Performance investigation of hybrid MDM-WDM-FSO link under influence of rainfall and fog conditions

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Free space optics (FSO) has regained considerable attention over the years due to higher data rate transmission capability and unlicensed bandwidths. Nevertheless, different atmospheric conditions result in the considerable deterioration of the performance of the link. The performance of MDM-WDM based FSO link has been analysed considering LP 00 and 01 modes employing AMI, NRZ and RZ modulation techniques. The system has been designed to transmit information at a data rate of 80 Gbps upto a transmission range of 6 kms under clear air conditions. The maximum transmission range under heavy fog and rain conditions reduces to 900 m and 950 m respectively.

1. Introduction

Over the years free space optical communication (FSO) technology has been widely accepted as one of the developing technology in the field of communication over the radio frequency (RF) technology for resolving the challenges of last mile local area access networks including bottleneck issues thus resulting in achievement of excellent immunity to the electromagnetic spectrum and higher bandwidth [1, 2]. FSO technology offers lower power consumption, unlicensed spectrum and provides full duplex connectivity for voice and video communication along with higher data rates as compared to RF technologies [3, 4]. FSO systems are compatible with existing technologies and offer fast and easy installation at comparatively lower cost along with no mutual interference and eavesdropping [5-8]. It has advantage over fiber optics as it provides both the high-capacity feature of optical communication system and the flexibility of wireless technologies [9].

The atmospheric channel over which the signal propagates changes dynamically over the time. Different external factors such as signal absorption, beam wandering, beam divergence and other environmental factors limit the maximum transmission reach and hamper the quality of laser beam carrying information to be communicated [4]. There are different types of atmospheric challenges existing in different parts of geographical regions at different times. It is important to design a system and ensure the accessibility and reliability of the FSO link avoiding degradations in the case of occurrence of fog, rain, snow, haze and other varying weather conditions. One of the major atmospheric attenuation happens due to from fog and rain [10-14].

Previously, researchers have reported different performance enhancement techniques which maximize the transmission capability and improves the link quality of FSO system. Advanced modulation formats have been incorporated to get maximum capacity of link to carry information by efficiently utilizing the network resource [15, 16].

Different schemes have been researched upon like adaptive optics compensation, diversity receiving technique, wavelength division multiplexing (WDM), partially coherent optical transmission technology. WDM technique has been a preferred choice for FSO systems due to its property of providing higher channel capacity. Implementation WDM using large number of channels, however, results in the increased level of interference between the neighbouring channels [17-19]. Therefore, techniques employing mode division multiplexing (MDM) has been introduced which enhance bandwidth resulting in the increase of overall system capacity and range of channel [6, 20-25]. It uses Eigen modes to transmit different channels through the generation of specific modes via modal decomposition methods [26, 27].

In [28], a quadrature phase shift keying (QPSK) signal has been transmitted over 1m FSO link for three quadrature amplitude modulation (QAM) modes using MDM and the performance of the overall system has been examined in the case of atmospheric turbulence. In [29], 400 Gbps of data has been sent over a range of 260 m by employing spatial diversity and multi input and multi output techniques using orbital angular momentum beams.

Also, 40Gbps of data using two OAM beams has been sent over 260 m FSO link on sixteen QAM data [30]. Following year 2017, evaluated the performance of MDM-OCDMA FSO at a range of 8 km under the influence of atmospheric turbulence [31]. In 2019, Hybrid MDM

WDM-FSO transmission system used Laguerre Gaussian (LG) modes to analyse the performance of Duobinary technique and AMI technique [32]. In the year 2020, MDM based FSO system has been analysed under dynamic atmospheric conditions by incorporating on–off keying and polarization shift keying modulation techniques [15]. Further in year 2021, OFDM technology has been deployed in FSO system to reduce the effect of channel fading [33].

In the present work, performance of hybrid MDM-WDM based FSO system has been studied and analysed considering linearly polarized (LP) 00 and 01 modes employing AMI, NRZ and RZ modulation techniques. The system has been designed to transmit the information at a data rate of 80 Gbps upto a transmission range of 6 kms under atmospheric turbulent conditions. The main contribution of the work is to predict the maximum link range for reliable communication of the signal for dynamic environmental conditions including fog and rain effects.

