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Mode Division Multiplexing in Free Space Optical Communication

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***Abstract*: In this work, a cost effective and high speed mode division multiplexing and optical code division multiplexing based hybrid FSO system is demonstrated. Proposed system has potential to support 100 Gbps bit rate and capacity to cater 10 simultaneous users. Diverse linear polarized modes are used under two Laguerre Gaussian modes to accomplish MDM. Use of MDM is considered to reduce the MAI and to lower the cost of the system. Further, investigation of proposed system is performed using shift zero cross correlation (SZCC) codes and comparison has been done with random diagonal (RD) OCDMA codes in terms of BER, Q factor and received power under different intensities of FOG.**

***Keywords*: Mode division multiplexing, Free space optical, OCDMA, Q factor, BER.**

1. Introduction

For the reliable and secure transmission of data without optical fibers, an utmost solution is free space optical transmission. FSO is competent technology which can cater fiber like data rates such as 40 Gbps. In optical fiber communication, trenching, rights of ways makes its deployment costly and time consuming. However, in free space optical, no trenching, no rights of ways are required because FSO is unlicensed and operate in air without and wired connection [1]. Security is more in FOS because it uses line of sight and any intrusion can acknowledge immediately [2]. There are various advantages of using FSO systems for communication including no fiber optic cables required, low expenses, no security upgrades, and so on [3]. Atmospheric turbulences greatly impact the system performance of FSO because this channel is troposphere based [4]. Utmost performance degrading factors in FSO are attenuation, pulse broadening and signal scattering due to different weather conditions such as frozen droplets, sand storms, rain etc. [5].

Optical code division multiplexing is also a prominent technique which is incorporated in the optical fiber systems due its better security. Use of OCDMA in FSO is also a great work to increase bandwidth efficiency and security. Each user in OCDMA gets unique code from transmitter, it may be 1 D codes, 2 D codes or 3 D codes. At receiver side, each users data can be taken by applying respective code filters. Comprised of the features of CDMA, OCDMA can transmit data seamlessly which further controls and manages networks easily. Optical code division over FSO is deployed for the first time in [6] using 2 D coding scheme. Multiple access interference in OCDMA also plays vital role in OCDMA systems. Cross-correlation in OCDMA code decreases the performance of the system. In this work, we are using shift ZCC and mode division multiplexing over FSO.

2. Code construction of Shift ZCC codes

For simplification of analysis, first the code construction is considered for three users and keeping the weight value as two.

Step 1: Generation of combined matrix

Here, use of two matrices has been done as the weight is considered to be two. First matrix is an identity matrix and the next matrix is a null matrix of same dimension as the identity matrix. Number of matrix taken equals to the weight value considered. The dimension of identity matrix is 3×3 as the number of users taken 3. Dimension of matrix equals to the number of active users. Therefore, two 3×3 dimension matrixes are

$$\begin{bmatrix} 1\,0\,1\,0 \\ 0\,1\,0\,1 \\ 1\,0\,1\,0 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

The two combined matrices together are shown as

$$\begin{bmatrix} 1\,0\,0\,0\,0\,0 \\ 0\,1\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0\,0 \end{bmatrix}$$

Step 2: Shifting ‘1’ in the combined matrix (Shift by = W×R-W-R+1)

Where, R is the corresponding row number, W is the weight of the proposed code. In each row, the 1 is shifted (right) by the above rules. Last row by=2×3-2-3+1=2 (last row R=3). Middle row by=2×2-2-2+1=1(middle row R=2). First row by=2×1-2-1+1=0(first row R=1). So the generalized formula for shifting is W×R-W-R+1. Last row shifting as per the above rule looks a

Middle Row Shifting

0 0 1 0 0 0 ⟶ 0 0 0 0 1 0

Last row shifting

0 1 0 0 0 0 ⟶ 0 0 1 0 0 0

First row shifting

1 0 0 0 0 0 ⟶ 1 0 0 0 0 0

Final Matrix Given as

$$\begin{bmatrix} 1\,0\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0\,0 \\ 0\,0\,0\,0\,1\,0 \end{bmatrix}$$

