performance of WDM based FSOC system under average rain intensities in India, the average value of rain intensity has been computed, from the collected meteorological rainfall data of four years, for each of the location. Since Mumbai is located on the windward side of the western Indian coast, the moist winds from Arabian sea cause very heavy rainfall (Jenamani et al. 2006). Consequently, Mumbai has recorded maximum average rain rate of 7.31 mm/h. As the moist winds travel towards the inland locations of the country, they get exhausted and dry out, resulting in lesser rainfall in the inland areas. Hence, the inland location of Hyderabad has recorded minimum rain rate of 2.35 mm/h. The rain rates recorded for Chennai, Kolkata, Pune and Chandigarh are 4.93 mm/h, 4.30 mm/h, 3.33 mm/h and 3.02 mm/h respectively. The attenuation due to rainfall has been found by calculating the specific attenuation constant using Eq. (3). It has been observed that the locations with higher rain intensities have recorded higher specific attenuation coefficient. Consequently, Mumbai has recorded maximum specific attenuation coefficient of 7.31 dB/km and Hyderabad has recorded minimum specific attenuation coefficient of 2.35 dB/km. Similarly, the specific attenuation coefficients of Chandigarh, Pune, Kolkata and Chennai are 3.02 dB/km, 3.33 dB/km, 4.3 dB/km and 4.93 dB/km. Table 2 shows the rain rates along with specific attenuation constants for all locations of India.

The 32-channel WDM based FSOC system has been simulated using Optisystem 13.0 software by incorporating the attenuation due to rain for all considered locations of India according to the simulation parameters defined in Table 1. In this work, the attenuation due to rain has been considered only and the additional losses like geometrical losses and other transmission losses have been ignored by considering the ideal link conditions for the FSOC link.

Table 1 Simulation parameters

| Link parameter                  | Value                   |
|--------------------------------|-------------------------|
| Bit rate                       | 10 Gbps                 |
| Laser power                    | 10 dBm                  |
| No. of channels                | 32                      |
| Channel spacing                | 100 GHz                 |
| Laser frequency                | (193.1–196.2) THz       |
| Transmitter aperture diameter  | 5 cm                    |
| Receiver aperture diameter     | 20 cm                   |
| Beam divergence                | 2.5 mrad                |
| Photodetector type             | APD                     |
| Dark current                   | 10 nA                   |
| Responsivity                   | 1 A/W                   |

Figure 2 shows the plot of received power of all locations against the link range. It has been observed that the received power decreases as the link range increases. Mumbai has
recorded minimum average power due to maximum average rainfall, whereas the received power is maximum in case of Hyderabad resulting from less attenuation due to minimum average rainfall. For a link range of 4 km, the received power is minimum for Mumbai with a value of $-28.4$ dBm and maximum for Hyderabad with a value of $-19.8$ dBm. Similarly, the received power for Chandigarh, Pune, Kolkata and Chennai is $-21.2$ dBm, $-21.8$ dBm, $-23.6$ dBm and $-24.6$ dBm respectively, corresponding to a link range of 4 km.

Figure 3 shows the plot of SNR versus link range for different locations of India. It is apparent that degradation in the value of SNR is observed with an increase in link range. The SNR for Mumbai is largely affected by attenuation due to high average rainfall, but the effects of rainfall on the value of SNR is minimum for Hyderabad due to low average rainfall intensity. The value of SNR is minimum for Mumbai with a value of 6.4 dB corresponding to link range of 4 km and it is maximum for Hyderabad with a value of 23.8 dB for same link range. The values of SNR for Chandigarh, Pune, Kolkata and Chennai are 21 dB, 19.8 dB, 16.2 dB and 14 dB respectively, for FSOC link operating at a link range of 4 km.