2. System description

Fig. 1 shows the schematic block diagram of the proposed MDM-WDM short-haul FSO link model to compare the performance of different atmospheric turbulent conditions. It is designed by using Optisystem Simulation Software version 17. Fig 2(a) and 2(b) represent the block diagrams of transmitters employing AMI and NRZ/RZ encoding techniques respectively. Fig. 3 shows the receiver side of the model.
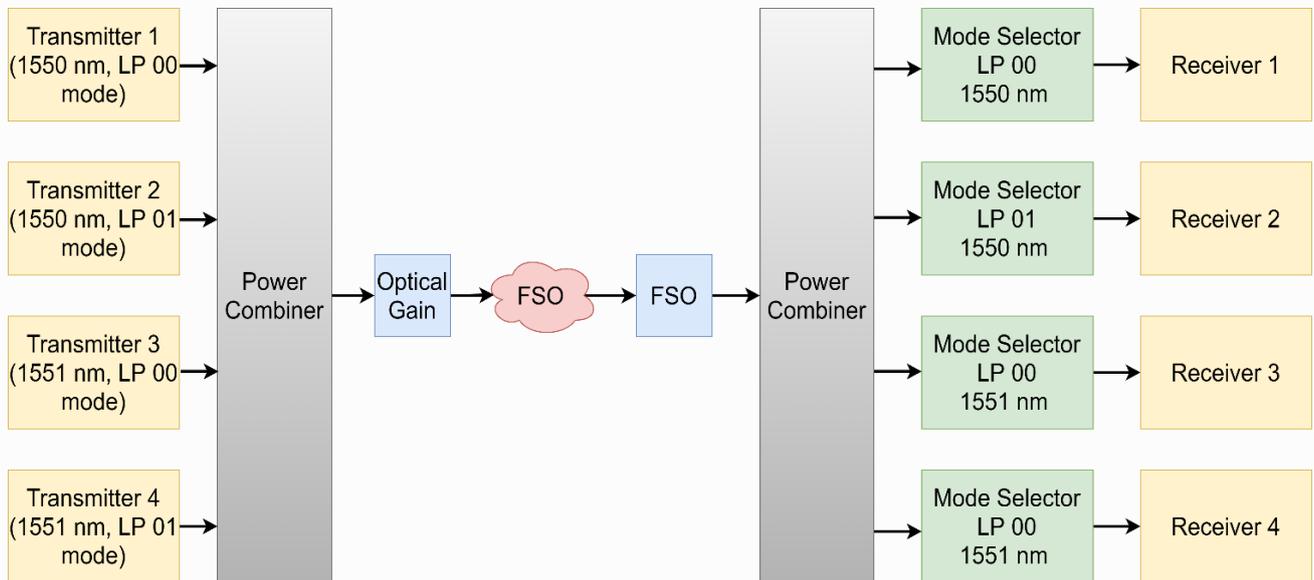

Fig. 1. Block diagram of MDM-WDM short-haul FSO link model (color online)
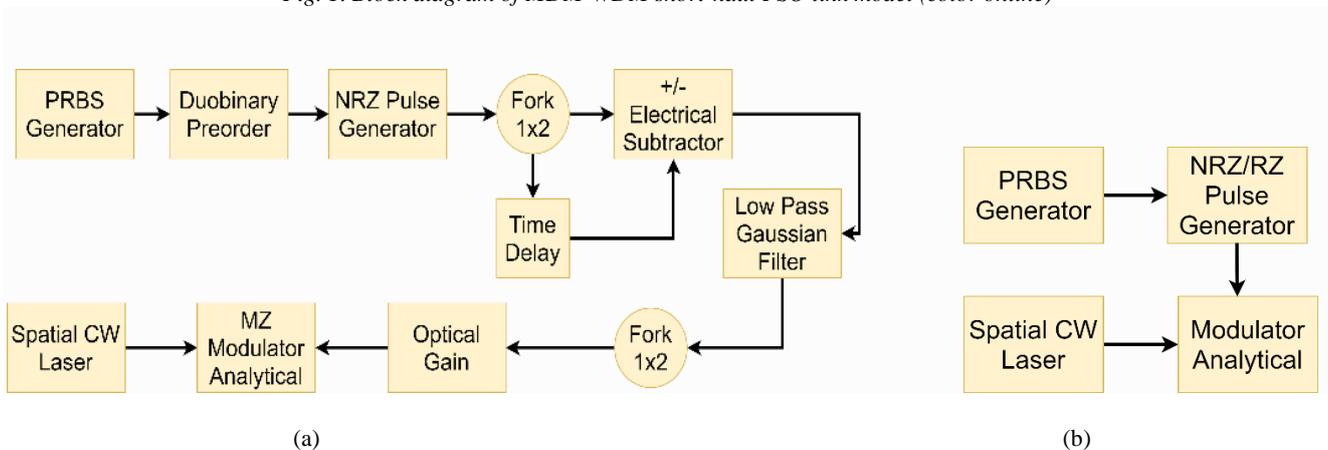

(a)   (b)