Step 3: Replacing

Next, replace W-1 right zeros by 1 right to the existing pulse or ‘1’. Replacing the single right ‘0’right to the existing pulse by 1 in every row (because W-1=2-1=1). Last row replacing

0 0 0 0 1 0 ⟶ 0 0 0 0 1 1

Middle Row replacing

0 0 1 0 0 0 ⟶ 0 0 1 1 0 0

First row replacing

1 0 0 0 0 0 ⟶ 1 1 0 0 0 0

The final SHIFTZCC code matrix is obtained as

$$\begin{bmatrix} 1\,1\,0\,0\,0\,0 \\ 0\,0\,1\,1\,0\,0 \\ 0\,0\,0\,0\,1\,1 \end{bmatrix}$$

In this work, this process is followed for k=5, w=3 and final matrix obtained is

$$\begin{bmatrix} 1\,1\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,1\,1\,1\,0\,0\,0\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,1\,1\,1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0\,0\,0\,1\,1\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,0\,1\,1\,1 \end{bmatrix} \quad (1)$$

3. System Setup

Figure 1 depicts the proposed system setup block diagram of ten user 100 Gbps optical code division and mode division multiplexed hybrid free space optical system. Mode division multiplexing is the most attractive technique in this work to reduce the cost of multi-wavelength architectures such as wavelength division multiplexing. In wavelength division multiplexing, N numbers of coherent intensity sources are required to generate N frequencies, which ultimately beef up the total expenditure of the system. MDM is an alternative to WDM because it can also support data rates similar to aforementioned technique and transmit data streams in parallel tributaries. Incorporation of MDM with OCDMA can support double the users with half lasers and therefore makes system cost efficient. Proposed system consists of laser source array with 15 different wavelengths and operated on power level of 10 dBm. Channel spacing among different wavelengths is fixed to 0.8 nm and laser linewidth is 10 MHz. For each user in the system, pseudo random bit sequence generator is used for the binary data stream generation and followed by pulse shaping module such as non-return to zero modulation format. NRZ is simply a no/off keying and this signal fed to intensity modulator (Mach Zehnder modulator). MZM has two input port, one for electrical pulse input and other is for optical intensity signal. Laser signals with different wavelengths are combined using power combines and choice of wavelengths is purely depends on the OCDMA code generation matrix. Here, use of shift zero cross correlation code has been done and code is designed for 5 users with weight 3. Wavelengths of the combiner selected according to this code as shown in equation (1). For the realization of different users, wavelengths are given below according to the codes

First user-1550, 1550.8, 1551.6
Second user-1552.4, 1553.2, 1554
Third user-1554.8, 1555.6, 1556.4
Fourth user-1557.2, 1558, 1558.8
Fifth user-1559.6, 1560.4, 1561.2

It is noteworthy that SZCC codes are constructed for 5 users and total 10 users are served by saving the cost of five users with the proposed system. Combined wavelengths of each user, followed by a mode generator and modulated with NRZ generator. Mode generator is incorporated after power combiner to provide different intensity profiles. Ten users are divided into two parts, wavelengths of the constructed code for five users remains same in both parts, however, only different is of mode profiles. All 10 linearly polarized modes fall under two Laguerre Gaussian modes such as LG01 and LG02. LP modes used for LG01 are LP11, LP12, LP13, LP14 and LP15. For next 5 users, LP modes of LG02 are LP21, LP22, LP23, LP24 and LP25. All the modulated signals from first 5 users and next five users are then combined and fed to free space optical channel. FSO channel is operated in conventional band with transmitter antenna size 5 cm and receiver antenna size 20 cm. Beam divergence of 0.1 mrad is taken to investigate the system.

