Performance Analysis of Free Space Optical Communication System Under Rain Weather Conditions: A Case Study for Inland and Coastal Locations of India

Harjeevan Singh (harjeevan68@gmail.com)
Chandigarh University
Nitin Mittal
Chandigarh University

Research Article

Keywords: Free Space Optical Communication, WDM, Rain Attenuation, Signal to Noise Ratio, Bit Error Rate, Q-Factor.

Posted Date: February 26th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-243293/v1

Version of Record: A version of this preprint was published at Optical and Quantum Electronics on April 9th, 2021. See the published version at https://doi.org/10.1007/s11082-021-02848-5.

Abstract

This work aims to investigate the performance of Free Space Optical Communication link under average and worst rain weather conditions of India. The meteorological data related to rainfall, from 2014 to 2017, 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, in terms of received power, signal to noise ratio, bit error rate and eye diagrams. The inland location of Hyderabad has given the best results in terms of above mentioned parameters as it has recorded minimum average rainfall of 2.35 mm/hr with minimum attenuation coefficient of 1.91 dB/km and can support a link range of 5.43 km, corresponding to bit error rate of order of 10^{-9} under average rain weather conditions. On the other hand, the average rainfall is maximum for the coastal area of Mumbai with a value of 7.31 mm/hr, resulting in maximum attenuation coefficient of 4.08 dB/km and the maximum link range 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 worst rain weather conditions also. So it has been concluded that the coastal areas of India have shown major degradation in the performance of the FSOC link as compared to inland locations of the country.

1 Introduction

Free Space Optical Communication (FSOC) system uses free space as an unguided media to transmit information using laser signal (Mansour et al. 2017). It is a line of sight based communication and consists of transceivers at both sides to transmit data in full duplex mode. It makes use of infrared, visible and ultraviolet band of spectrum to transmit information using optical signal (Khalighi and Uysal 2014; Chowdhury et al. 2018). 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 (Al-Gailani et al. 2012). 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 (Suriza et al. 2013). 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). 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 durings the period of south-west monsoon (June to September). On the other hand, Souther part of India receive good amount of rainfall during post-monsoon period (October to 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 worst rain 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: Section II 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 III will discuss about the attenuation of FSOC link due to rain and the mathematical models in order to find out the attenuation coefficients. Section IV 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 V will include the discussion of simulation results followed by conclusion in section VI.

2 Related Work

The study conducted by Alkholidi and Altowij analyzed the effects of rain weather conditions of Yemen on the performance of Free Space Optical 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 coeffiecient for Taiz is also maximum. The attenuation coefficient has been calculated for light, medium and heavy rainfall conditions.The attenuation coefficient varies from 0.036–0.18 dB/km for light rain, 0.24–0.37 dB/km for medium rain and 0.45–0.69 dB/km for heavy rain scenario. In addition to this, the atmospheric attenuation has also been studied according to the raindrop radius and it has been concluded that the atmospheric attenuation decreases with increase in rain drop radius. 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/hr has been recorded which corresponds to exceedance probability of 0.000187% and the lowest rain rate of 12 mm/hr has been recorded with the exceedance probability of 0.91989%. The attenuation corresponding to maximum rain rate of 168 mm/hr is 32 dB/km, whereas the lowest rain rate of 12 mm/hr 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. Further, the attenuation due to rain has been evaluated for the link distances ranging from 1 km to 5 km. It has been found that in order to acheve link availability of 99.99%, power margins of 33 dB, 45 dB, 54 dB and 60 dB are required for FSOC links having link ranges from 2–5 km respectively. 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. The wavelength of laser signal has been chosen to be 1550 nm and the size of raindrop is considered to be 0.003 cm. Under average rainfall conditions, Sylhet has recorded maximum rainfall of 11.11 mm/hr with attenuation coefficient of 5.965 dB/km and Rajshahi has received minimum rainfall of 3.44 mm/hr with attenuation coefficient of 0.869 dB/km. On the other hand, Chittagong has received maximum rainfall of 50.16 mm/hr with attenuation coefficient of 12.512 dB/km and Rajshahi has received minimum rainfall of 11.58 mm/hr with attenuation coefficient of 6.145 dB/km under worst rainfall conditions. Hence, it can be concluded that effects of rain weather conditions of Bangladesh are significant for FSOC links. 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

[illegible] est 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. Along with this, a Graphical User Interface (GUI) has been developed to provide an approximation of availability of FSOC link in terms of probability of connection. 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 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 worst rain weather conditions, the maximum link distance has been found out to be 1.91 km. Based on the results of the study, it has been concluded that rain weather conditions of Libya does not have any significant effect on the performance of FSOC links. 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). The probability of attenuation has been calculated from the recorded rain intensities. It has been found that rain rates less than 25 mm/hr do not result in major degradation of performance of FSOC links. For rain rates greater than 25 mm/hr, the probability of attenuation of 10 dB/km is equal to 35%. Similarly, the probability of attenuation of 10 dB/km to 15 dB/km, corresponding to varying rain rates from 25 to 50 mm/hr has been found out to be 81%. Moreover, the maximum attenuation due to rainfall has been computed as 22 dB/km with probability of occurrence less than 3%. In addition to this, it has been analyzed that the link range varies from 3.2 km 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 location. 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 upto 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

 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):

$$\alpha_{rain} = 4.343 \int_0^{\infty} Q(D, \lambda, m) N(D) dD \qquad (1)$$

where *Q* represents the extinction cross section (mm^2) and it is a function of diameter *(D)* of drop, wavelength (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):

$$\alpha_{rain}(\mathrm{dB/km}) = kR^{\alpha} \qquad (2)$$

where *R* represents the intensity of rainfall (mm/hr), *k* and *α* represents the power law parameters whose values depend upon the size of rain drop and temperature of rain. The values of *k* and *α* 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):

$$\alpha_{rain}(\mathrm{dB/km}) = 1.076R^{0.67} \qquad (3)$$

4 Simulation Design

FSOC system mainly comprises of three sections namely, transmitter, propagating channel and receiver. The simulation model has been designed using Optisystem software. The transmitter section comprises of Pseudo-Random bit sequence (PBRS) 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, transmitting at the rate of 10 Gbps, 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

 (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-FSOC link in order to increase the maximum achievable link range (Dayal et al. 2017). Multibeam 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 operating at power of 10 dBm and spacing between each channel is 100 GHz. 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.

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
Trasnsmitter 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

5 Results And Discussions

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 (Chennai, Hyderabad, Pune, Mumbai, Kolkata and Chandigarh) 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 worst case conditions of rain weather in India.

5.1 Performance Analysis of FSOC system under average rain 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/hr. 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/hr. The rain rates recorded for Chennai, Kolkata, Pune and Chandigarh are 4.93 mm/hr, 4.30 mm/hr, 3.33 mm/hr and 3.02 mm/hr 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.

Table 2 Average Rain Rates and Specific Attenuation Coefficicents of different locations of India

Location Name	Average Rain Rate (in mm/hr)	Specific Attenuation Coefficient (in dB/Km)
Chandigarh	3.02	2.26
Mumbai	7.31	4.08
Pune	3.33	2.41
Kolkata	4.3	2.86
Hyderabad	2.35	1.91
Chennai	4.93	3.13

The 32-channel WDM based FSOC system has been simulated using Optisystem software by incorporating the attenuation due to rain for all considered locations of India according to the simulation parameters defined in Table 1.

Fig. 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.

Fig. 3 shows the plot of SNR versus link range for different locations of India. It is clearly 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 less average rain 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.

Fig. 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.

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,

Table 3 Performance analysis of WDM-FSOC system for different locations of India under average rain weather conditions

Location Name	Attenuation in dB/km	Maximum Link Distance (in km)	Q-Factor	BER
Chandigarh	2.26	4.95	5.61	9.93×10^{-9}
Mumbai	4.08	3.48	5.65	7.80×10^{-9}
Pune	2.41	4.77	5.63	9.15×10^{-9}
Kolkata	2.86	4.32	5.62	9.32×10^{-9}
Hyderabad	1.91	5.43	5.63	8.95×10^{-9}
Chennai	3.13	4.09	5.66	7.73×10^{-9}

Hyderabad has recorded the best bit error rate performance under average rain 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 rain 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, 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}. Table 3 shows the optimal link ranges of all locations of India, corresponding to BER of order of 10^{-9} under average rain weather conditions. The performance analysis of WDM based FSOC system under average rain weather conditions has been shown in Table 3.