Fig. 2. Block diagram of transmitter, (a): AMI transmitter, (b): NRZ/RZ transmitter
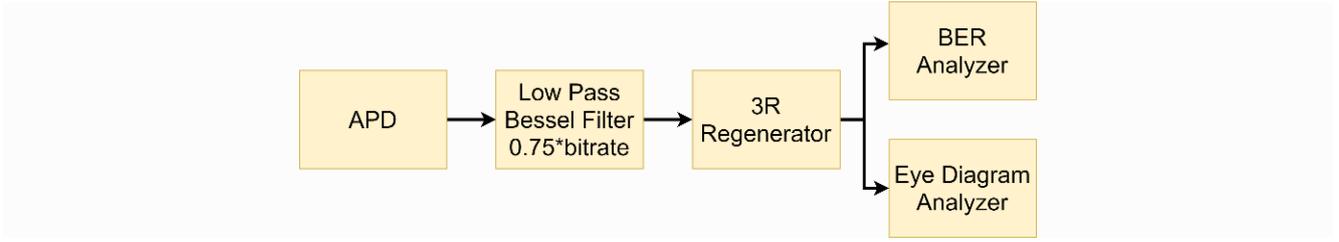
Fig. 3. MDM-WDM short-haul FSO link Receiver

Four independent channels each carrying a data of 20 Gbps over a transmission range of 6000 m represent the four transmitters of the system. in which first two channels (Transmitter 1 and Transmitter 2) transmit on a wavelength of 1550 nm at LP (Linearly Polarized) 00 and LP 01 mode and other two channels (Transmitter 3 and Transmitter 4) transmit on 1551 nm of wavelength at mode LP 00 and LP 01. The excitation of the two modes LP 00 and LP 01 has been done by spatial continuous wave (CW) laser and each mode transmits the pair of transmitters at different wavelengths of 1550 nm and 1551 nm.

Fig. 4 represents excited LP 00 and LP 01 modes generated from spatial laser. The outputs of all the transmitters have been merged through power combiner and amplified by using optical gain amplifier with a 16 dB gain and then transmitted on FSO link over the distance of 6000 m.
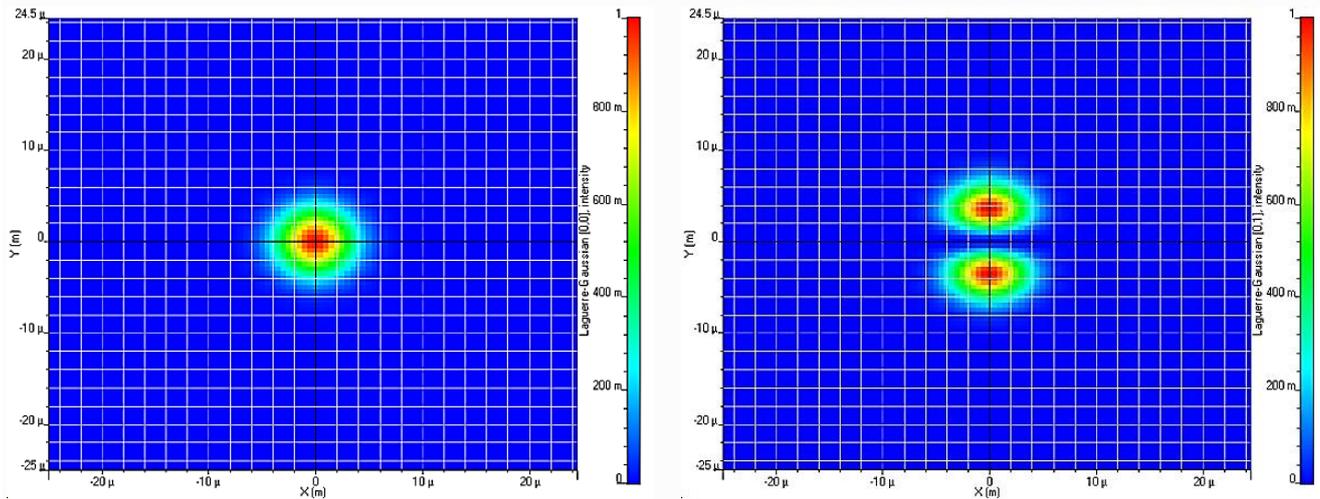

Fig. 4. 2D top view of spatial LP 00 and LP 01 modes (color online)

The link equation determining the received power of the FSO channel is represented by [34]:

$$Pr = Pt \frac{d_2^2}{[d_1 + (D*L)]^2} * 10^{(-a*\frac{L}{10})} \qquad (1)$$

In this, P_r defines the received power at the other end, P_t represents the power radiated from transmitter side, d_1 and d_2 represent the aperture diameters of transmitter and receiver specified in meters respectively, D defines the beam divergence in μrad, a is the factor representing atmospheric attenuation dB/km and L defines the propagation range in km.