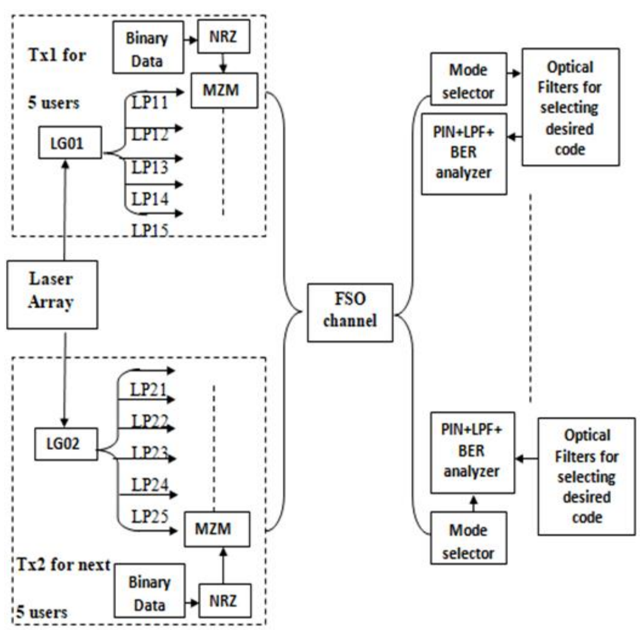


Fig. 1. Block diagram of proposed MDM-OCDMA-FSO system

A. Analysis of atmospheric turbulences

Atmospheric turbulence or weather instabilities are the prominent performance degrading factor in free space optic communication. Investigation of proposed system is also performed under different versions of FOG. Attenuations are in the context of turbulences given in Table 1. After FSO channel, a power splitter is placed to divide two signals. One is for first 5 users and other one is for next five users. Mode selectors are placed in front of all the divided signals in order to select the specific LP mode according to the transmitter. Mode selectors are followed by filters to select specific wavelengths as SZCC codes for each user. Photo-detector is used to convert electrical to optical signal and after that signal fed to low pass filter and BER analyzer.

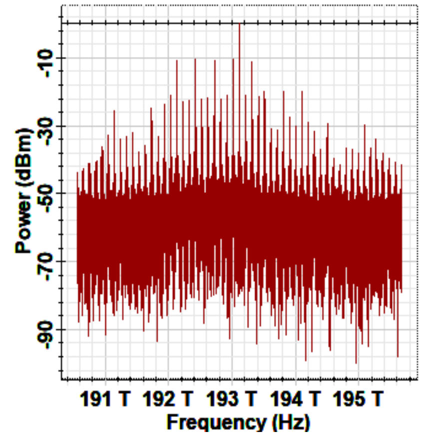
Table 1
Atmospheric turbulences and attenuation

Atmospheric Turbulences	Attenuation (dB/Km)
Clear weather	0.14
Light Fog	9
Medium Fog	12
Heavy Fog	16

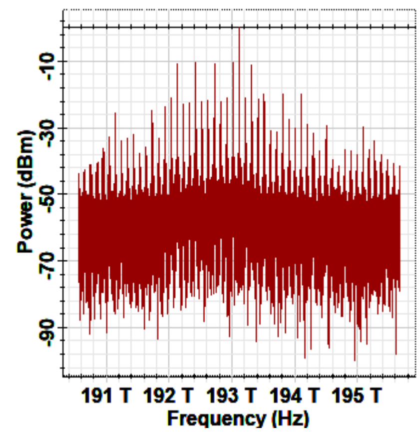
4. Results and discussion

Investigation of proposed system of optical code division multiplexing and mode division multiplexing is done over free space optical system. Moreover, different weather conditions are studied and their effects on the proposed system are carried out. Optical spectrum of the carrier signal is depiction of centre frequency of carrier signal and power of the signal. Figure 2 (a) represents the optical spectrum analyzer's output for the carriers of five users with respect to their power and centre frequencies. Next five users are also depicted in Figure 2 (b). It is evident that wavelengths of the first five users and last five users are same.