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 rain 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 FSOC system under worst rain weather conditions

This section aims to evaluate the performance of FSOC system under the worst case rain weather conditions for all the locations. In order to define the worst rain 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/hr and Hyderabad has recorded minimum rain intensity of 37.7 mm/hr. 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 4 shows the rain rates and the corresponding attenuation coefficients for other locations of India under worst case rainfall conditions.

Attenuation Coefficicents of different locations of India

Location Name	Average Rain Rate (in mm/hr)	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

The received power has been plotted against link range in Fig. 7 for worst case rain weather conditions. The impact of the worst weather conditions of rainfall is maximum for Mumbai due to maximum rainfall of 177.6 mm/hr while it is minimum for Hyderabad as the worst case rainfall intensity is 37.7 mm/hr 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 power for Chandigarh, Pune, Kolkata and Chennai are -32.9 dBm, -39.9 dBm, -36.7 dBm and -59.3 dBm respectively.

The worst case rain 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 worst rain 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 worst rainfall conditions. The SNR is least affected in case of Hyderabad due to less rainfall under worst case scenario 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 worst rain 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 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 worst rain weather conditions.

The BER performance of WDM based FSOC system with link range has been illustrated in Fig. 10 under worst rain weather conditions. The increase in link range degrades the performance of FSOC system significantly. Under the effect of worst rain 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

 case of Mumbai under worst rain 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}. Table 5 shows the performance analysis of WDM based FSOC link under the worst scenario of rain weather.

Table 5 Performance analysis of WDM-FSOC system for different locations of India under worst rain weather conditions

Location Name	Attenuation in dB/km	Maximum Link Distance (in km)	Q-Factor	BER
Chandigarh	13.4	1.57	5.67	7.07e-9
Mumbai	34.6	0.78	5.69	6.30e-9
Pune	16.9	1.33	5.65	8.02e-9
Kolkata	15.3	1.43	5.62	9.41e-9
Hyderabad	12.2	1.68	5.62	9.32e-9
Chennai	26.6	0.95	5.75	4.57e-9

Fig. 11 shows the eye diagrams of WDM based FSOC system for various locations of India under worst rain weather conditions, corresponding to link range of 1 km. It can be observed that the effects of worst rainfall conditions on received data is minimum in case of Hyderabad as per the clear opened eye digrams. But the received data gets degraded very badly as it propagates through the free space optical channel with worst rain conditions 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 worst conditions of rain weather. However, the effects of worst rain conditions are comparatively less for inland locations of Chandigarh, Pune and Kolkata.

6 Conclusion

In this work, the performance of WDM based FSOC system has been investigated under average and worst case rain weather conditions of India by considering various locations. The targeted locations for this study includes the coastal and inland locations of the country. The meteorological data, related to rain intensities from 2014 to 2017, has been studied in order to calculate the attenuation coefficients due to rain for all locations of India. Under average rain weather conditions, Mumbai has recorded maximum rain intensities of 7.31 mm/hr, whereas Hyderabad has recorded minimum rain intensities of 2.35 mm/hr. Consequently, the attenuation coefficient for Mumbai is maximum with a value of 4.08 dB/km. On the other hand, the attenuation coefficient of Hyderabad is minimum having value of 1.91 dB/km corresponding to average rain weather conditions. The performance analysis of WDM based FSOC system has been done in terms of received power, SNR, Q-Factor, BER and eye diagrams. Due to excessive rainfall in the coastal area of Mumbai, Mumbai has demonstrated maximum degradation in the performance of 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, the performance of FSOC system is least affected by average rain 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 rain 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}. Similarly, the maximum link distances for delivering BER of order of 10^{-9} for Chandigarh, Pune, Kolkata and Chennai are 4.95 km, 4.77 km, 4.32 km and 4.09 km respectively.

Under the effects of worst rain weather conditions, the maximum rain intensity of 177.6 mm/hr for Mumbai results in maximum attenuation of 34.6 dB/km. In addition to this, the received power in case of Mumbai has fallen to -75.3 dBm for link range of 2 km and the link distance of 1 km has delivered SNR of 0 dB for Mumbai. Similarly, the coastal area of Chennai has witnessed drastic degradation in the system performance under worst rain weather conditions. On the other hand, attenuation coefficient is minimum for Hyderabad having a value of 12.2 dB/km, resulting from the rain intensity of 37.7 mm/hr under worst case scenario. The values of received power and SNR for Hyderabad are – 30.5 dBm and 2.2 dB respectively for a link range of 2 km under the effects of worst rainfall. The maximum link distance for delivering BER of 10^{-9} gets limited to 0.78 km for Mumbai while it is maximum for Hyderabad with a value of 1.68 km for worst case rain conditions. The maximum link distances for Chandigarh, Pune, Kolkata and Chennai range from 0.95 km to 1.57 km, corresponding to BER of order of 10^{-9} under the worst case of rain weather.

Hence, it can be concluded that the coastal areas of Mumbai and Chennai undergo severe

attenuation under average and worst rain weather conditions as compared to other inland locations of country. On the other hand, the inland location of Hyderabad has delivered best system performance under average and worst case of rainfall conditions. 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.

Declarations

Funding - Not Applicable

Conflicts of interest/Competing interests - The authors have no Conflicts of interest or Competing interests.

Availability of data and material - Not Applicable

Authors' contributions-

Conceptualization: [Harjeevan Singh]; Methodology: [Harjeevan Singh]; Formal analysis and investigation: [Harjeevan Singh]; Writing - original draft preparation: [Harjeevan Singh]; Writing – review and editing: [Nitin Mittal]; Supervision: [Nitin Mittal].

Acknowledgements

We are really thankful to India Meteorological Department for providing the meteorological data related to weather conditions for carrying out this research work.

References

1. Al-Gailani, S.A., Mohammad, A.B., Shaddad, R.Q.: Evaluation of a 1 Gb/s free space optic system in typical Malaysian weather. ICP 2012–3rd International Conference on Photonics 2012, Proceedings. 121–124: (2012). https://doi.org/10.1109/ICP.2012.6379839
2. 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). https://doi.org/10.1016/j.ijleo.2013.10.018
3. Alkholidi, A., Altowij, K.: Effect of Clear Atmospheric Turbulence on Quality of Free Space Optical Communications in Western Asia. In: Optical Communications Systems. Rijeka, Intech Open Access (2012)
4. Alkholidi, A.G., Altowij, K.S.: Free Space Optical Communications — Theory and Practices. In: Contemporary Issues in Wireless Communications. Rijeka, Intech Open Access (2014)
5. Attri, S.D., Tyagi, A.: CLIMATE PROFILE OF INDIA. Environment Monitoring and Research Center. New Delhi, India, India Meteorology Department (2010)
6. 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 Journal of Science and Technology. **10**, 1–11 (2017). https://doi.org/10.17485/ijst/2017/v10i45/110582
7. 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). https://doi.org/10.1016/j.ijleo.2016.08.061
8. 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. Journal of Lightwave Technology. **35**, 4282–4288 (2017). https://doi.org/10.1109/JLT.2017.2732459
9. Chowdhury, M.Z., Hossan, M.T., Islam, A., Jang, Y.M.: A Comparative Survey of Optical Wireless Technologies: Architectures and Applications. IEEE Access. **6**, 9819–9840 (2018). https://doi.org/10.1109/ACCESS.2018.2792419

