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COMPARISON OF MD & ZCC ONE DIMENSION CODE FOR OPTICAL-CDMA OVER MULTI-MODE FIBER BASED ON LAGUERRE-GAUSSIAN MODES

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Abstract

This paper compares multi diagonal (MD) and zero cross-correlation (ZCC) one-dimension codes for optical code division multiple access (Optical-CDMA). In our system, Laguerre-Gaussian modes over a multi-mode fiber (MMF) transmission system based on two different codes have been proposed. Computer simulation software (Opti-system) is used to design the system in a short-haul local-area network (LAN) to evaluate high-capacity optical data links. In the design, the data is transmitted via Spatial vertical-cavity surface-emitting laser (on Spatial VCSEL) with a 1550 nm wavelength. The adopted Laguerre-Gaussian modes are (LG 0 3, LG 02 and LG 01). Over different distances, we evaluate our system by conducting several simulation experiments to measure the parameters: Bit error rates, Q-Factor and eye diagrams.

Keywords: Laguerre-Gaussian mode, Multi diagonal code, Multi-mode fiber, Optical-CDMA, Zero cross-correlation code.

1. Introduction

World widely, consumer demands for data have risen dramatically over the last decade. It is predicted to increase at an even faster rate of cheaper bit rates, which is the key factor in the world's fiber optic telecommunications infrastructure. However, fiber optics need to enhance the capacity, and it is an essential technology to transfer a larger amount of data [1, 2]. In the literature, numerous techniques have been proposed, such as orthogonal frequency-division multiple access (OFDMA), wavelength division multiple access (WDMA), mode division multiplexing (MDM) and time-division multiple access (TDMA) [3-5]. These techniques have been employed to enhance data transmission capacity for fiber optic communication [1, 4, 6, 7]. However, a large volume of data is needed to be transmitted by these techniques to meet future requirements of the end-users, due to the high capacity of data projected in the future.

Optical Code Division Multiplexing Access (Optical-CDMA) technique is a robust technique that benefits from excess bandwidth in multimode optical fiber (MMOF) to conduct asynchronous and random access [8, 9]. This technique is crucial due to the high capacity of data projected in the future. It is well known that the existing optical transmission channel that operates over single-mode fiber (SMF) will reach its fundamental capacity limits [10, 11]. However, a channel capacity beyond the Shannon limit of SMF can be achieved with the help of MMF, where the signal is multiplexed in different spatial modes [11, 12]. To increase single-mode transmission capacity and avoid foreseen "capacity crunch", researchers have been motivated to employ MMF as an alternative [13-15]. Optical-CDMA simplifies and decentralizes network control to improve spectral efficiency and information security. Consequently, it increases flexibility in bandwidth granularity and allows synchronous and simultaneous transmission medium to be shared by many users have received more attention in recent years [8]. Optical-CDMA techniques enable full access for the entire channel by various users asynchronously [16, 17]. There are many kinds of techniques that produce unique codes for each user in the spectral domain [18]. By providing different codes for each user, this technique overcomes the issue of multiple access interference (MAl). It can be performed by using the feature of ideal in-phase cross-correlation of any code [19].

Different codes are stated for SAC-Optical-CDMA systems, where certain factors need to be considered in selecting a code. In which consider the cross-correlation function as the most significant, which easily helps to reduce the interference caused by different users. Additionally, the auto-correlation of the code is an essential factor where the desired signal can be detected effectively. Some of the other codes that have been proposed also have their own various issues. For example, complicated code generation (e.g., OOC and MFH codes), lengthy code and unideal (e.g., OOC), and wideband source or narrow filter bandwidth requirements (e.g., zero cross-correlation) [20]. In this study, we compare one-dimension code of multi diagonal (MD) and zero cross-correlation (ZCC) for Optical-CDMA over MMF based on Laguerre-Gaussian (LG) Modes. The code is presented in a binary sequence and has the feature of the good auto-correlation, and the transmission system is performed for high-capacity optical data links short-haul local-area network (LAN).