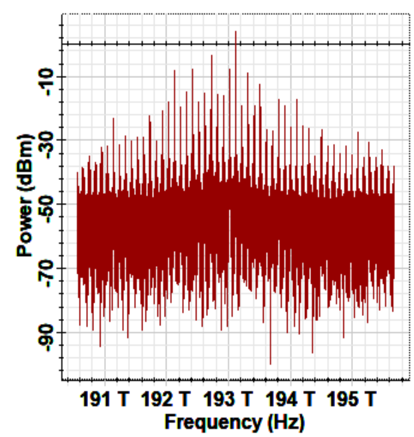
Ten users are divided into two parts, wavelengths of the constructed code for five users remains same in both parts, however, only different is of mode profiles. All 10 linearly polarized modes fall under two Laguerre Gaussian modes such as LG01 and LG02. LP modes used for LG01 are LP11, LP12, LP13, LP14 and LP15 are shown in Figure 3 (a), (b), (c), (d) and (e) respectively. It is perceived that each LP mode is assigned to each wavelength differently. Azimuthal number of the LP modes is kept fixed and radial number is varied from 1 to 5. As radial number increases, more circles are surrounded azimuthal peaks. The Multimode Generator attaches mode profiles to the input signal X and Y polarizations. A Laguerre-Gaussian profile is attached to each polarization. Additionally, single-mode inputs can be converted to a multimode signal scaled by a user-defined power distribution.



(a)



(b)



(c)

Fig. 2. Optical spectrum of (a) fist five users (b) next five users (c) multiplexed signal of ten users

Ten users are divided into two parts, wavelengths of the constructed code for five users remains same in both parts, however, only different is of mode profiles. All 10 linearly polarized modes fall under two Laguerre Gaussian modes such as LG01 and LG02. LP modes used for LG01 are LP11, LP12, LP13, LP14 and LP15 are shown in Figure 3 (a), (b), (c), (d) and (e) respectively. It is perceived that each LP mode is

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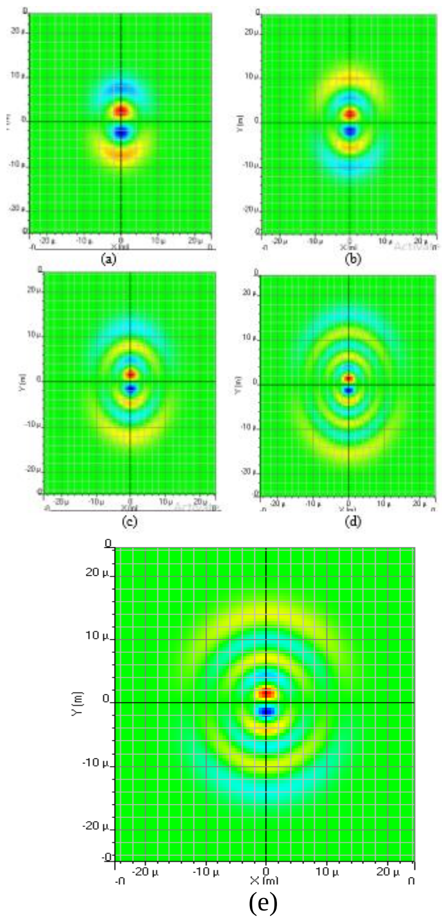
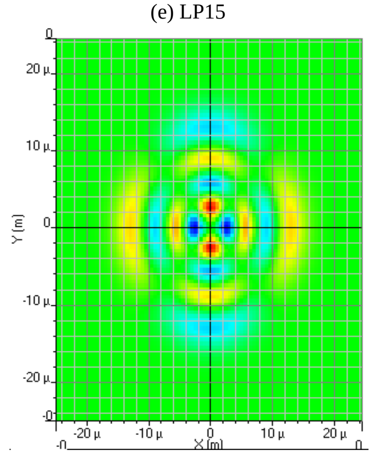