10. Dayal, N., Singh, P., Kaur, P.: Long Range Cost-Effective WDM-FSO System Using Hybrid Optical Amplifiers. Wireless Personal Communications. **97**, 6055–6067 (2017). https://doi.org/10.1007/s11277-017-4826-7
11. Ghassemlooy, Z., Popoola, W., Rajbhandari, S.: Optical Wireless Communication: System and Channel Modelling with Matlab. CRC Press: (2013)
12. Ghassemlooy, Z., Popoola, W., Rajbhandari, S.: Optical Wireless Communication: System and Channel Modelling with Matlab. CRC Publisher, Boca Raton (2019)
13. Grover, M., Singh, P., Kaur, P., Madhu, C.: Multibeam WDM-FSO System: An Optimum Solution for Clear and Hazy Weather Conditions. Wireless Personal Communications. **97**, 5783–5795 (2017). https://doi.org/10.1007/s11277-017-4810-2
14. 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)
15. Kaur, S.: Analysis of inter-satellite free-space optical link performance considering different system parameters. Opto-electronics Review. **27**, 10–13 (2019). https://doi.org/10.1016/j.opelre.2018.11.002
16. Kaushal, H., Jain, V.K., Subrat, K.: Free Space Optical Communication. Springer: (2017)
17. Kaushal, H., Kaddoum, G.: Optical Communication in Space: Challenges and Mitigation Techniques. IEEE Communications Surveys and Tutorials. **19**, 57–96 (2017). https://doi.org/10.1109/COMST.2016.2603518
18. Khalighi, M.A., Uysal, M.: Survey on free space optical communication: A communication theory perspective. IEEE Communications Surveys and Tutorials. **16**, 2231–2258 (2014). https://doi.org/10.1109/COMST.2014.2329501
19. Mansour, A., Mesleh, R., Abaza, M.: New challenges in wireless and free space optical communications. Optics and Lasers in Engineering. **89**, 95–108 (2017). https://doi.org/10.1016/j.optlaseng.2016.03.027
20. Mohale, J., Handura, M.R., Olwal, T.O., Nyirenda, C.N.: Feasibility study of free-space optical communication for South Africa. Optical Engineering. **55**, 056108 (2016). https://doi.org/10.1117/1.oe.55.5.056108
21. 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 Journal of Optical Communications and Networking. **9**, 1085–1096 (2017)
22. Olsen, R., Rogers, D., Hodge, D.: The aR b Relation in the Calculation of Rain Attenuation. IEEE Transactions on Antennas and Propagation. **26**, 318–329 (1978). https://doi.org/10.1109/TAP.1978.1141845
23. 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)

24. 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. Wireless Personal Communications. **71**, 1577–1595 (2013). https://doi.org/10.1007/s11277-012-0893-y
25. Robinson, S., Jasmine, S.: Performance Analysis of Hybrid WDM-FSO System under Various Weather Conditions. Frequenz. **70**, 1–9 (2016). https://doi.org/10.1515/freq-2015-0287
26. Rouissat, M., Borsali, A.R., Chikh-Bled, M.E.: Free Space Optical Channel Characterization and Modeling with Focus on Algeria Weather Conditions. International Journal of Computer Network and Information Security. **4**, 17–23 (2012). https://doi.org/10.5815/ijcnis.2012.03.03
27. Shahiduzzaman, K., Haider, M.F., Karmaker, B.K.: Terrestrial free space optical communications in bangladesh: transmission channel characterization. International Journal of Electrical and Computer Engineering. **9**, 3130–3138 (2019). https://doi.org/10.11591/ijece.v9i4.pp3130-3138
28. Sharma, K., Grewal, S.K.: Capacity analysis of free space optical communication system under atmospheric turbulence. Optical and Quantum Electronics. **52**, 1–18 (2020). https://doi.org/10.1007/s11082-020-2200-6
29. Son, I.K., Mao, S.: A survey of free space optical networks. Digital Communications and Networks. **3**, 67–77 (2017). https://doi.org/10.1016/j.dcan.2016.11.002
30. Suriza, A.Z., Md Rafiqul, I., Wajdi, A.K., Naji, A.W.: Proposed parameters of specific rain attenuation prediction for Free Space Optics link operating in tropical region. Journal of Atmospheric and Solar-Terrestrial Physics. **94**, 93–99 (2013). https://doi.org/10.1016/j.jastp.2012.11.008
31. 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. Optical Fiber Technology. **53**, 102004 (2019). https://doi.org/10.1016/j.yofte.2019.102004
32. Twati, M., Badi, M.: Analysis of Rain Effects on Free Space Optics Based on Data Measured in the Libyan Climate. International Journal of Information and Electronics Engineering. **4**, 469–472 (2014). https://doi.org/10.7763/ijiee.2014.v4.485
33. 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. Optical and Quantum Electronics. 52,306, (2020). https://doi.org/10.1007/s11082-020-02424-3
34. 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. Optics Communications. **435**, 394–398 (2019). https://doi.org/10.1016/j.optcom.2018.11.060