At the receiver side the output from the FSO has been fed to Optical amplifier with a gain and noise figure of 12 dB and 4 dB respectively to provide boost in the signal. The received signal carrying four different channels at a wavelength of 1550 nm and 1551 nm have been divided by power splitter into four different paths. The mode selector extracts the LP 00 and LP 01 modes at different wavelengths. The received output mode is then fed to avalanche photodiode (APD) followed by low pass bessel filter. To estimate the overall performance of MDM based FSO system, eye diagram analyser and bit error rate (BER) tester have been utilized in the system. Fog consists of spherical water droplets of varying sizes resulting in the signal attenuation because of Mie scattering. As per the meteorological terms fog is defined when the visibility in the atmosphere drops to near 1 km. Considering the shape of fog particles to be spherical, Mie theory can be applied to calculate particle's scattering cross section C_S and particle radius by r. The value of normalized scattering efficiency Q_S can be estimated theoretically by:

$$Q_S = \frac{c_S}{\pi r^2} \qquad (2)$$

Due to fog, the scattering of optical signal may be given in respect of atmospheric attenuation coefficient β_λ [35]:

$$\beta_\lambda = \int_0^\infty \pi r^2 Q_s \left(\frac{2\pi r}{\lambda}, n'\right) N(r) dr \qquad (3)$$

In this, the real part of refractive index is represented by 'n', particle size distribution as $N(r)$ and $2\pi r/\lambda$ as size parameter. The empirical models should be used to estimate the induced attenuation resulting due to the complexity associated with the physical properties of fog. The empirical relationship given by Kruse model, relating V to fog induced attenuation is given by:

$$V(km) = \frac{10 \log_{10} T_{th}}{\beta_\lambda} \left(\frac{\lambda}{\lambda_0}\right)^{-q} \qquad (4)$$

where T_{th} represents the visual threshold considered as 2%, λ_0 defines the maximum spectrum of solar band and the coefficient relating particle size distribution is represented by q. There are three different methodologies for predication of rain attenuation model: first includes the computation of the specific attenuation, second involves the computation of rain height and third includes methodology to calculate attenuation [36, 37].

One of the most commonly used model to specify the empirical formula that represents law and facts to compute specific attenuation is Marshal and Palmer model. Specific rain attenuation is given by [38]:

$$\gamma(dB/km) = kR^\alpha \qquad (5)$$

In this, rain rate is represented by R in mm/hr and k, α are constants that depend upon frequency, temperature and the rain drop size distribution, Parameters 'k' and 'α' can be calculated by:

$$\log_{10} k = \sum_{j=1}^{4} a_j \exp\left[-\left(\frac{\log_{10} f - b_j}{c_j}\right)^2\right] + m_k \log_{10} f + c_k \qquad (6)$$

$$\alpha = \sum_{j=1}^{5} a_j \exp\left[-\left(\frac{\log_{10} f - b_j}{c_j}\right)^2\right] m_\alpha \log_{10} f + c_\alpha \qquad (7)$$

where, f represents the frequency ranging from 1 to 1000 GHz, k is either k_H or k_V, a is either a_H or a_V where V and H represent the coefficients of vertical path polarization (V) and horizontal polarization (H) respectively.

The calculation of effective rain height H_R is given by the empirical expression given by

$$H_R = \begin{cases} H_0; & R \leq 10 \ mm/hr \\ H_0 + \log\left(\frac{R}{10}\right); & R > 10 \ mm/hr \end{cases} \qquad (8)$$

where, H_0 represents the 0° C isotherm height.

Total attenuation of the rain is determined as [39]:

$$A(dB) = \gamma_R(dB/km) \times L_{eff}(km) \qquad (9)$$

In this, the specific attenuation is given by γ_R (dB/km) and the effective path length is represented by L_{eff} (km).

3. Results and discussion

The results obtained from the analysis of proposed MDM-WDM based FSO system for fog and rain attenuation has been shown in this section. First, different modulation techniques have been analysed for clear air conditions considering four MDM-WDM channels. Next the performance of the overall system has been analysed for prediction of maximum transmission distance under the effect of fog and rain turbulent weather conditions. Table 1 depicts the basic simulation parameters for the proposed hybrid MDM-WDM FSO model. Attenuation coefficients in case of thin, thick and heavy fog weather conditions have been considered as 9, 16 and 22 dB/km respectively. Coefficient values for light, medium and heavy rain are 6.27, 9.64 and 19.29 dB/km respectively [40-42].