Figure 4 shows the relation between Q-Factor and link range for different locations of India. It has been observed that there is a significant decrease in the value of Q-Factor with an increase in link range. Since the transmitted optical signal is degraded badly due to high average rainfall, Mumbai has recorded minimum values of Q-Factor as a result of attenuation due to high rainfall. On the other hand, the degrading effects of rainfall are less for Hyderabad due to low average rainfall and hence, the Q-Factor is maximum for Hyderabad.
as compared to other locations. Mumbai has recorded minimum value of Q-Factor of 2.7 while Hyderabad has recorded maximum value of Q-Factor of 17.8 at a link range of 4 km. In addition to this, the Q-Factor for Chandigarh, Pune, Kolkata and Chennai is 13.3 dB, 11.7 dB, 8 dB and 6.3 dB respectively for a link range of 4 km. Table 3 shows the overall comparison of WDM-FSOC system’s performance for different locations of India under the scenario of average rainfall. For the given link ranges, it can be observed that the WDM-FSOC system delivers best performance for Hyderabad, experiencing less average rainfall weather conditions and the system performance degrades for Mumbai as the average rainfall intensity is maximum for Mumbai.

The bit error rate performance of WDM-based FSOC system with link range has been depicted for all locations of India in Fig. 5. It has been observed that the bit error rate performance deteriorates with an increase in link range. As a result of low rain intensities, Hyderabad has recorded the best bit error rate performance under average rainfall weather conditions and the maximum link distance corresponding to BER of order of $10^{-9}$ is 5.43 km. On the other hand, the high average rainfall rate of Mumbai has impaired the BER performance of Mumbai and hence, the maximum link distance corresponding to BER of $10^{-9}$ is limited to 3.48 km only. Similarly, the maximum link distances for Chandigarh,
Table 3  Performance analysis of WDM-FSOC system for different locations of India under average rainfall weather conditions

| Location name | Link range = 1 km |  | Link range = 2 km |  | Link range = 3 km |  |
|---------------|-----------------|---|-----------------|---|-----------------|---|
|               | Received power  | SNR (dB) | Q factor | Received power  | SNR (dB) | Q factor | Received power  | SNR (dB) | Q factor |
| Chandigarh    | − 2.5           | 58.4     | 120.9     | − 10.7          | 42       | 81.5     | − 16.4          | 30.5     | 34.3     |
| Mumbai        | − 4.3           | 54.7     | 116.8     | − 14.3          | 34.7     | 49.7     | − 21.9          | 19.5     | 11.4     |
| Pune          | − 2.6           | 58.1     | 120.6     | − 11            | 41.4     | 79       | − 16.9          | 29.6     | 31.5     |
| Kolkata       | − 3.1           | 57.2     | 119.7     | − 11.9          | 39.6     | 71       | − 18.2          | 26.9     | 24.3     |
| Hyderabad     | − 2.1           | 59.1     | 121.5     | − 10            | 43.4     | 87.3     | − 15.4          | 32.6     | 41.5     |
| Chennai       | − 3.3           | 56.6     | 119.2     | − 12.4          | 38.5     | 66.2     | − 19            | 25.2     | 20.6     |
Pune, Kolkata and Chennai are 4.95 km, 4.77 km, 4.32 km and 4.09 km respectively, corresponding to BER of order of $10^{-9}$. The maximum achievable link distances for different locations of India, corresponding to bit error rate of order of $10^{-9}$, under average rainfall weather conditions have been shown in Table 4.

The eye diagrams of WDM based FSOC system have been shown in Fig. 6 for different locations of India, corresponding to link range of 4 km. The clear opened eye diagrams for Hyderabad indicates that the received data is not much degraded by the average rainfall weather conditions. However, eye diagram for Mumbai depicts the maximum degradation of received data due to high rain rates. Moreover, the eye diagram for the coastal area of Chennai has also demonstrated the impairment of received data. In addition to this, the eye diagrams for Chandigarh, Pune and Kolkata shows the less degradation of data signal.

### 5.2 Performance analysis of WDM-FSOC system under heavy rainfall weather conditions

This section aims to evaluate the performance of FSOC system under the heavy rainfall weather conditions for all the locations. In order to define the heavy rainfall conditions, the maximum rain intensities during the past 4 years have been considered from statistical weather data. Mumbai has recorded maximum rain intensity of 177.6 mm/h.