Fig. 3. Mode profiles of LP modes (a) LP11 (b) LP12 (c) LP13 (d) LP14 (e) LP15



(a)

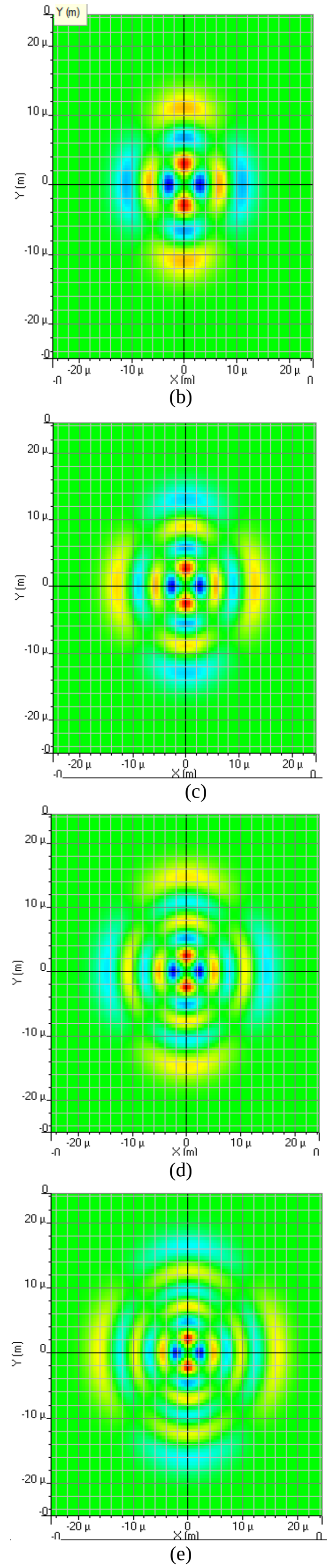
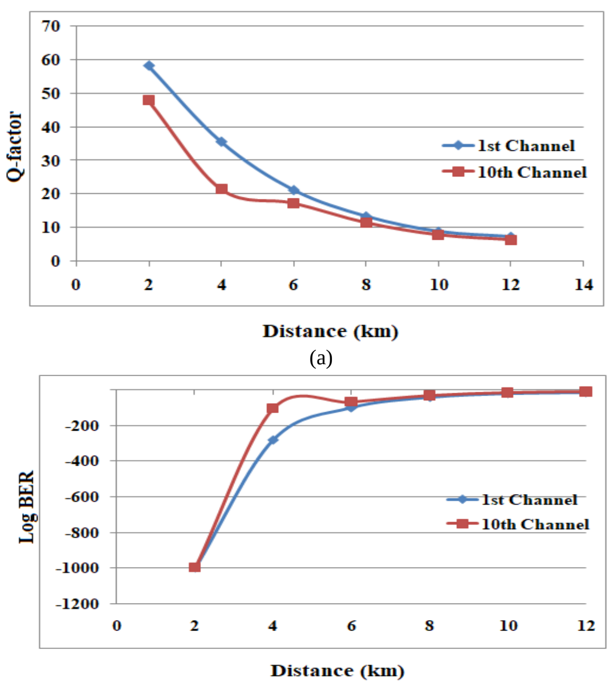