Table 1. System Parameters

Parameter	Value
Attenuation	0.14 (clear air)
Line width of spatial laser	10 MHz
Range	5000 m-6000 m
Spatial laser wavelength	1550 nm & 1551 nm
Transmitter antenna aperture diameter	5 cm
Power of spatial laser	0 dBm
Receiver antenna aperture diameter	20 cm
APD responsivity	1 A/W
Dark current of APDv	10 nA
APD gain	3
APD ionization ratio	0.9

Fig. 5 shows that the three different modulation techniques AMI, NRZ and RZ have been analysed under clear air condition considering 0.14 dB/km attenuation. Fig. 5 and 5(b), represent the measured BER values with respect to FSO propagation ranges for channel 1 and channel 2 operating at wavelength of 1550 nm employing LP 00 mode and LP 01 mode respectively. Similarly, Fig. 5(c) and 5(d), represent channel 3 and channel 4 operating at wavelength of 1551 nm considering LP 00 and LP 01 modes respectively.
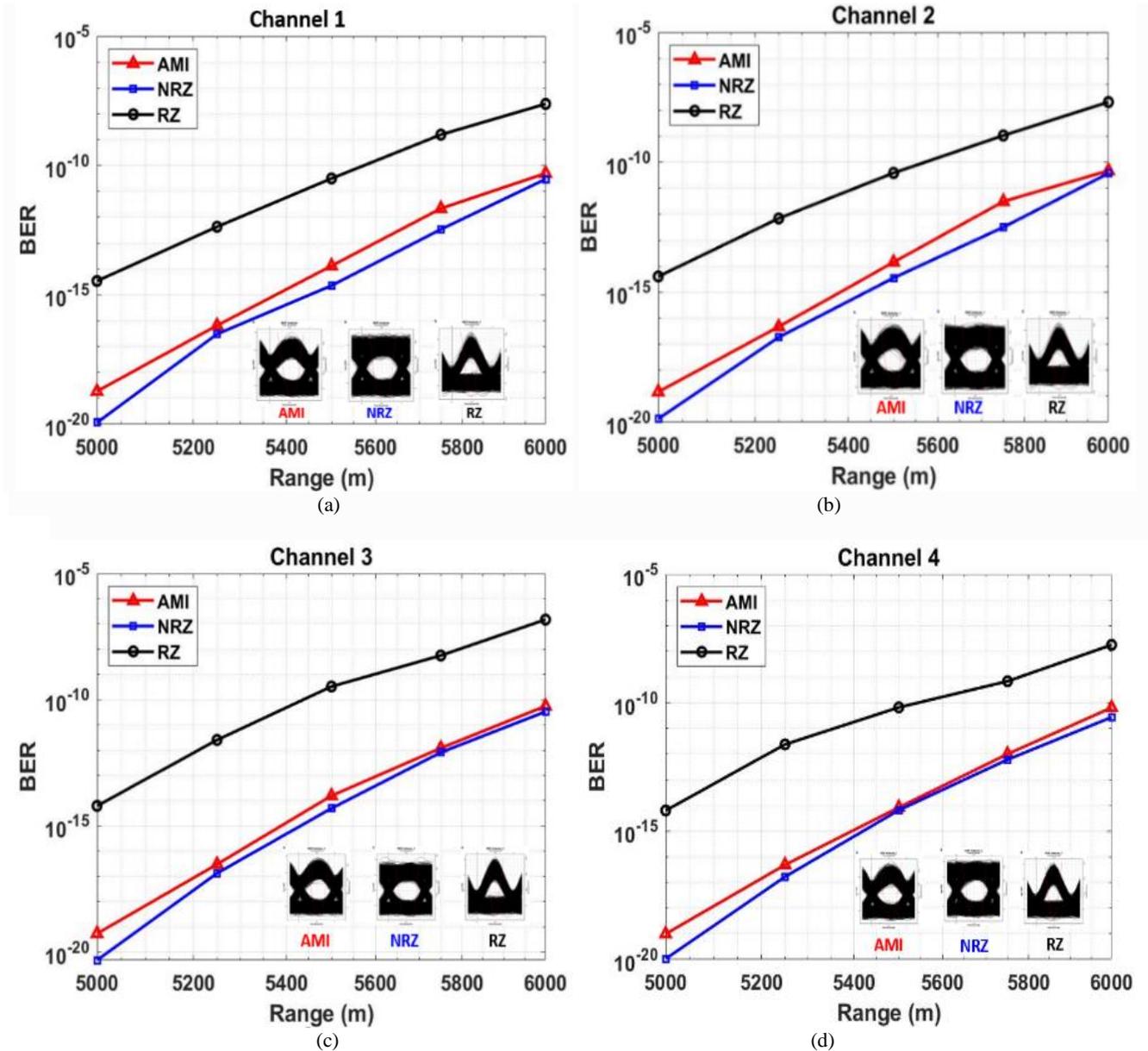
Fig. 5. BER versus range comparing AMI, NRZ and RZ encoding techniques for: (a) channel 1, (b) channel 2, (c) channel 3 and (d) channel 4 (color online)

BER values in case of channel 1 have been listed in Table 2. It has been examined from Fig. 5(a) and Table 2 that NRZ exhibits lesser BER value over the propagation range of 5000-6000 m. AMI and NRZ encoding techniques perform better than RZ under clear air condition.