This paper is structured as follows. The code design of 1D-ZCC and 1D-MD are described in Sections 2 and 3, respectively. The Optical-CDMA system model is presented in Section 4. Section 5 discusses the performance evaluation of the system in terms of Q-Factor, bit-error rates (BER) and eye diagrams. In Section 6, we conclude the paper and identify some future directions.

2.1D Zero Cross-Correlation Code Construction

ZCC code is usually can be used in Optical-CDMA because it has a zero-correlation feature, which can be used to enhance the optical system performance. A high code cardinality is taken into consideration in order to design an optimal ZCC set (has good auto and cross-correlation properties) and to provide a maximum possible number of users (with minimum code weight and code length). Accordingly, minimizing error probabilities and a guaranteed QoS can be achieved [8]. Lately, on systems based on optical-CDMA, ZCC is implemented for Spectral Amplitude Coding (SAC) [21-24]. The features of code cross-correlation can produce good system performance in terms of BER and Q-factor. Here, we represent ZCC code by $K \times L$ matrix, where K is the number of rows as well as demonstrate the number of simultaneous users. Whereas L defines the columns' number and describes the minimum code length. We take advantage of mapping and transformation techniques. The methods of constructing a family of ZCC is shown in Table 1.

Table 1. Construction of ZCC Encoder with *K*=3, *W*=2.

Wavelengths	User1	User2	User3
1548.4	1	0	0
1549.2	0	1	0
1550	0	0	1
1550.8	1	0	0
1551.6	0	1	0
1552.4	0	0	1

K (Number of active use) and L (generate a set of minimum length) are given as:

$$K = w + 1 \tag{1}$$

$$L = w(w + 1) \tag{2}$$

with the basic ZCC code, the matrix is generated as follow:

$$ZCC(w + 1) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \tag{3}$$

The increase in the number of users (using the following map) can occur as follows:

$$ZCC(w = 2) = \begin{bmatrix} Z_1 & 0 \\ 0 & Z_1 \end{bmatrix} \tag{4}$$

In ZCC codes for three users. The unit code matrix for this code is:

$$ZCC(w = 2) = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

3. 1D Multi Diagonal Code

The *MD* code is defined by three factors λc, W and N, where λc is the in-phase cross-correlation, W defines the code and N represents the code length [25-27].

Additionally, *Y* and *X* are the code sequence defined as follows: $Y=\{y_1, y_2\ldots yN\}$ and $X=\{x_1, x_2\ldots, xN\}$. The cross-correlation expression can be expressed by $\lambda c = \sum_i^N x_i y_i$. When λc is zero, 0 it means that the code has the properties of zero cross=correlation. a $K \times N$ matrix represents the matrix of *MD* code which means it depends on the code weight (W) and the number of users (K). It is worth mentioning that the weight value can be free chosen because it needs to be more than 1 ($W > 1$). Now, the design of (1D MD) can be performed as follows:

Using the value of (W) and (K), the sequence of a diagonal matrix is constructed. Additionally, in each matrix i represents an index of rows (where $i = 1,2,3,\ldots,K$), and j defines the number of the diagonal matrix. The following formula is used to compute the *MD* sequences for each diagonal matrix:

$$Si,jw = \begin{cases} (in+1-j), Jw = \text{even} \\ i \qquad for\ Jw = \text{old} \end{cases} \tag{6}$$

$$Si,1 = \begin{bmatrix} 1 \\ 2 \\ 3 \\ . \\ . \\ . \\ K \end{bmatrix}, Si,2 = \begin{bmatrix} K \\ . \\ . \\ . \\ 3 \\ 2 \\ 1 \end{bmatrix} \tag{7}$$

In *Si,j* matrices, each number is the position of one in *Ti,j* matrices where the matrices have dimensions with ($K \times K$). The *Ti,j* matrices can be obtained as follows:

$$Ti,j = [Si,j]_{K\times K}, Ti,2 = [Si,j]_{K\times K}, Ti,w = [Si,j]_{K\times K} \tag{8}$$

$$Ti,1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ . & . & . \\ 0 & 0 & 1 \end{bmatrix}_{K\times K}, Ti,2 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ . & . & . \\ 1 & 0 & 0 \end{bmatrix}_{K\times K} \tag{9}$$