![BER versus link range for different locations of India under average rainfall weather conditions](image)

**Table 4** Maximum achievable link ranges for different locations of India under average rainfall weather conditions

| Location name | Attenuation in dB/km | Maximum link distance (in km) | BER         |
|---------------|-----------------------|-------------------------------|-------------|
| Chandigarh    | 2.26                  | 4.95                          | $9.93 \times 10^{-9}$ |
| Mumbai        | 4.08                  | 3.48                          | $7.80 \times 10^{-9}$ |
| Pune          | 2.41                  | 4.77                          | $9.15 \times 10^{-9}$ |
| Kolkata       | 2.86                  | 4.32                          | $9.32 \times 10^{-9}$ |
| Hyderabad     | 1.91                  | 5.43                          | $8.95 \times 10^{-9}$ |
| Chennai       | 3.13                  | 4.09                          | $7.73 \times 10^{-9}$ |
and Hyderabad has recorded minimum rain intensity of 37.7 mm/h. Hence, FSOC link undergoes maximum attenuation of 34.6 dB/km for Mumbai and the attenuation of FSOC link is 12.2 dB/km in case of Hyderabad. Table 5 shows the rain rates and the corresponding attenuation coefficients for other locations of India under heavy rainfall weather conditions.

The received power has been plotted against link range in Fig. 7 for heavy rainfall weather conditions. The impact of heavy rainfall is maximum for Mumbai due to maximum rain rate of 177.6 mm/h while it is minimum for Hyderabad as the maximum rainfall intensity is 37.7 mm/h only. Consequently, the received power is minimum for Mumbai with a value of −75.3 dBm and it is maximum for Hyderabad with a value of −30.5 dBm corresponding to link distance of 2 km. For a link range of 2 km, the values of received
Table 5  Maximum rain rates and specific attenuation coefficients of different locations of India

| Location name | Maximum rain rate (in mm/h) | Specific attenuation coefficient (in dB/Km) |
|---------------|----------------------------|-------------------------------------------|
| Chandigarh    | 43.3                       | 13.4                                      |
| Mumbai        | 177.6                      | 34.6                                      |
| Pune          | 61.2                       | 16.9                                      |
| Kolkata       | 52.8                       | 15.3                                      |
| Hyderabad     | 37.7                       | 12.2                                      |
| Chennai       | 119.8                      | 26.6                                      |

Fig. 6  (continued)

Fig. 7  Received power versus link range for different locations of India under heavy rainfall weather conditions
power for Chandigarh, Pune, Kolkata and Chennai are $-32.9$ dBm, $-39.9$ dBm, $-36.7$ dBm and $-59.3$ dBm respectively.

The heavy rainfall weather conditions have significantly affected the values of SNR as shown in Fig. 8. As the link range is increased, the SNR of WDM based FSOC system degrades significantly under the heavy rainfall weather conditions. For Mumbai, the value of SNR becomes 0 dB at a link range of 1 km due to maximum rain intensity. In addition to this, the received SNR becomes 0 dB for a link range of 1.2 km in case of Chennai under heavy rainfall conditions. The SNR is least affected in case of Hyderabad due to less rainfall under heavy rainfall weather conditions and the SNR has a value of 2.2 dB at a link range of 2 km.

The variation in Q-Factor with link range has been depicted in Fig. 9 under the effects of heavy rainfall weather conditions and it clearly demonstrates the decrease in Q-Factor with an increase in link range. Moreover, it can be observed that the Q-Factor becomes zero for link distances less than 1 km in the case of Mumbai as a result of maximum rainfall.
rainfall intensity. Similarly, the value of Q-Factor becomes zero in case of Chennai for link distances less than 1.2 km. The values of Q-factor for Chandigarh, Pune, Kolkata and Hyderabad at a link distance of 1.2 km are 26.1, 11, 16.5 and 34.4 respectively. Hence, it can be concluded that Hyderabad has recorded maximum Q-Factor under heavy rainfall weather conditions. The overall comparison of WDM-FSOC system’s performance for different locations of India under the scenario of heavy rainfall has been depicted in Table 6. The heavy rainfall in Mumbai have severely deteriorated the performance of WDM-FSOC system and on the other hand, the system performance is comparatively less affected in case of Hyderabad as the maximum rainfall intensity is minimum for Hyderabad. So, it can be concluded that longer FSOC links are not feasible under heavy rainfall weather conditions for the considered locations of India.