Table 2. BER of channel 1 under clear air conditions

Range(m)	AMI	NRZ	RZ
5000	1.86×10^{-19}	1.15×10^{-20}	3.43×10^{-15}
5250	6.55×10^{-17}	3.04×10^{-17}	4.29×10^{-13}
5500	1.32×10^{-14}	2.28×10^{-15}	3.15×10^{-11}
5750	2.18×10^{-12}	3.41×10^{-13}	1.56×10^{-09}
6000	4.98×10^{-11}	2.98×10^{-11}	2.40×10^{-08}

Table 3 depicts the BER as a function of transmission range in case of channel 2. As seen from Fig. 5(b) and Table 3, NRZ technique performs better as compared to other two encoding techniques. On the other hand, RZ encoding technique results in maximum BER values of 4.03×10^{-15} and 2.06×10^{-08} over the propagation range from 5000 m to 6000 m respectively. Similarly, from Table 3 and Table 4 and Table 5 it has been observed that NRZ exhibits minimum BER values within the transmission range considered. Maximum transmission range upto 6 kms has been achieved under clear air conditions as depicted by the clear eye opening and acceptable BER. Hence NRZ encoding technique has been set for the rest of the analysis.

Table 3. BER of channel 2 under clear air conditions

Range(m)	AMI	NRZ	RZ
5000	1.46×10^{-19}	1.35×10^{-20}	4.03×10^{-15}
5250	4.70×10^{-17}	1.85×10^{-17}	6.93×10^{-13}
5500	1.43×10^{-14}	3.55×10^{-15}	3.88×10^{-11}
5750	3.09×10^{-12}	3.16×10^{-13}	1.07×10^{-09}
6000	4.75×10^{-11}	3.74×10^{-11}	2.06×10^{-08}

Table 4. BER of channel 3 under clear air conditions

Range(m)	AMI	NRZ	RZ
5000	5.36×10^{-20}	4.76×10^{-21}	6.18×10^{-15}
5250	3.01×10^{-17}	1.33×10^{-17}	1.27×10^{-12}
5500	1.56×10^{-14}	4.94×10^{-15}	4.76×10^{-11}
5750	1.21×10^{-12}	8.13×10^{-13}	1.41×10^{-09}
6000	5.60×10^{-11}	3.36×10^{-11}	1.87×10^{-08}

Table 5. BER of channel 4 under clear air conditions

Range(m)	AMI	NRZ	RZ
5000	9.96×10^{-20}	1.07×10^{-20}	6.37×10^{-15}
5250	4.85×10^{-17}	1.67×10^{-17}	2.37×10^{-12}
5500	8.38×10^{-15}	6.54×10^{-15}	6.56×10^{-11}
5750	1.48×10^{-12}	6.09×10^{-13}	6.84×10^{-10}
6000	6.43×10^{-11}	2.72×10^{-11}	1.78×10^{-08}

Further to predict the maximum transmission range of the system under turbulent environmental conditions, the performance of the MDM-WDM FSO system has been analysed. Fig. 6 shows that the overall performance of the FSO link has been examined under the influence of different fog conditions. It can be observed from Fig. 6(a) that under the impact of thin fog having an attenuation of 9 dB/km, BER varies from 10^{-25} to 10^{-05} for the transmission range of 1300 m to 1600 m. A similar performance has been observed in case of all the four channels over the considered propagation range.

In the case of thick fog with an attenuation of 16 dB/km, maximum possible link range reduces to 1100 m as shown in the Fig. 6(b). A BER of 10^{-05} has been observed in case of channel 1 at this transmission range.