The combination of diagonals matrices constructs the matrix of the *MD* code of power $K \times N$. In the matrix, each row composes a single code sequence.

$$MD = [Ti,1]: [Ti,2]_{K\times K} \tag{10}$$

In *MD* codes for three users, the unit code matrix for this code is defined as follows (as shown in Table 2):

$$MD(w=2) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix} \tag{11}$$

Table 2. Construction of the *MD* Encoder with *K*=3, *W*=2.

Wavelengths	User1	User2	User3
1548.4	1	0	0
1549.2	0	1	0
1550	0	0	1
1550.8	0	0	1
1551.6	0	1	0
1552.4	1	0	0

4. System Model

Figure 1 shows the block diagram of our proposed system. We simulated the system using opti-system software for design the system [28, 29] and MATLAB used to represent the results [30, 31]. As shown in Fig. 1, the system contains three components:

1. Transmitter.
2. The MMF.
3. Receiver.

The transmitter consists of the following components:

1. Spatial VCSEL.
2. Encoding,
3. PRBSG.
4. Modulator and NRZ pulse generator.
5. Power combiner.

On one hand, spatial VCSEL power is set to 1 dBm with different code weights. At 1.866 Gbps, a different set of modes is generated that operates over one wavelength of 1550 nm. As shown in Figs. 2 and 3, the modes are Laguerre-Gaussian modes: LG 0 1, LG 0 2, and LG 0 3, where LG modes are described mathematically as:

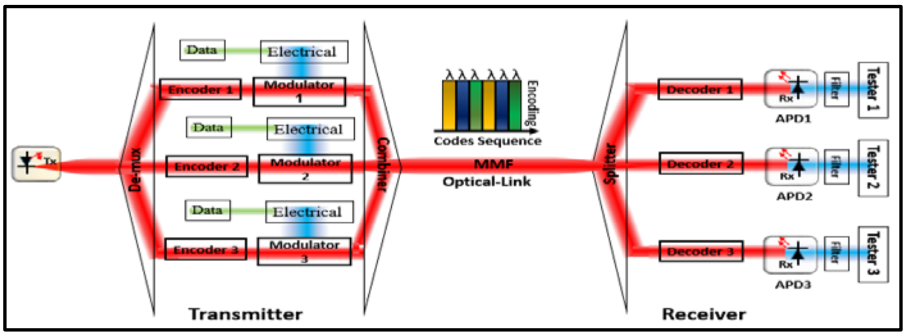

Fig. 1. Optical-CDMA over MMF system model.

Here we define $\psi n, m(r, \varphi)$ as follows:

$$\psi\, n, m(r, \varphi) = \left(\frac{2r^2}{W_0^2}\right)^{\left|\frac{n}{2}\right|} L_m^n\left(\frac{2r^2}{W_0^2}\right) exp\left(\frac{r^2}{W_0^2}\right) exp\left(j\frac{\pi r^2}{\lambda R_0^2}\right)\begin{Bmatrix} Sin(|n|\varphi), n \geq 0 \\ Cos(|n|\varphi), n \geq 0 \end{Bmatrix} \tag{12}$$

where $W_0$is spot size, R refers to the radius of curvature, and L (n, and m) is the Laguerre Polynomial. Whereas n and m represent Y (the radial index) and X (the azimuthal index) indexes, respectively.

On the other hand, a code is generated at the encoder by assigning the wavelengths. The wavelengths are chosen according to a unique code given to every user. According to given data and NRZ, Mach Zehnder Modulator (MZM) is used to modulate users' wavelengths. Then, each user's output will be combined and transmitted onto the fiber. In the design, the second part is optic fiber link (MMF): the attenuation is assigned as 0.25 dB-Km, the core radius is set to 50 nm with an 8 km maximum distance link. The last part of the design is the receiver, where the incoming signal from MMF splits by power splitter into three decoders and three users. After that, to perform a conversion from optical to electrical domain, we used Photo-detector (APD) and then, Low Pass Bessel Filter (LPBF). Finally, the analyser is the last component in the receiver paper.