Figures

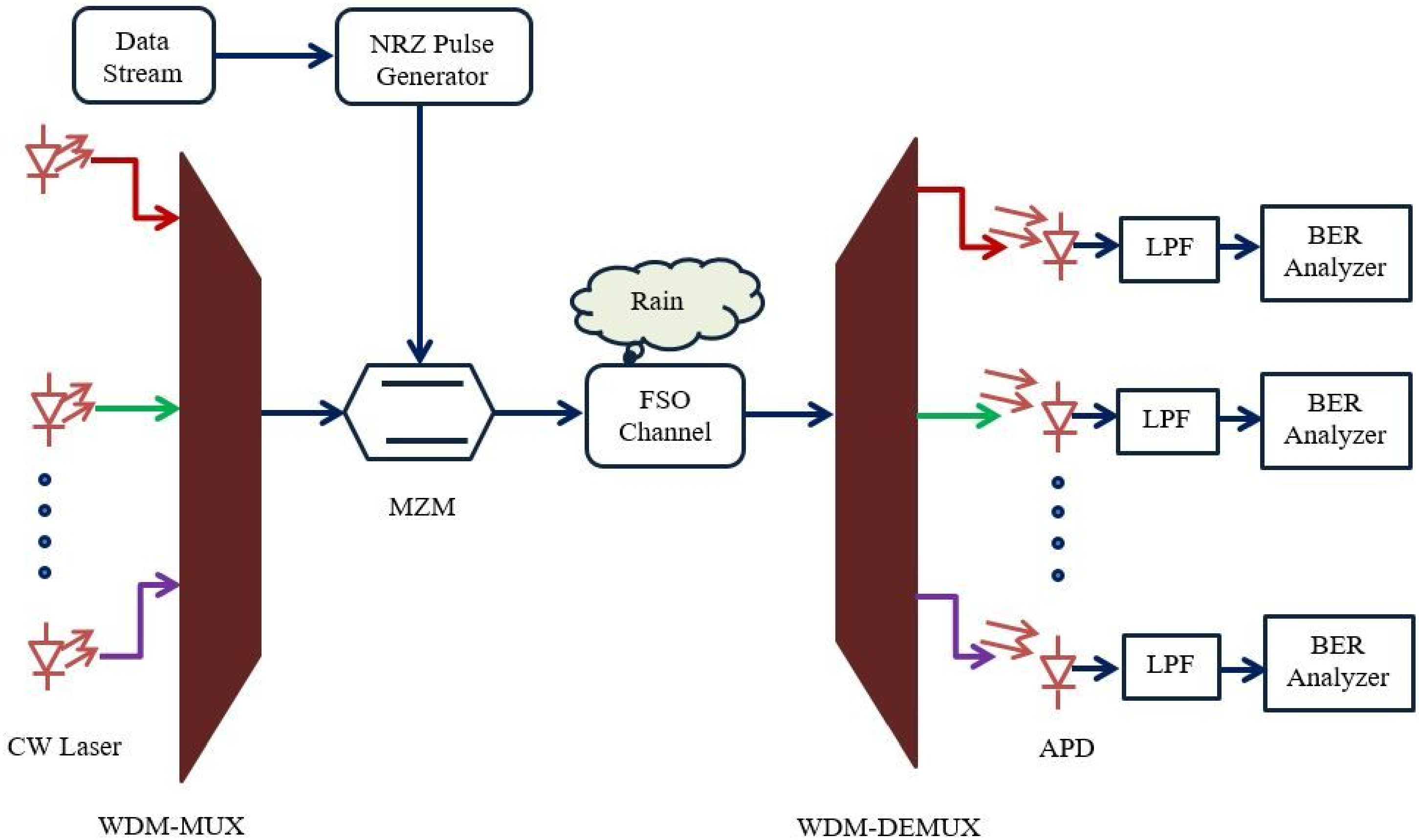
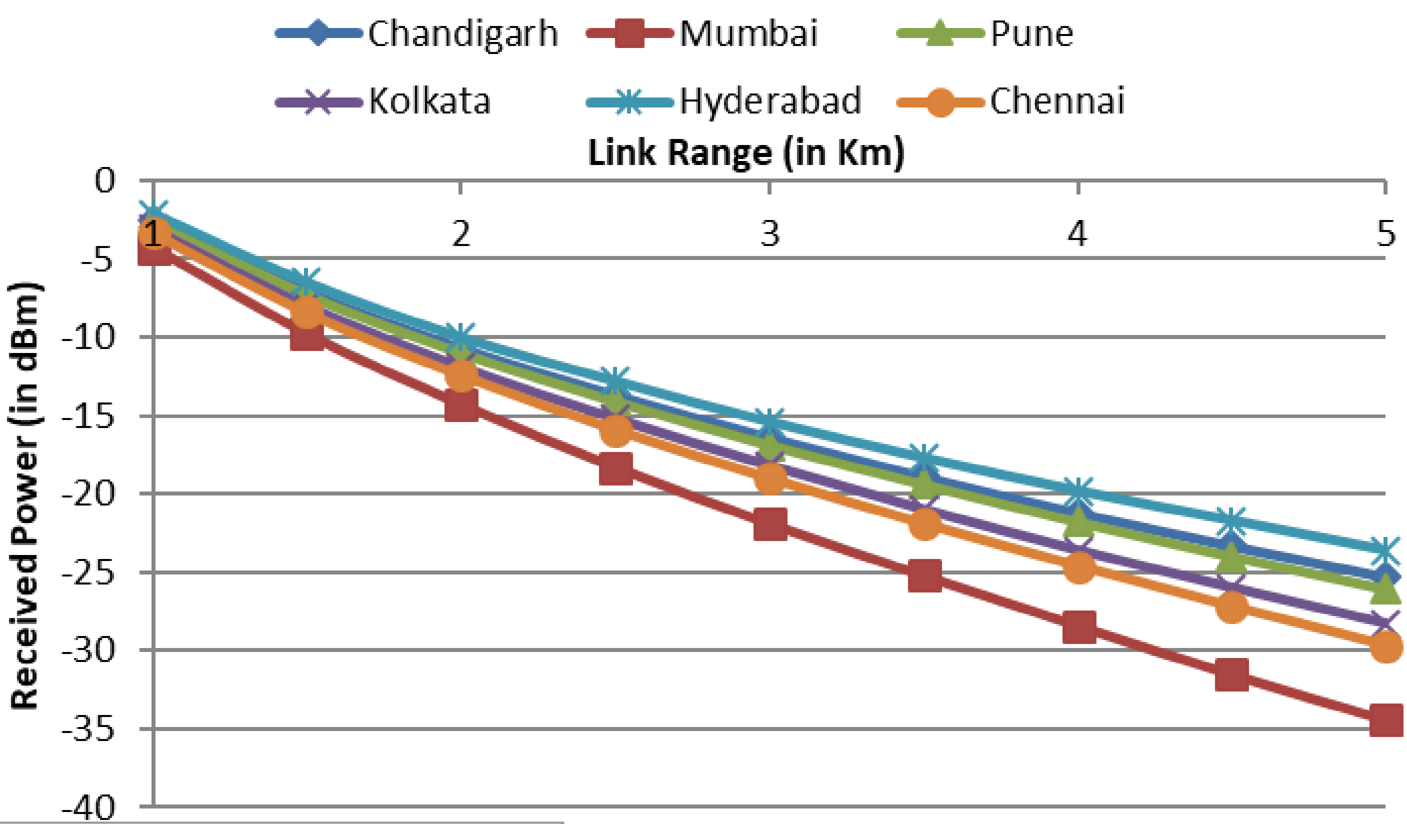


Figure 1

Design of 32 Channel WDM-FSOC system



Loading [MathJax]/jax/output/CommonHTML/jax.js

Figure 2

Received Power versus Link Range for different locations of India under average rain weather conditions

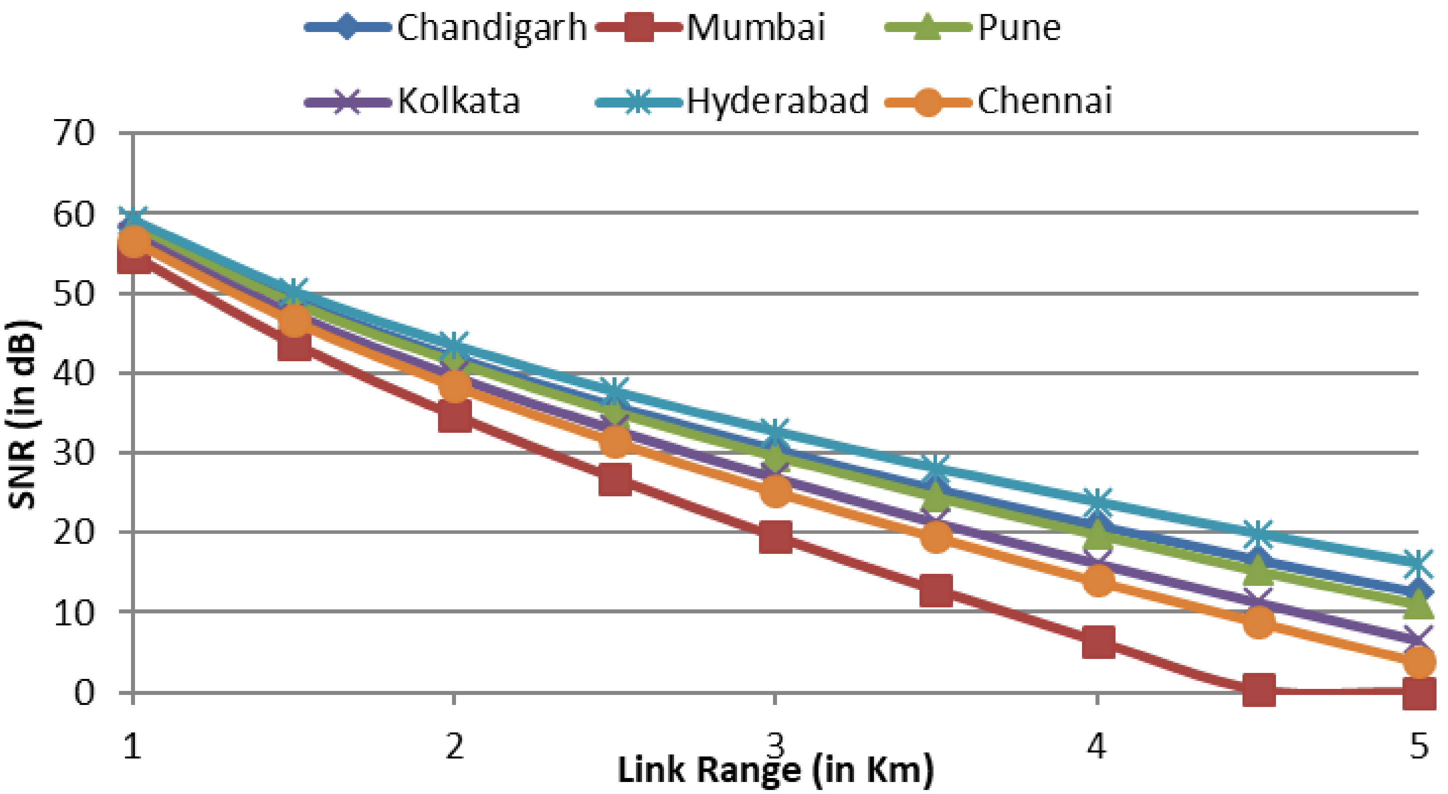


Figure 3

SNR versus Link Range for different locations of India under average rain weather conditions