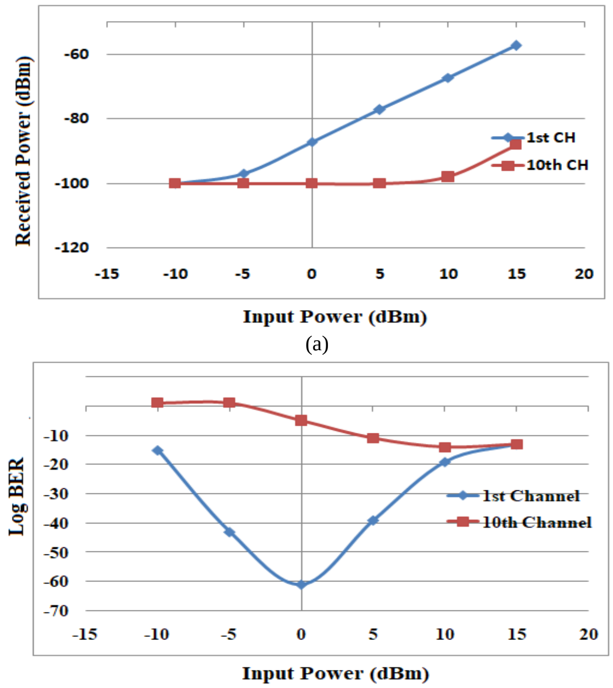
Fig. 4. Mode profiles of LP modes of (a) LP21 (b) LP22 (c) LP23 (d) LP24 (e) LP25

The Fig. 4 illustrates the linearly polarized modes for next 5 users, LP modes of LG02 are LP21, LP22, LP23, LP24 and LP25 as depicted in Figure. Azimuthal number is two and four azimuthal peaks are there. Radial numbers are varied from 1-5. Figure 5 (a) illustrates performance of OCDMA-MDM based ten users system that are transmitted over free space optical link and distance is varied from 2 km to 12 km with the difference of 2 km. Investigation of the proposed system has been done at different distances in terms of Q factor for 1st channel (user) and 10th channel (user). It is perceived that highest Q factor is obtained at 2 km and Q factor tends to decrease with increase in transmission distance. Performance of 1 user is better as compared to 10th user and this is due to difference in LP mode profiles. Linearly polarized mode LP11 has less mode coupling and LP15 has more, due to this LP11 performs better. Figure 5 (b) depicts the system performance at diverse distances of free space optical channel in terms of log BER. It is noteworthy that there are more and more errors in the systems, as distance prolongs. Minimum log BER is attained at 2 km and least log BER is obtained at 12 km. Comparison of first user and 10th user is carried out and it is perceived that first user is better than tenth user. System works successfully for distance of 12 km within acceptable range of BER as given by international telecommunication union i.e. 10^{-9}.



(a)
(b)
Fig. 5. Representation of distance versus (a) Q factor (b) Log BER of proposed system

The Fig. 5 (a) shows that highest Q factor is 58.25 of first channel and 7.22 at 12 km. At same distances, the Q factor is 47.86 and 6.42 respectively. Received power of the 1st and last channel of the proposed OCDMA-MDM-FSO system using shift ZCC codes is shown in Figure 6. Input power form laser source is varied for all the users. Input power levels altered from -10 dBm to 15 dBm with difference of 5 dBm. It is observed that more power coupling to the FSO, provide beset results and in Figure 6, received power is studied with the variation of input power. Result reveals that maximum power received in case of 1st user due to LP mode 11.



(a)
(b)
Fig. 6. Input powers versus (a) Received Power (b) Log BER of proposed system

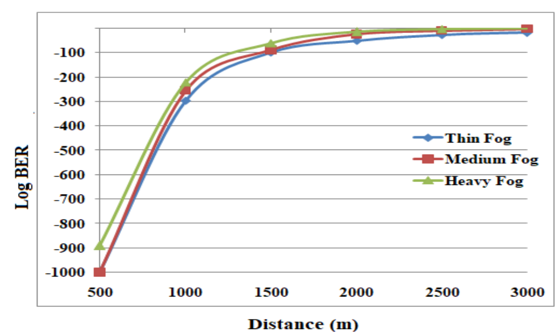
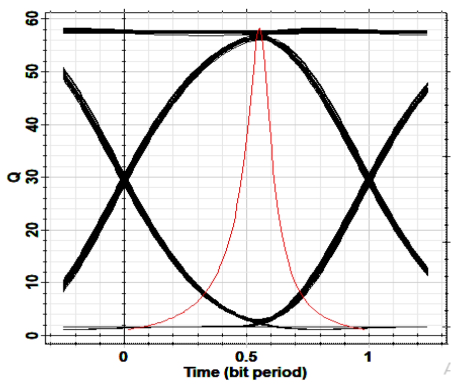