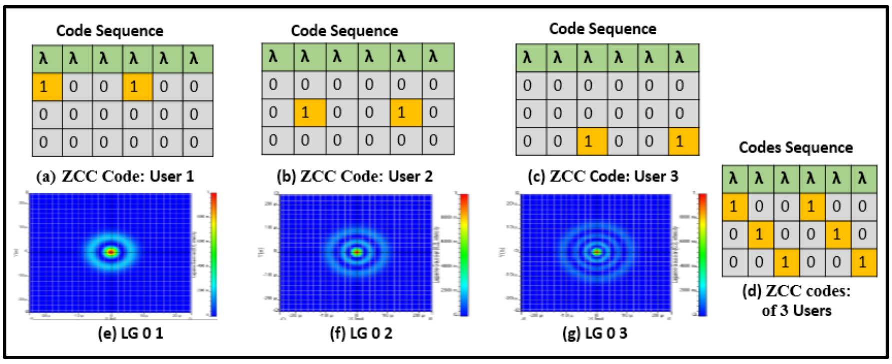

Fig. 2. Three Laguerre-Gaussian modes with 1D ZCC codes.

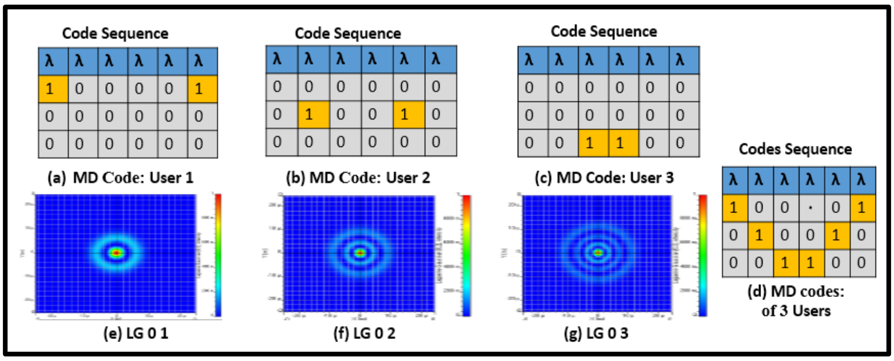

Fig. 3. Three Laguerre-Gaussian modes with 1D-MD codes.

5. Results and Discussion

In this section, we present and discuss the achieved outcomes from simulating our proposed system. The system is evaluated in terms of the achieved BER and Q-factor for each code at different MMF distances. The evaluation is depicted in Figs. 4 to 7. Then, the results of both codes are separately in Figs. 8 and 9, respectively.

BER and Q-factor of the 1D-ZCC codes over different MMF distances are shown in Figs. 4 and 5, respectively. In the simulation, the adopted distances are started from 2 km to 9 km. The figures demonstrate that the obtained results at distances 2 km to 8 km are accepted. Nevertheless, the outcomes in 9 km seem to be not good. Similarly, however, for 1D-MD codes, in Figs. 6 and 7, the system showed accepted results in both BER and Q-factor at the distances 2 km to 8 km. The findings of Q-factor and BER are (2.26E-07, 1.29E-07, and 7.75E-07) and (5.04445, 5.15033, and 4.80361), respectively. However, the results at 9 km were not accepted.