Under the influence of heavy fog at an attenuation of 22 dB/km, the FSO link range further gets reduced to 900 m as shown in the Fig. 6(c) evaluating a minimum BER of 10^{-05} for channel 3. The results shows that FSO link performance degrades, and maximum link length reduces from 1600 m for thin fog to 1100 m for thick fog and then to 900 m for heavy fog.
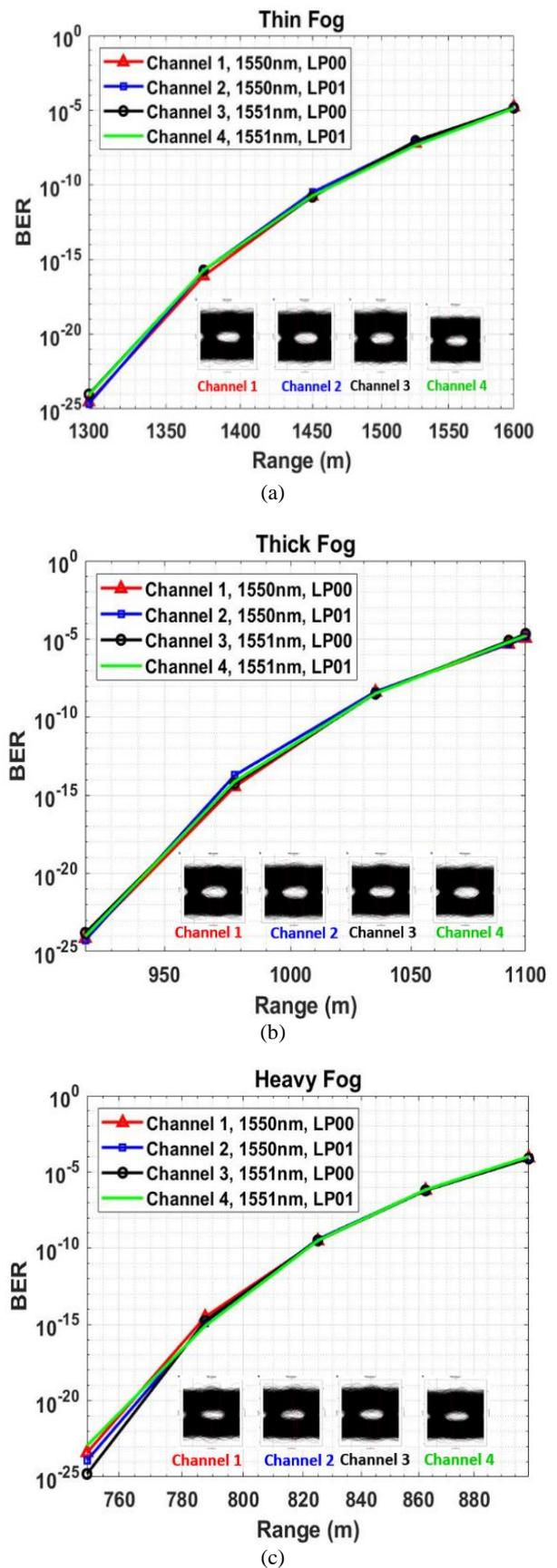

(a)

(b)

(c)

Fig. 6. BER versus range under different fog conditions, (a) Thin fog, (b) Thick fog and (c) Heavy fog (color online)