Loading [MathJax]/jax/output/CommonHTML/jax.js

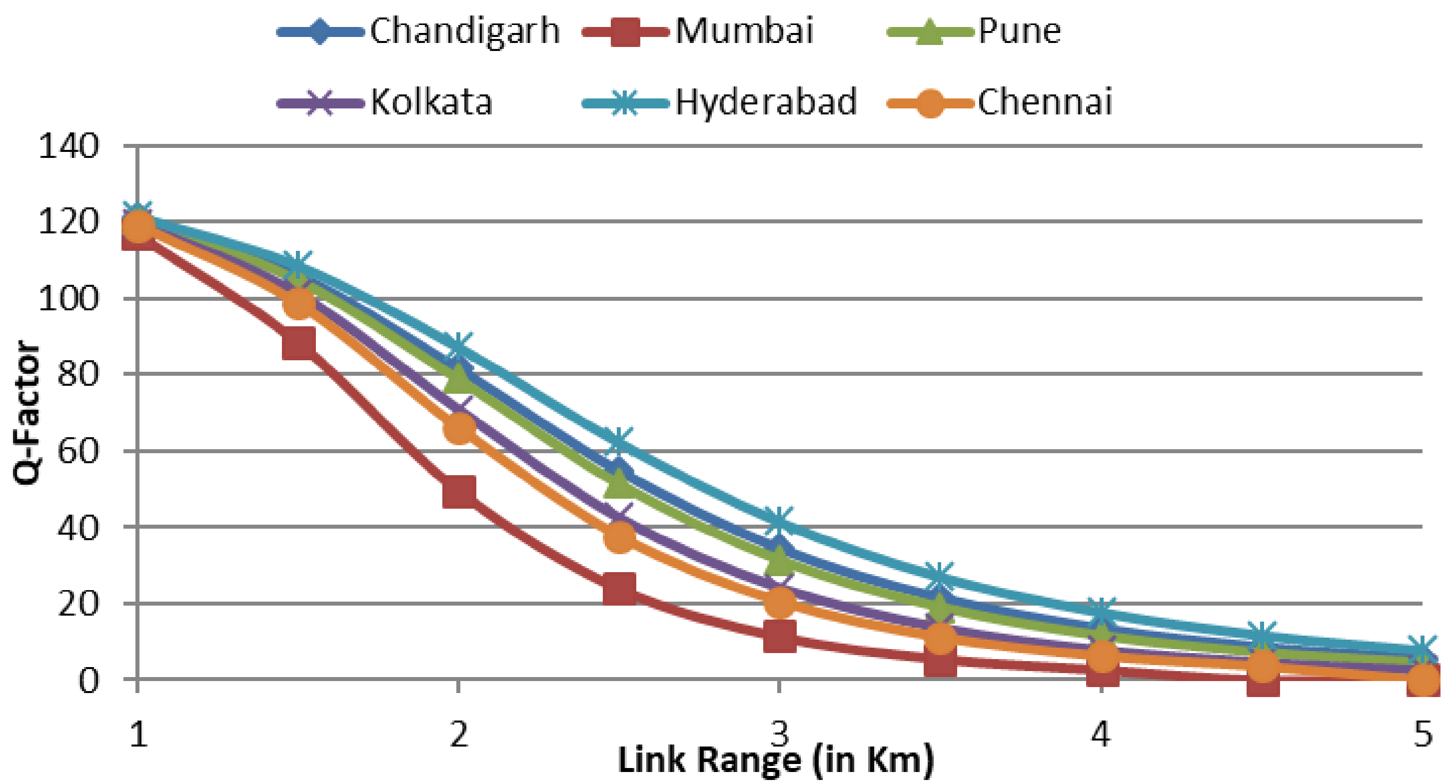


Figure 4

Q-Factor versus Link Range for different locations of India under average rain weather conditions

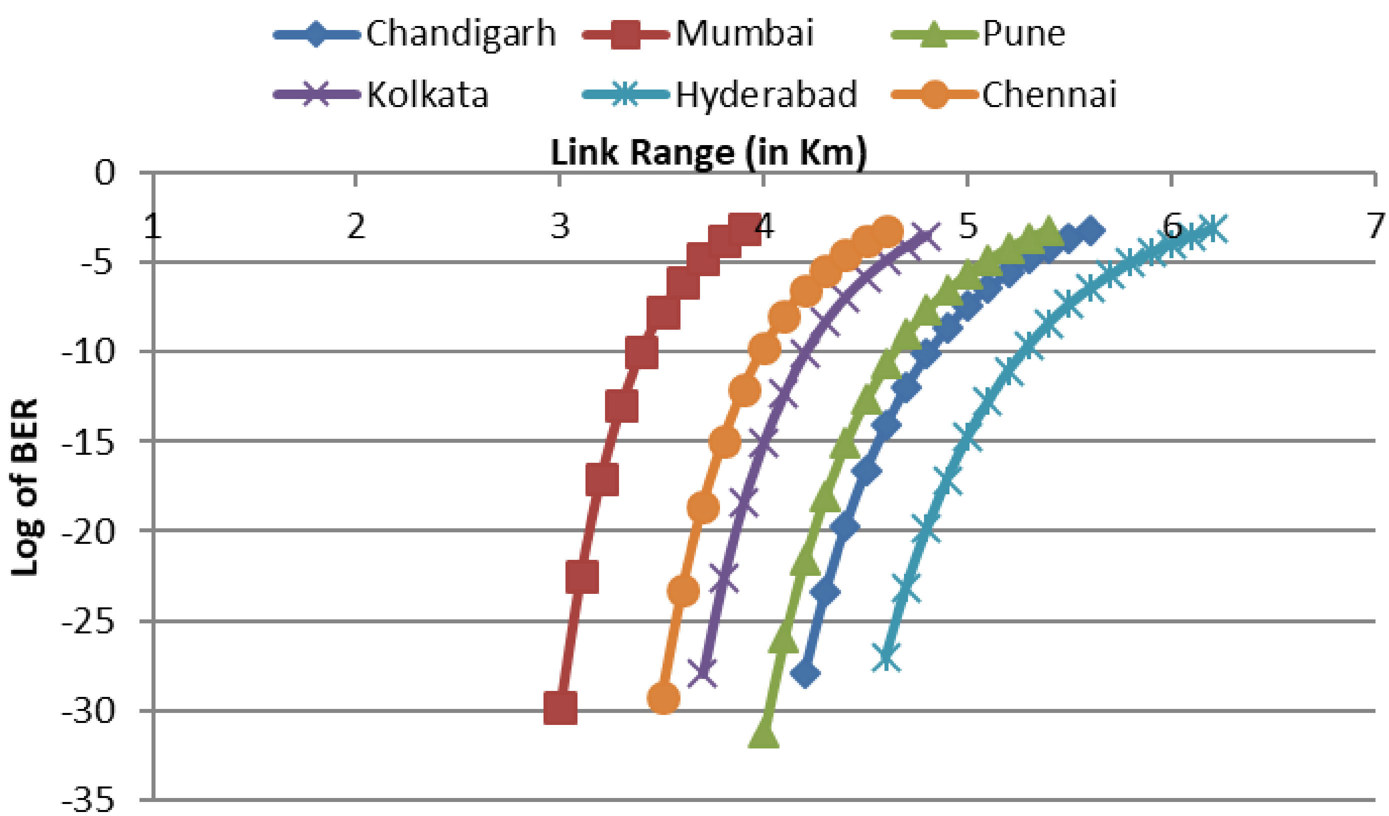


Figure 5

Loading [MathJax]/jax/output/CommonHTML/jax.js

BER versus Link Range for different locations of India under average rain weather conditions