The BER performance of WDM based FSOC system with link range has been illustrated in Fig. 10 under heavy rainfall weather conditions. The increase in link range degrades the BER performance of FSOC system significantly. Under the effect of heavy rainfall intensity, Hyderabad can support link distance of 1.68 km, corresponding to BER of order of $10^{-9}$. On the other hand, the maximum link distance corresponding to BER of order of $10^{-9}$ is limited to 0.78 km in case of Mumbai under heavy rainfall weather conditions. In addition to this, the optimal link distances for Chandigarh, Pune, Kolkata and Chennai are 1.57 km, 1.33 km, 1.43 km and 0.95 km respectively, corresponding to BER of order of $10^{-9}$. The maximum achievable link distances for different locations of India, corresponding to bit error rate of order of $10^{-9}$, under heavy rainfall weather conditions have been shown in Table 7.

Figure 11 shows the eye diagrams of WDM based FSOC system for various locations of India under heavy rainfall weather conditions, corresponding to link range of 1 km. It can be observed that the effects of heavy rainfall on received data is minimum in case of Hyderabad as per the clear eye diagrams with maximum opening. But the received data gets degraded very badly as it propagates through the free space optical communication channel experiencing heavy rainfall in case of Mumbai and the eye diagram has almost zero opening indicating severe impairment of optical signal. Moreover, the eye diagram for Chennai also depicts the deterioration of data signal under conditions of heavy rainfall. However, the effects of heavy rainfall conditions are comparatively lesser for inland locations of Chandigarh, Pune and Kolkata.

6 Conclusion

In this work, the performance of WDM-FSOC system has been investigated under average and heavy rainfall weather conditions of India by considering various geographical locations. The targeted locations for this study include the coastal and inland locations of the country. The coastal location of Mumbai has recorded maximum average rainfall rate of 7.31 mm/h under average rainfall weather conditions, whereas the average rainfall rate is minimum in case of Hyderabad having a value of 2.35 mm/h. Consequently, the attenuation coefficient for Mumbai is maximum with a value of 4.08 dB/km and Hyderabad has recorded minimum attenuation coefficient with a value of 1.91 dB/km, corresponding to average rainfall weather conditions. Due to excessive rainfall, the coastal area of Mumbai has demonstrated maximum degradation in the performance of WDM-FSOC system as compared to other locations and the values of received power, SNR and Q-Factor are $-28.4$ dBm, 6.4 dB and 2.7 respectively, corresponding to link range of 4 km. However,
### Table 6  Performance analysis of WDM-FSOC system for different locations of India under heavy rainfall weather conditions

| Location name | Link range = 0.6 km | | | Link range = 1 km | | | Link range = 2 km | |
|---------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
|               | Received power (dBm) | SNR (dB) | Q factor | Received power (dBm) | SNR (dB) | Q factor | Received power (dBm) | SNR (dB) | Q factor |
| Chandigarh    | −3.9     | 55.45    | 117.8     | −13.6     | 36.1     | 55.6     | −32.9     | 0        | 0        |
| Mumbai        | −16.6    | 30       | 32.9     | −34.8     | 0        | 0        | −75.3     | 0        | 0        |
| Pune          | −6       | 51.3     | 110.8    | −17.1     | 29.1     | 30.1     | −39.9     | 0        | 0        |
| Kolkata       | −5.1     | 53.2     | 114.4    | −15.5     | 32.3     | 40.4     | −36.7     | 0        | 0        |
| Hyderabad     | −3.2     | 56.9     | 119.5    | −12.4     | 38.5     | 66.2     | −30.5     | 2.2      | 0        |
| Chennai       | −11.8    | 39.6     | 71.2     | −26.8     | 9.7      | 3.9      | −59.3     | 0        | 0        |
the performance of WDM-FSOC system is least affected by average rainfall weather conditions of Hyderabad and the values of received power, SNR and Q-Factor are − 19.8 dBm, 23.8 dB and 17.8 for a link range of 4 km. Similarly, the coastal location of Chennai has also suffered in terms of system performance under the effects of average rainfall weather conditions as compared to other inland locations of country. Moreover, the achievable link distance corresponding to bit error rate of order of $10^{-9}$ is limited to 3.48 km only for Mumbai, while the transmission of data can be carried upto link range of 5.43 km in case of Hyderabad for acceptable BER of order of $10^{-9}$. In addition to this, the maximum link distances for delivering BER of order of $10^{-9}$ for Chandigarh, Pune, Kolkata and Chennai range from 4.09 to 4.95 km.