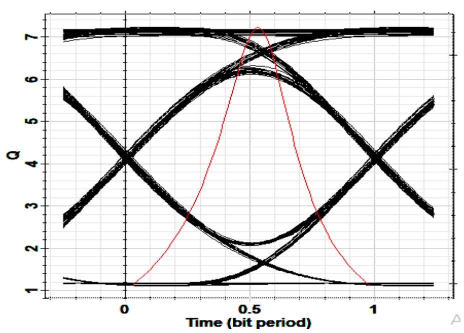
Fig. 7. Effect of different Fog conditions of proposed system

Figure 6 (b) represents the Log BER versus different input powers. It is evident that with the increase in input power coupling, Log BER of the system decreases. First users surpass the performance of tenth user due to least errors and least power coupling to LP11 linearly polarized mode. Further, diverse atmospheric conditions are investigated in the proposed system such as clear weather, light Fog or thin Fog, medium Fog and heavy Fog. Attenuation of clear weather is 0.1 dB/km, light Fog is 9 dB/km, medium Fog is 12 dB/km and heavy Fog is 16 dB/km. Distance of the system is varied from 500 m to 3000 m and bit error rate is analyzed to check the performance of proposed system in the diverse atmospheric conditions. Results revealed that as Fog becomes intense i.e. light fog to heavy fog, log BER increases. Performance of the system under light fog is best and in case of heavy Fog is worst as given in 7. Moreover, maximum link length coverage of the system is calculated from the BER under different Fog conditions and it is evident that system under light Fog can cover distance of 3300 km within acceptable limit of BER. Also, reach of the system is calculated as 2600 km and 2100 km in case of medium fog and heavy fog respectively.

The Fig. 8 depicts the eye diagram of the proposed system at 2 km and 12 km link distance. It is perceived that wide eye opening is attained at 2 km due to less losses and eye closer is more increase of 12 km eye diagram.

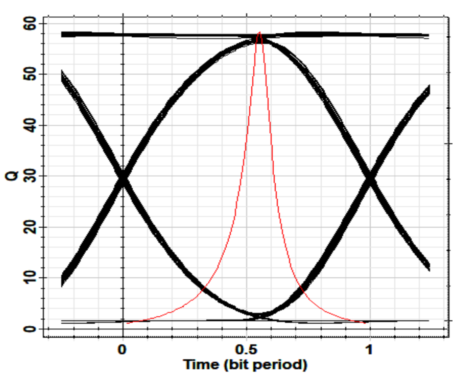


(a)

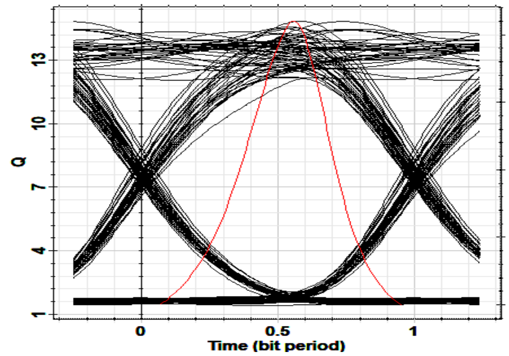


(b)

Fig. 8. Eye diagrams of proposed system at (a) 2 km (b) 12 km FSO link length



(a)