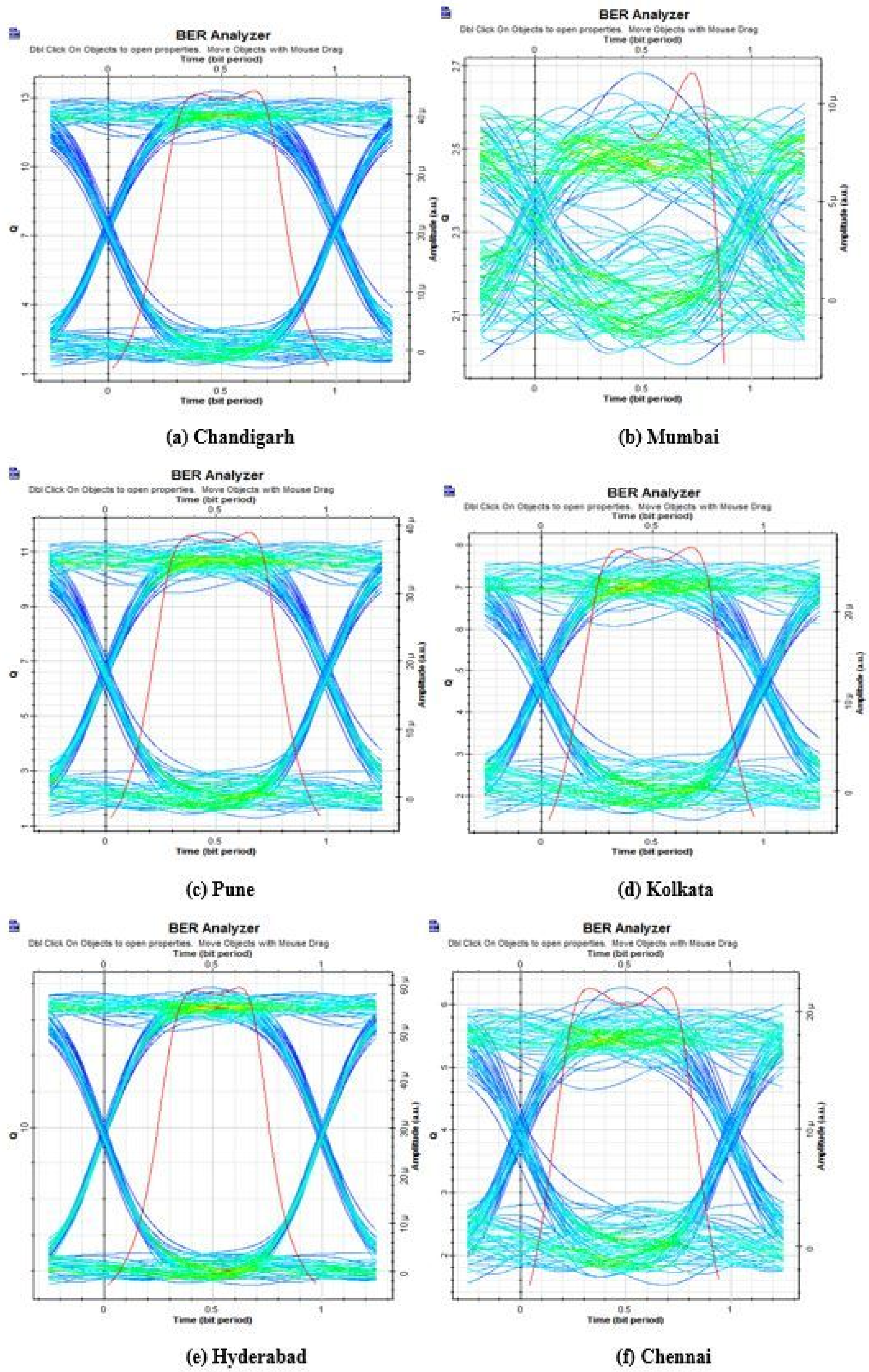


Figure 6

Eye Digrams of WDM-FSOC system for different locations of India at a link range of 4 km under average rain weather conditions

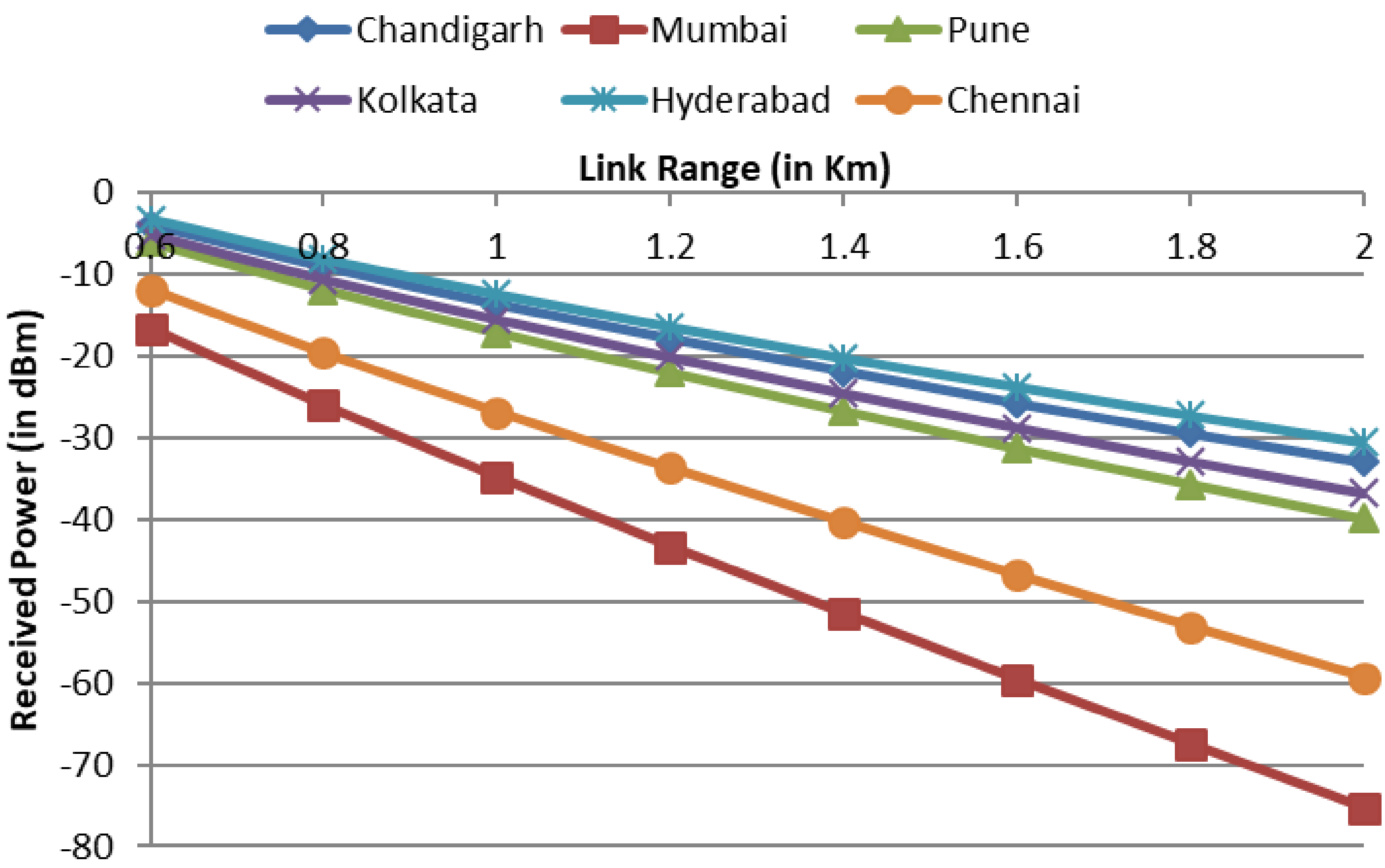


Figure 7

Received Power versus Link Range for different locations of India under worst rain weather conditions