Under heavy rainfall weather conditions, the maximum achievable link distances for coastal areas of Mumbai and Chennai have reduced to 0.78 km and 0.95 km respectively, corresponding to bit error rate of order of $10^{-9}$. Hence, the coastal areas of Mumbai and Chennai have witnessed drastic degradation in system performance as compared to other locations under the scenario of heavy rainfall. In order to ensure the connectivity during severe attenuation scenario in the coastal areas of India, Radio-Frequency (RF) links can be used as back-up links to support FSOC links.

Fig. 10  BER versus link range for different locations of India under heavy rainfall weather conditions

Table 7  Maximum achievable link ranges for different locations of India under heavy rainfall weather conditions

| Location name | Attenuation in dB/km | Maximum link distance (in km) | BER        |
|---------------|-----------------------|-------------------------------|------------|
| Chandigarh   | 13.4                  | 1.57                          | $7.07 \times 10^{-9}$ |
| Mumbai       | 34.6                  | 0.78                          | $6.30 \times 10^{-9}$ |
| Pune         | 16.9                  | 1.33                          | $8.02 \times 10^{-9}$ |
| Kolkata      | 15.3                  | 1.43                          | $9.41 \times 10^{-9}$ |
| Hyderabad    | 12.2                  | 1.68                          | $9.32 \times 10^{-9}$ |
| Chennai      | 26.6                  | 0.95                          | $4.57 \times 10^{-9}$ |
Fig. 11 Eye diagrams of WDM-FSOC system for different locations of India at a link range of 1 km under heavy rainfall weather conditions
Acknowledgements We are really thankful to India Meteorological Department for providing the meteorological data related to weather conditions for carrying out this research work.

Authors’ contributions Conceptualization: [HS]; Methodology: [HS]; Formal analysis and investigation: [HS]; Writing—original draft preparation: [HS]; Writing—review and editing: [NM]; Supervision: [NM].

Funding Not applicable.

Declarations

Conflict of interest The authors have no Conflicts of interest or Competing interests.

References

Ai, D.H., Trung, H.D., Tuan, D.T.: On the ASER performance of amplify-and-forward relaying MIMO/FSO systems using SC-QAM signals over log-normal and gamma-gamma atmospheric turbulence channels and pointing error impairments. J. Inf. Telecommun. 4, 267–281 (2020)

Al-Gailani, S.A., Mohammad, A.B., Sheikh, U.U., Shaddad, R.Q.: Determination of rain attenuation parameters for free space optical link in tropical rain. Optik 125, 1575–1578 (2014)

Alkholidi, A., Altowij, K.: Effect of clear atmospheric turbulence on quality of free space optical communications in Western Asia. In: Optical Communications Systems. Intech Open Access, Rijeka (2012)

Alkholidi, A.G., Altowij, K.S.: Free space optical communications: theory and practices. In: Khatib, M. (eds.) Contemporary Issues in Wireless Communications. Intech Open Access, Rijeka, Croatia (2014)

Attri, S.D., Tyagi, A.: Climate Profile of India. Environment Monitoring and Research Center, India Meteorology Department, New Delhi (2010)