The effect of different rain conditions on the performance of FSO link has also been investigated as shown in Fig. 7. Fig. 7 (a) demonstrate that the maximum transmission reach using the proposed MDM-WDM based FSO system with acceptable BER is 2000 m under the effect of light rain conditions. It can be observed from Figure that under the effect of light rain having an attenuation of 6.27 dB/km, BER varies from 10^{-24} to 10^{-05} for the maximum transmission range of 1600 m to 2000 m. A similar performance in case of all the four channels over the measured propagation range has been observed. In the case of medium rain condition having an attenuation of 9.64 dB/km, maximum possible link range reduces to 1600 m as shown in Fig. 7 (b). A minimum value of BER of 10^{-04} has been observed in case of channel 2 at this transmission range. Under the influence of heavy rain having an attenuation of 19.28 dB/km, the system's link range further gets reduced to 950 m as shown in Fig. 7 (c) evaluating a minimum BER of 10^{-06} for channel 3. From the results, it can be examined that FSO link performance deteriorates, and maximum link length reduces from 2000 m for light rain to 1600 m for medium rain and then to 950 m in the case heavy rain conditions.
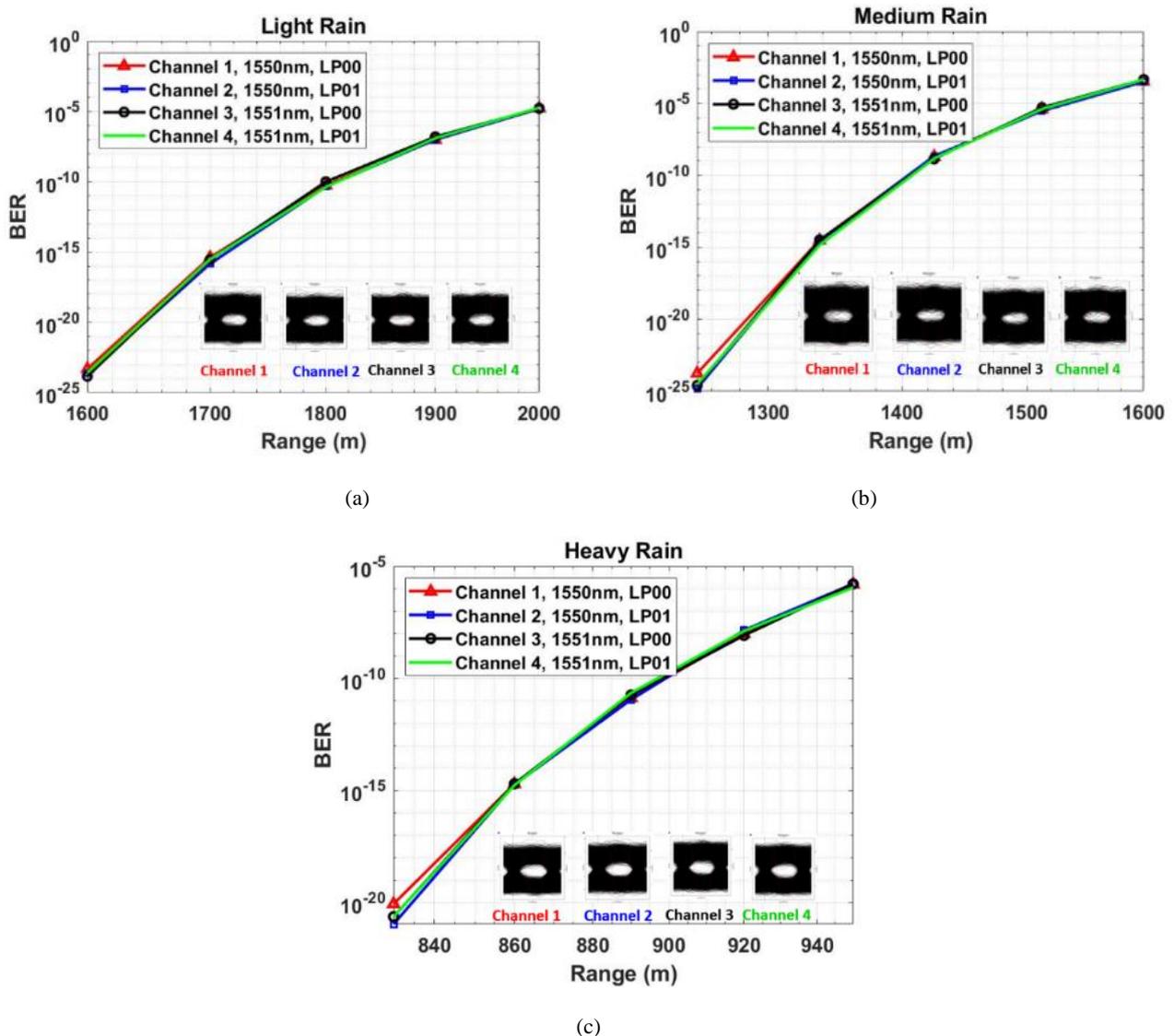

(a)   (b)

(c)

Fig. 7. BER versus range under different rain conditions, (a) Light rain, (b) Medium rain and (c) Heavy rain (color online)

Table 6 represents the comparison of the previous published work with the proposed system considering data rate and range as performance parameters.

Table 6. Comparison of result with previous work

Parameters	Ref [3]	Ref [43]	Ref [31]	Ref [32]	Ref [44]	Proposed Work
Data Rate	10 Gbps	320 Gbps	100 Gbps	1.6 Gbps	100 Gbps	80 Gbps
Range	2 Km	130 m	8 Km	900 m	10 Km	6 Km
System	MIMO	DWDM-FSO	MDM-OCDMA FSO	MDM WDM-FSO	OCDMA-PDM-FSO	MDM-FSO
Modulation techniques	NRZ, RZ and CSRZ	RZ and NRZ	OCDMA	Duobinary and AMI	NRZ	AMI, NRZ and RZ
Atmospheric Conditions	Fog, cloud	Clear and fog	Fog	-	Clear and fog	Clear, Fog & rain

4. Conclusion

In this work we present four channel FSO communication system incorporating hybrid MDM-WDM modulation scheme to improvise the overall system capacity and propagation range. The proposed system ensures successful transmission of signal at 80 Gbps upto a propagation range of 6000 m under clear air conditions using LP modes. The effect of atmospheric turbulence on the FSO system performance by different atmospheric conditions of fog and rain has also been numerically investigated. The results show that NRZ modulation technique offers better performance than AMI and RZ encoding techniques, as it gives lowest acceptable BER in case of all the four channels. Transmission of signal under thin, thick and heavy fog conditions have been achieved upto a propagation distance of 900 m, 1100 m and 1600 m respectively. The maximum transmission range reduces to 950 m in case of heavy rains. Further, the system may be investigated by employing other advanced modulation technique. The effect of different internal system parameters such as input power, data rate and channel spacing may be analyzed for enhancement of performance of the proposed system.

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