Loading [MathJax]/jax/output/CommonHTML/jax.js

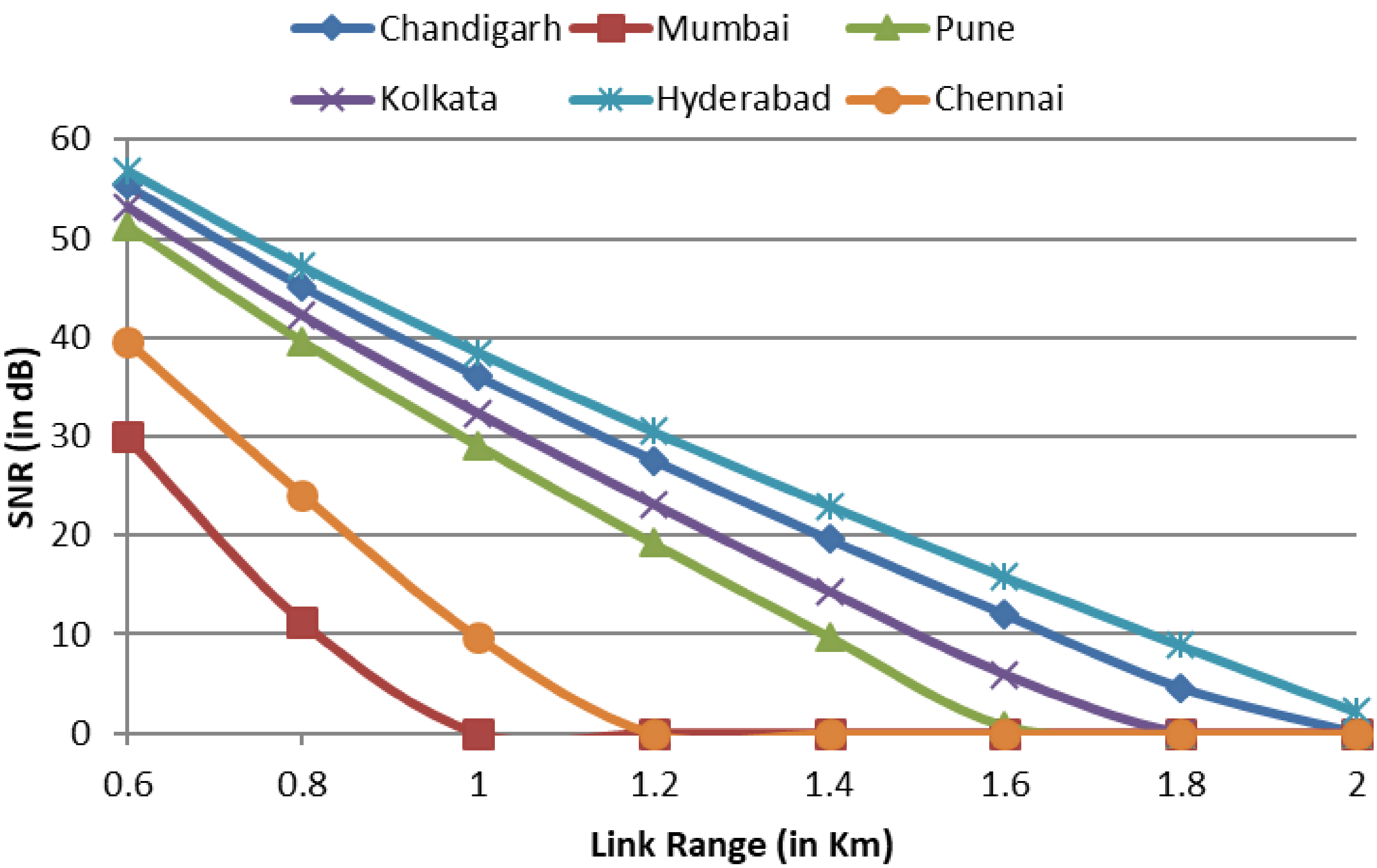


Figure 8

SNR versus Link Range for different locations of India under worst rain weather conditions

Loading [MathJax]/jax/output/CommonHTML/jax.js

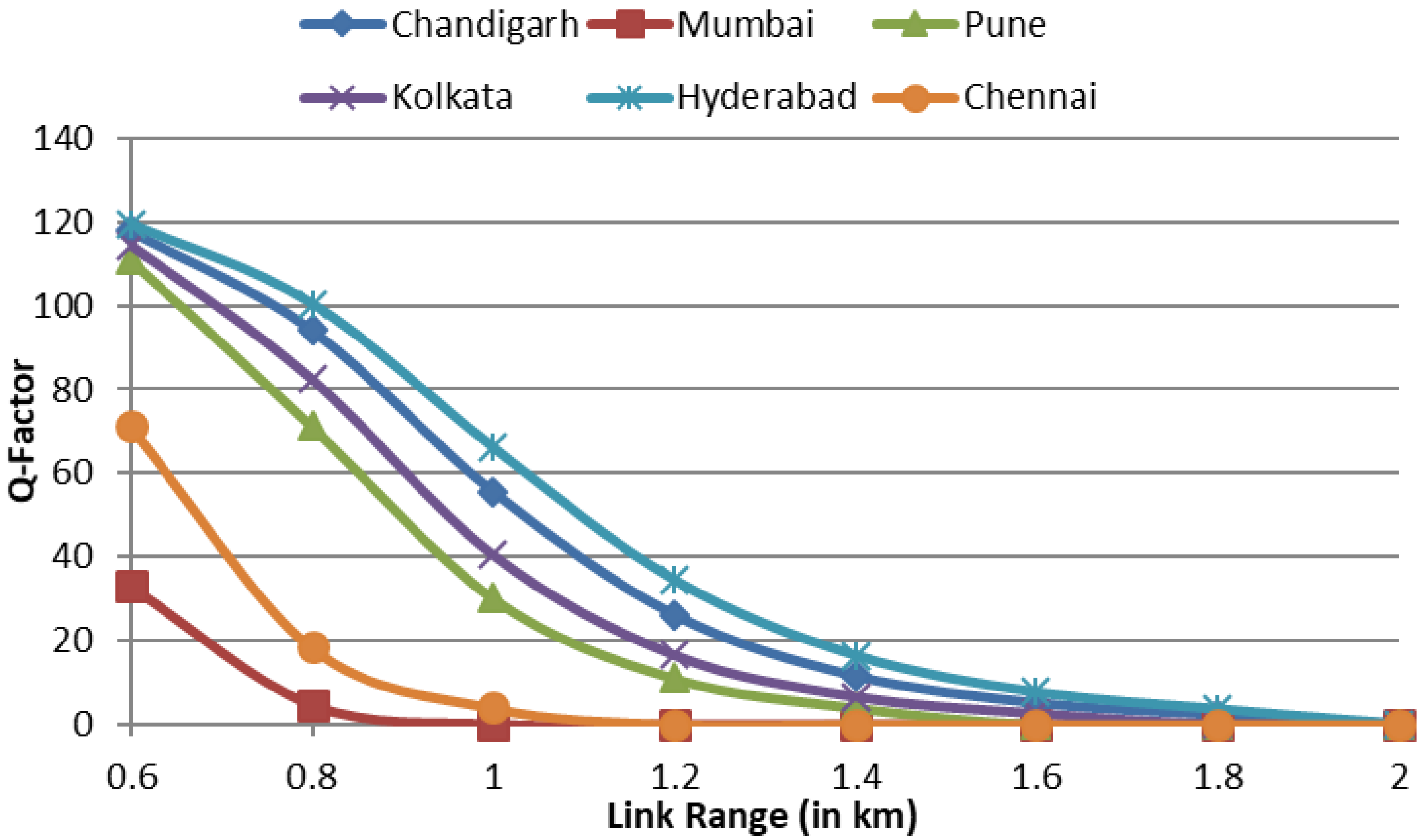


Figure 9

Q-Factor versus Link Range for different locations of India under worst rain weather conditions