Aveta, F., Refai, H.H., Lopresti, P.G.: Cognitive multi-point free space optical communication: real-time users discovery using unsupervised machine learning. IEEE Access 8, 207575–207588 (2020)

Bamba Dath, C.A., Niane, A., Mbaye, M., Boye Faye, N.A.: Wireless optical signal availability and link range analyses over strong fluctuating meteorological conditions with case study in Senegal. Indian J. Sci. Technol. 10, 1–11 (2017)

Basahel, A., Rafiqul, I.M., Suriza, A.Z., Habaebi, M.H.: Availability analysis of free-space-optical links based on rain rate and visibility statistics from tropical a climate. Optik 127, 10316–10321 (2016)
Basahel, A.A., Islam, M.R., Zabidi, S.A., Habaebi, M.H.: Availability assessment of free-space-optics links with rain data from tropical climates. J. Lightwave Technol. 35, 4282–4288 (2017)

Briantcev, D., Trichili, A., Ooi, B.S., Alouini, M.-S.: Crosstalk suppression in structured light free-space optical communication. IEEE Open J. Commun. Soc. 1, 1623–1631 (2020)

Brien, D.C.O., Katz, M.: Optical wireless communications within fourth-generation wireless systems. J. Opt. Netw. 4, 312–322 (2005)

Chowdhury, M.Z., Hussan, M.T., Islam, A., Jang, Y.M.: A comparative survey of optical wireless technologies: architectures and applications. IEEE Access 6, 9819–9840 (2018)

Dayal, N., Singh, P., Kaur, P.: Long range cost-effective WDM-FSO system using hybrid optical amplifiers. Wireless Pers. Commun. 97, 6055–6067 (2017)

Ghassemlooy, Z., Popoola, W., Rajbhandari, S.: Optical Wireless Communication: System and Channel Modelling with Matlab. CRC Press, Boca Raton (2013)

Ghassemlooy, Z., Popoola, W., Rajbhandari, S.: Optical Wireless Communication: System and Channel Modelling with Matlab. CRC Publisher, Boca Raton (2019)

Grover, M., Singh, P., Kaur, P., Madhu, C.: Multibeam WDM-FSO system: an optimum solution for clear and hazy weather conditions. Wirel. Pers. Commun. 97, 5783–5795 (2017)

Guiomar, F.P., Lorences-riesgo, A., Ranzal, D., Rocco, F., Sousa, A.N., Fernandes, M.A., Brandão, B.T., Carena, A., Teixeira, A.L., Medeiros, M.C.R., Monteiro, P.P.: Adaptive probabilistic shaped modulation for high-capacity free-space optical links. J. Lightwave Technol. 38, 6529–6541 (2020)

Jenamani, R.K., Bhan, S.C., Kalsi, S.R.: Observational/forecasting aspects of the meteorological event that caused a record highest rainfall in Mumbai. Curr. Sci. 90, 1344–1362 (2006)

Kakati, D., Arya, S.C.: Performance of 120 Gbps single channel coherent DP-16-QAM in terrestrial FSO link under different weather conditions. Optik 178, 1230–1239 (2019)

Kashif, H., Khan, M.N., Altalbe, A.: Hybrid optical-radio transmission system link quality: link budget analysis. IEEE Access 8, 65983–65992 (2020)

Kaur, S.: Analysis of inter-satellite free-space optical link performance considering different system parameters. Opto-Electron. Rev. 27, 10–13 (2019)

Kaushal, H., Kaddoum, G.: Optical communication in space: challenges and mitigation techniques. IEEE Commun. Surv. Tutor. 19, 57–96 (2017)

Kaushal, H., Jain, V.K., Subrat, K.: Free Space Optical Communication. Springer, Berlin (2017)

Lorences-riesgo, A., Guiomar, F.P., Sousa, A.N., Teixeira, A.L., Muga, N.J., Medeiros, M.C.R., Monteiro, P.P.: 200G outdoor free-space-optics link using a single-photonodiode receiver. J. Lightwave Technol. 38, 394–400 (2019)