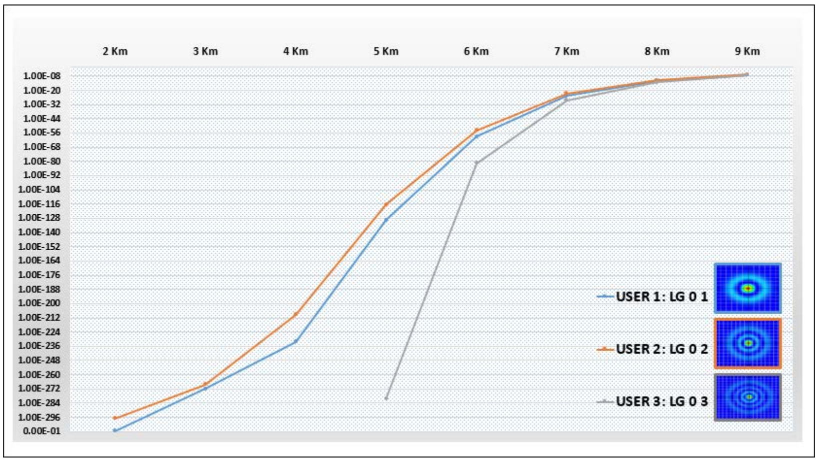

Fig. 4. BER results of three 1D-ZCC codes over different MMF distances.

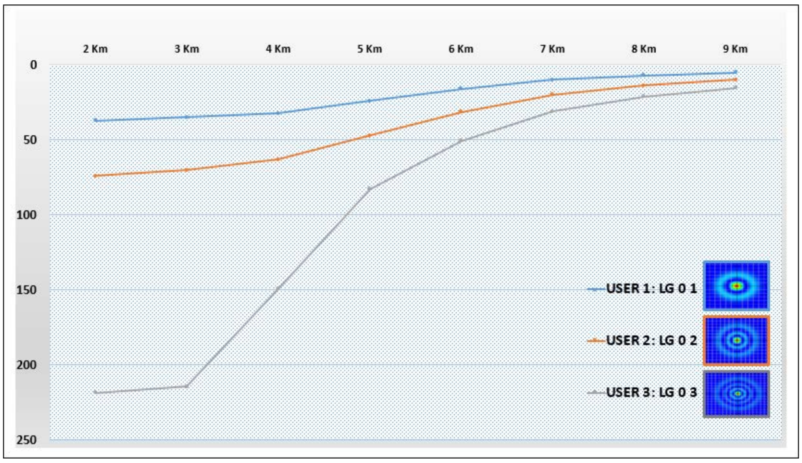

Fig. 5. Q-Factor results of three 1D-ZCC codes over different MMF distances.

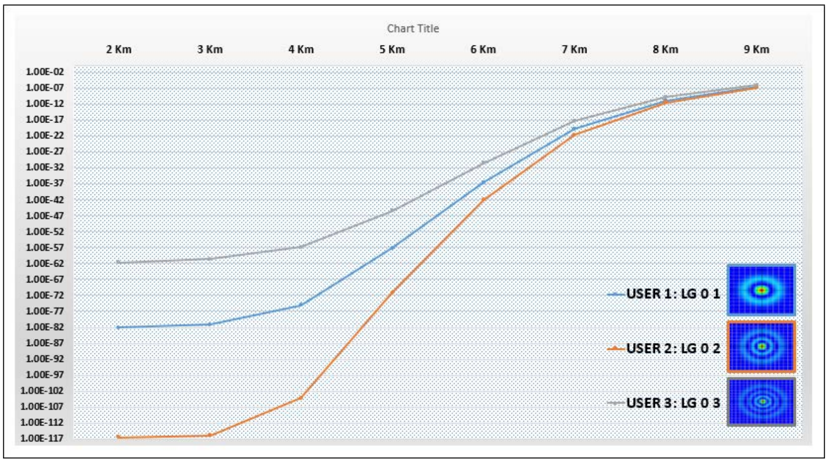

Fig. 6. BER results of three 1D-MD codes over different MMF distances.