Loading [MathJax]/jax/output/CommonHTML/jax.js

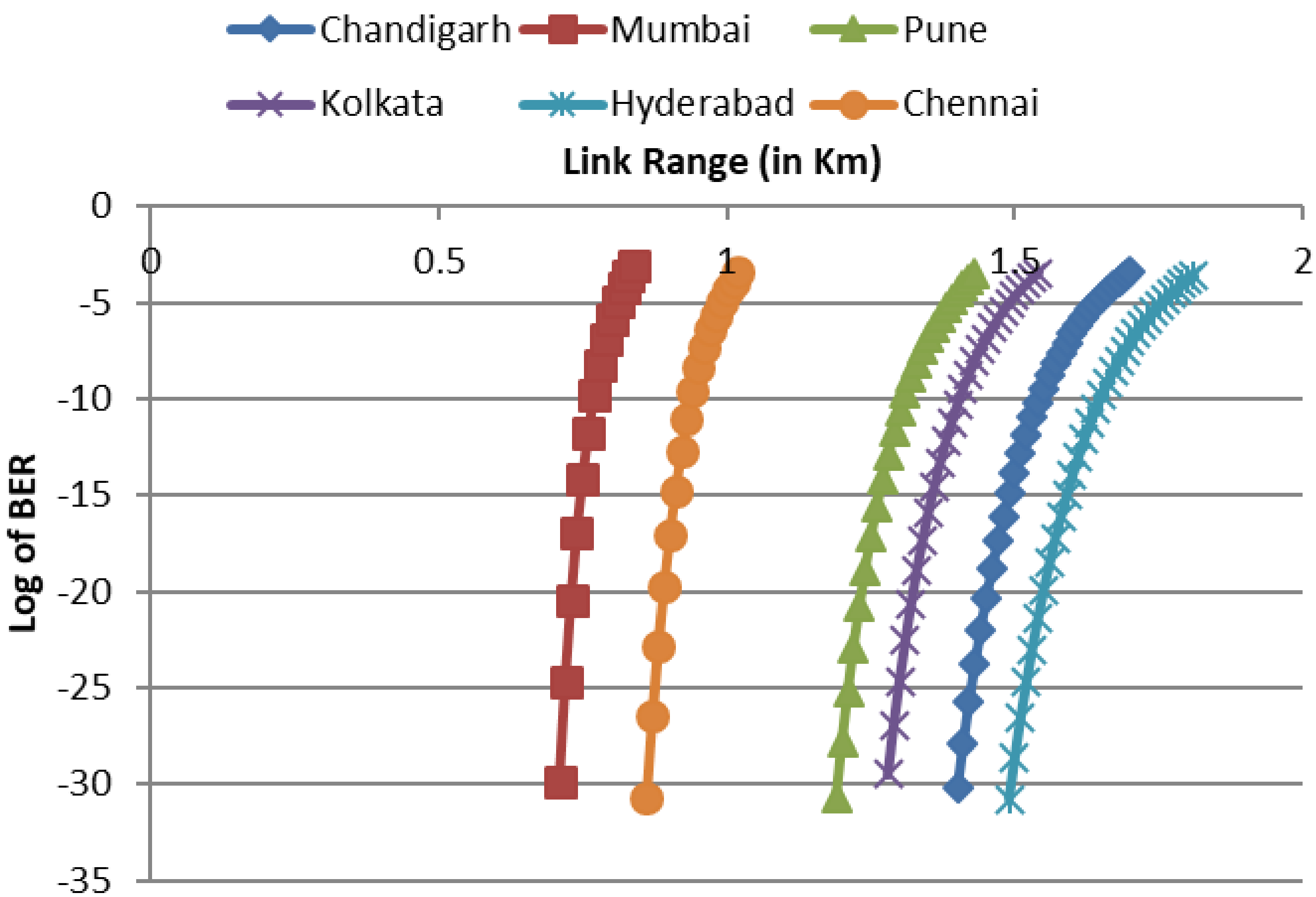


Figure 10

BER versus Link Range for different locations of India under worst rain weather conditions

Loading [MathJax]/jax/output/CommonHTML/jax.js

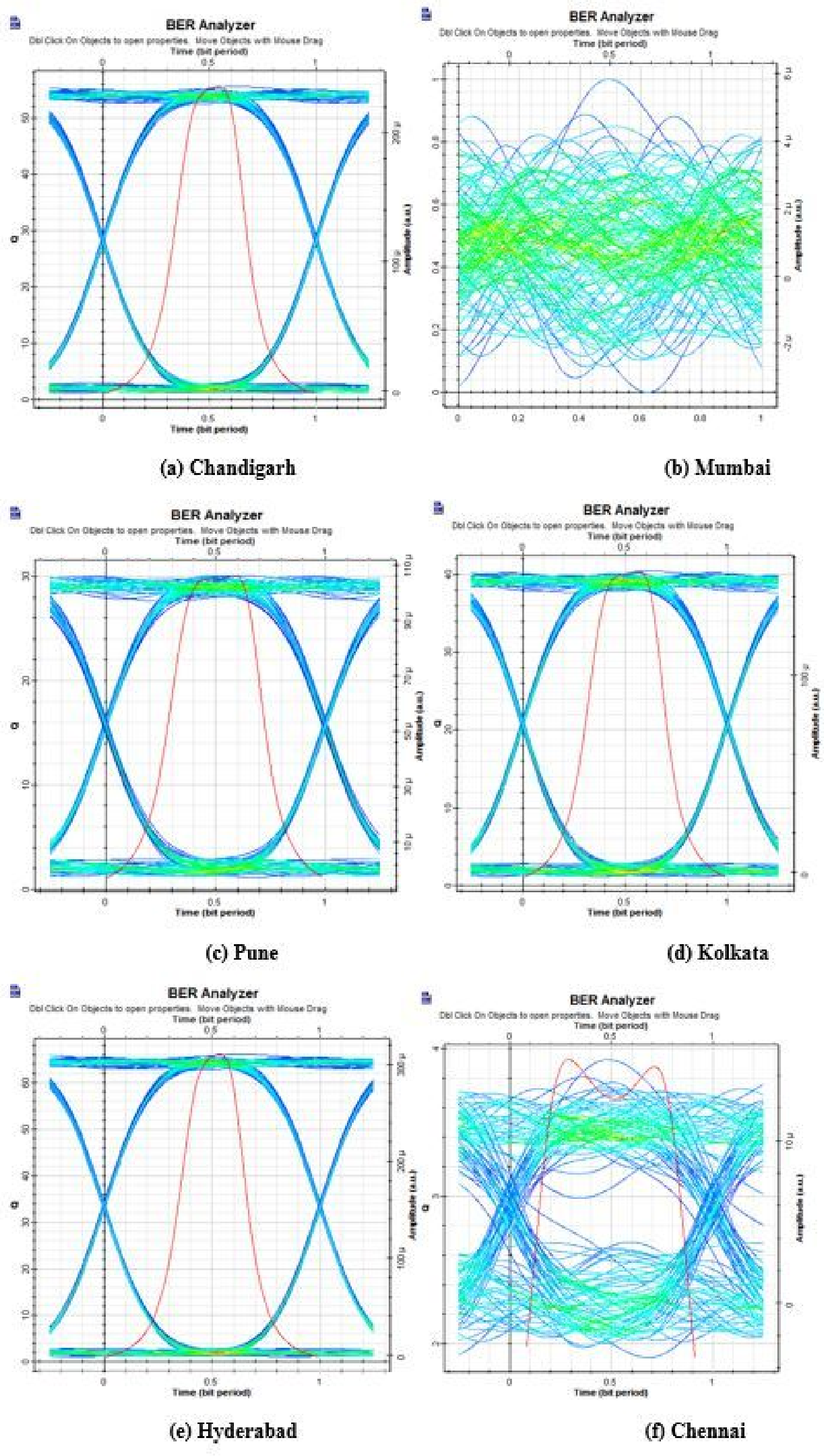


Figure 11

Eye Digrams of WDM-FSOC system for different locations of India at a link range of 1 km under worst rain weather conditions