Mansour, A., Mesleh, R., Abaza, M.: New challenges in wireless and free space optical communications. Opt. Lasers Eng. 89, 95–108 (2017)

Mirza, J., Ghafoor, S., Hussain, A.: A full duplex ultra-wideband over free-space optics architecture based on polarization multiplexing and wavelength reuse. Microw. Opt. Technol. Lett. 62, 3999–4006 (2020)

Mohale, J., Handura, M.R., Olwal, T.O., Nyirenda, C.N.: Feasibility study of free-space optical communication for South Africa. Opt. Eng. 55, 056108 (2016)

Nam, S.S., Alouini, M., Zhang, L., Ko, Y.: Threshold-based multiple optical signal selection scheme for free-space optical wavelength division multiplexing systems. IEEE J. Opt. Commun. Netw. 9, 1085–1096 (2017)

Olsen, R., Rogers, D., Hodge, D.: The aR b relation in the calculation of rain attenuation. IEEE Trans. Antennas Propag. 26, 318–329 (1978)

Qin, Y., Ma, M., Li, H., Lin, J.: Scheduling transmission of multimedia video traffic on optical access networks. In: The Ninth International Conference on Communications Systems, ICCS 2004, pp. 107–111, Singapore (2004).

Rashed, A.N.Z., El-Halawany, M.M.E.: Transmission characteristics evaluation under bad weather conditions in optical wireless links with different optical transmission windows. Wirel. Pers. Commun. 71, 1577–1595 (2013)

Robinson, S., Jasmine, S.: Performance analysis of hybrid WDM-FSO system under various weather conditions. Frequenz 70, 1–9 (2016)

Rouissat, M., Borsali, A.R., Chikh-Bled, M.E.: Free space optical channel characterization and modeling with focus on Algeria weather conditions. Int. J. Comput. Netw. Inf. Secur. 4, 17–23 (2012)

Shahiduzzaman, K., Haider, M.F., Karmaker, B.K.: Terrestrial free space optical communications in Bangladesh: transmission channel characterization. Int. J. Electr. Comput. Eng. 9, 3130–3138 (2019)
Sharma, K., Grewal, S.K.: Capacity analysis of free space optical communication system under atmospheric turbulence. Opt. Quant. Electron. 52, 1–18 (2020)
Son, I.K., Mao, S.: A survey of free space optical networks. Digit. Commun. Netw. 3, 67–77 (2017)
Suriza, A.Z., Md Rafiqu, I., Wajdi, A.K., Naji, A.W.: Proposed parameters of specific rain attenuation prediction for free space optics link operating in tropical region. J. Atmos. Sol. Terr. Phys. 94, 93–99 (2013)
Tan, L., Chen, Y., Zhao, L., Yu, S., Kang, D., Yang, Q., Ma, J.: Optimal coupling condition analysis of free-space optical communication receiver based on few-mode fiber. Opt. Fiber Technol. 53, 102004 (2019)
Twati, M., Badi, M.: Analysis of rain effects on free space optics based on data measured in the Libyan climate. Int. J. Inf. Electron. Eng. 4, 469–472 (2014)
Yeh, C., Guo, B., Chang, Y., Chow, C., Gu, C.: Bidirectional free space optical communication (FSO) in WDM access network with 1000-m supportable free space link. Opt. Commun. 435, 394–398 (2019)
Yeh, C.-H., Luo, C.-M., Xie, Y.-R., Chow, C., Chen, R., Tseng, M.: Demonstration of 1: Gbps real—time optical wireless communication by simple transmission scheme. Opt. Quant. Electron. 52, 1–7 (2020)
Zhang, R., Peng, P., Li, X., Liu, S., Zhou, Q., He, J., Chen, Y., Shen, S., Yao, S., Chang, G.-K.: 4 × 100-Gb/s PAM-4 FSO transmission based on polarization modulation and direct detection. IEEE Photonics Technol. Lett. 31, 755–758 (2019)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.