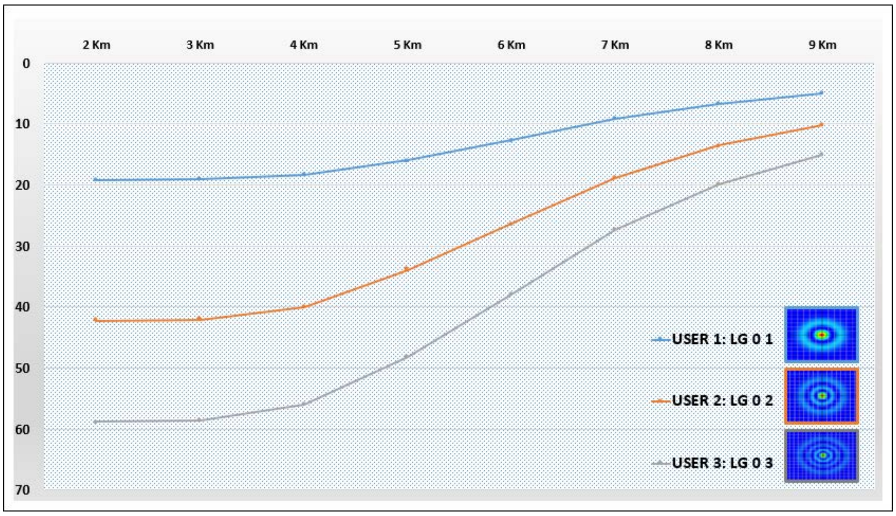

Fig. 7. Q-Factor results of three 1D-MD codes over different MMF distances.

In Figs. 8 and 9, comparison results of 1D-ZCC and 1D-MD codes are carried out in terms of obtained BER and Q-factor, respectively. Both figures demonstrate that 1D-ZCC codes give better results than 1D-MD codes in the Optical-CDMA system based on LG modes over MMF. Furthermore, at the 8 km distance, for both1D-MD and 1D-ZCC codes, the system is evaluated in terms of eye pattern as displayed on eye diagram visualizer for (LG 0 1: User 1, LG 0 2: User 2, and LG 0 3: User 3) (see Fig. 10). Additionally, all channels can be seen to have an open and clear eye. Additionally, the eye diagram results are better with using 1D-ZCC code compared to 1D-MD codes with an acceptable range of Q-factor and BER.

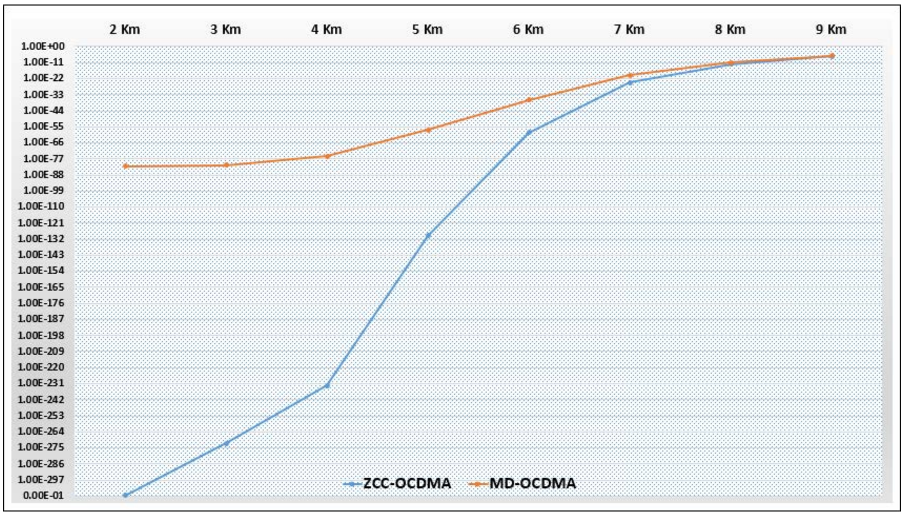

Fig. 8. BER results of 1D zero cross correlation and 1D multi diagonal codes over different MMF distances.