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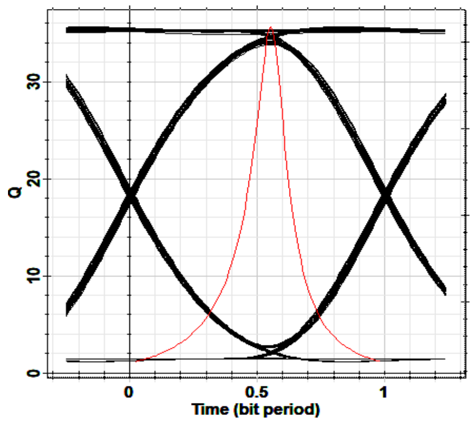
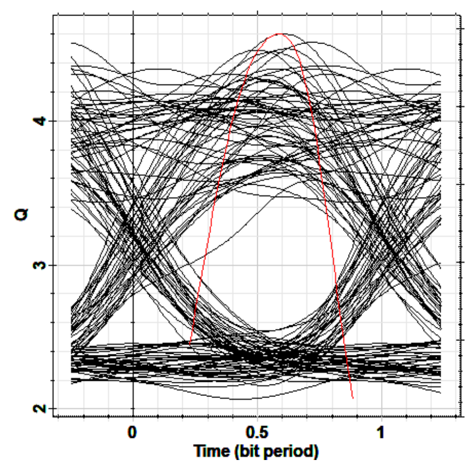
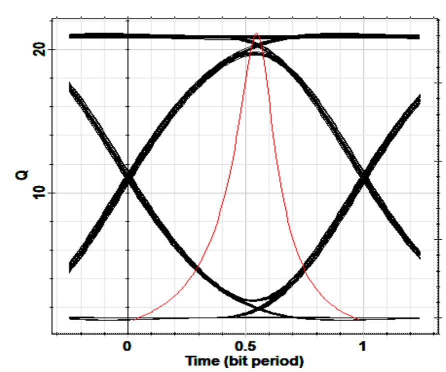


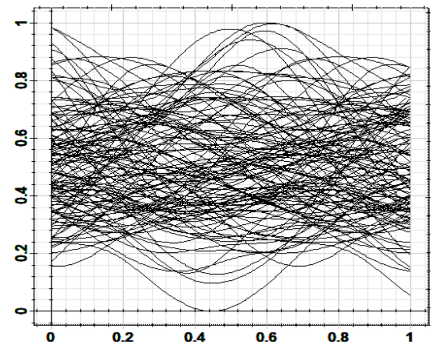
(c)



(d)



(e)



(f)

Fig. 9. Eye diagram of proposed system for (a) (b) light fog (c) (d) medium fog (e) (f) heavy fog at 500 m and 3000 m respectively

The Fig. 9 depicts the eye diagrams of the system at 500 m and 3000 m for different fog conditions. It is observed that eye opening is more even at 3000 m for light fog and fully errors eye is obtained for heavy fog for 3000 m.

5. Conclusion

A cost effective and high speed mode division multiplexing and optical code division multiplexing based hybrid FSO system is demonstrated. Proposed system has potential to support 100 Gbps bit rate and capacity to cater 10 simultaneous users. Diverse linear polarized modes are used under two Laguerre Gaussian modes to accomplish MDM. Further, investigation of proposed system is performed using shift zero cross correlation (SZCC) codes and comparison has been done with random diagonal (RD) OCDMA codes under different intensities of FOG. Results revealed that proposed SZCC OCDMA-MDM-FSO system works for 12 km within acceptable range of BER and RD codes can achieve only 8 km link distance. Reach of the system under light fog, medium fog and heavy fog in case of RD codes is 1500, 1250 m and 1000 km respectively. Reach prolongs to 3300 m, 2600 m and 2100 m for light fog, medium fog and heavy fog respectively when SZCC codes are used. Further it is concluded that LP11 modes performs better than other modes and 1st channel has higher performance than 10th user. Therefore, proposed system is flexible, economical; performance enhanced and high speed FSO system.

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