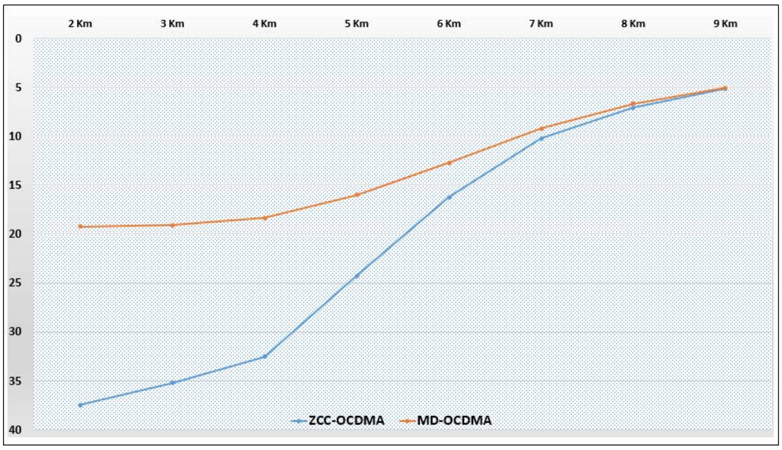

Fig. 9. Q-Factor results of 1D zero cross correlation and 1D multi diagonal codes over different MMF distances.

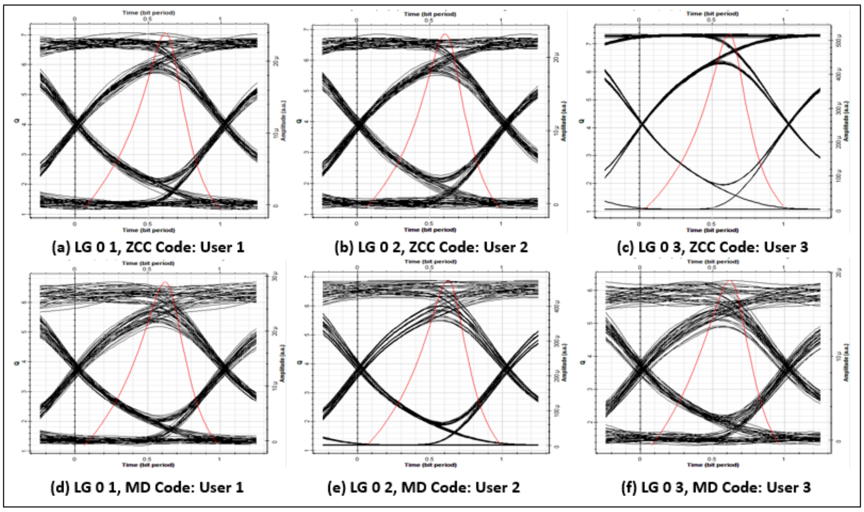

Fig. 10. Eye diagram for 1D-ZCC and 1D-MD codes at a distance 8 km.

6. Conclusion

In this study, a comparison of 1D-ZCC and 1D-MD codes for Optical-CDMA over MMF transmission that operate through wavelength 1550 nm. Different codes have been used as a data encoding with Laguerre-Gaussian modes in Optical-CDMA over MMF link. To get the lowest BER and Q-Factor and longest possible distance, the codes must be chosen carefully. Consequently, improving the capacity and security in a communication system. In comparison to 1D-MD codes, the simulation demented that the encoding of 1D-ZCC codes have better results than other codes. A successful transmission data has been obtained over 8 Km MMF with accepted eye diagrams, Q-factor and BER. Additionally, the outcomes were not accepted for 9 km because of the nonlinearity and distortion of MMF. We believe that Artificial Intelligence (AI) can help to tackle this issue since AI algorithms enable optical communication to transmission data over long distances.

Abbreviations	
1D	One-Dimensional
AI	Artificial Intelligence
BER	Bit Error Rate
LAN	Local-area network
LG	Laguerre-Gaussian
MAI	Multiple access interference
MD	Multi diagonal
MDM	Mode division multiplexing
MMF	Multi-mode fiber
NRZ	Non-Return-to-Zero
OFDMA	Orthogonal frequency-division multiple access
Optical-CDMA	Optical code division multiple access
Q-Factor	Quality Factor
SMF	Single-mode fiber
Spatial VCSEL	Spatial vertical-cavity surface-emitting laser
TDMA	Time-division multiple access
WDMA	Wavelength division multiple access
ZCC	Zero cross-correlation

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