Design and performance analysis of GPON-employed two-dimensional multidiagonal OCDMA code

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Abstract. Two-dimensional (2-D) spectral/spatial codes are utilized for optical code division multiple access (OCDMA)-based passive optical network (PON). In this work, 2-D multidiagonal (2D-MD) codes are used for the first time to the best of our knowledge in OCDMA-PON at data rates up to 15 Gbps. 2D-MD codes are very easy to construct and offer zero cross correlation. We showed a simpler implementation compared to similar published work. A complete PON system addressing downstream as well as upstream communication link is demonstrated at data rates up to 15 Gbps. Four downstream wavelengths (1546, 1546.3, 1547.8, and 1548.1 nm) and four upstream wavelengths (1310, 1310.3, 1311.8, and 1312.1 nm) are used to carry the modulated signal over single-mode fiber length of 25 km. The system performance is analyzed using bit error rate and *Q*-factor parameters for different data rates. *© 2020 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.59.7.076105]

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1 Introduction

The performance of optical code division multiple access (OCDMA) systems is primarily affected by the phase-induced intensity noise (PIIN) and multiple access interference (MAI).[1] OCDMA systems can be classified according to the coding scheme as one-dimensional (1-D) and hybrid codes. 1-D codes are further classified as temporal coding, spectral amplitude coding (SAC), and spatial coding. When two or more coding techniques are combined, it is called hybrid coding, as described in Ref. 1. In SAC, the spectral bandwidth is split and the light source is decomposed into individual wavelengths. In spatial coding, multifiber cables or multicore fibers are used to generate the spatial code patterns, where the optical pulses of each user is distributed spatially over the fibers. The 1-D codes provide good system performance. However, their main drawback is the need for long code lengths to accommodate a large number of users, hence large amount of bandwidth is needed. Two-dimensional (2-D) codes are proposed to resolve this issue. 2-D codes can be constructed by combining different 1-D codes such as spectral/time, spectral/spatial, and spatial/time domains. The main focus of this work is to utilize spectral/spatial 2-D codes in OCDMA passive optical networks (PONs).

Yang et al.'s work was based on spatial/spectral codes, namely 2-D maximal-area matrices (M-matrices) as given in Ref. 2. These codes are designed using 1-D M-sequences. Lin et al.[3] developed a 2-D spatial/spectral code family with MAI cancellation property for suppressing the PIIN and improving the noncoherent OCDMA system performance. The code family used here is called 2-D perfect difference (2D-PD) code, which is constructed based on 1D-PD codes. Yang et al.[4] developed 2-D spectral/spatial code based on modified quadratic congruence (MQC) code

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and M-sequence code. Tunable fiber Bragg gratings and optical splitters/combiners are used in the implementation of this code.

Receiver noise sources such as shot noise, PIIN, and thermal noise are typically taken into consideration in analyzing the implementation of any code. Yang et al.[4] performed a comparison of MQC-based code with M-matrix codes. They confirmed that the MQC-based code can support larger number of simultaneous users. A new 2-D spectral/spatial code called 2-D diluted perfect difference (2D-DPD) code, based on the 1D-PD code and the dilution method is presented in Ref. 5. In Ref. 6, a new 2-D codes family, known as 2-D multidiagonal (2D-MD) codes, is proposed and constructed at 1 and 2 Gbps, which is based on the 1D-MD code described in Ref. 7. The proposed 2D-MD code has zero cross correlation. Therefore, the MAI is fully eliminated and the PIIN is suppressed significantly. The performance of 2D-MD code is compared with 1D-MD code, 2D-PD code, and 2D-DPD code. It was concluded that 2D-MD code offers better performance compared to other codes. The analytical and the simulation results revealed that the proposed 2D-MD code outperforms other codes because of its versatility. In Ref. 8, 2D single-weight zero cross correlation (2D-SWZCC) code is proposed which is developed to be implemented in noncoherent OCDMA system. This code is based on 1D-SWZCC code, given in Ref. 9. A single-weight code is characterized by zero cross correlation and a high number of users. Numerical simulation results of this code showed that the code enhances the system capabilities by increasing its supported data rate; thus enhancing its capacity and reducing the system required signal-to-noise ratio. The simulated system has four users each with −10 dBm power and data rate of 1 Gbps. Tseng et al.[10] proposed an extended M-sequence/extended perfect difference code family for 2-D spectral/spatial OCDMA PON. A new 2-D hybrid code 2D-ZCC/MD for spectral/spatial OCDMA system is proposed in Ref. 11. This code has been evaluated for 622-Mbps OCDMA system and its performance is compared with 1D-RD and 1D-MDW codes. The authors had showed that the 2D ZCC/MD code family accommodates large number of users at high data rate. Imtiaz et al.[12] proposed a 2-D enhanced multidiagonal (2D-EMD) code used for OCDMA-PON. The 2D-EMD code is analyzed and compared with other codes and shown it is able to support next generation PONs at 622 Mbps and 1 Gbps. In Ref. 13, 2-D wavelength/time encoding code for minimizing MAI was proposed. The proposed code uses 2D-MDPHC at 1.25 Gbps. In Ref. 14, new algorithm to generate 2-D fixed right shifting (2D-FRS) code sequences was proposed based on spectral/spatial incoherent OCDMA system. In Ref. 15, new technique for generation 2-D optical zero-correlation zone (ZCZ) sequence with ZCZ was proposed.

The majority of published work proposed new algorithms to increase the cardinality of a basic OCDMA system at data rates up to 1.25 Gbps. The purpose of this work is to achieve large number of users based on SAC-OCDMA architecture with 2D-MD codes for gigabit pasive optical network applications operating at higher data rates. A 2D-MD code is constructed using 1D-MD code combined with spatial coding to create the second dimension. This 2D-MD code is used in PON system. The PON system contains an optical line terminal (OLT) unit, backbone optical fibers, remote node (RN), and optical network units (ONUs). The system supports six users with 15 Gbps/user in a bidirectional PON implemented using 25-km single-mode fiber (SMF) length.

The remainder of this paper are organized as follows. In Sec. 2, the 2D-MD code is discussed. Section 3 presents the proposed system architecture and the description of spectral/spatial transmitter and receiver modules. It also describes the structure of ONUs for both the upstream and downstream communication links. Section 4 illustrates the performance analysis of the system in terms of BER, Q-factor, and eye diagrams. Section 5 presents the conclusions.

2 Two-Dimensional Multidiagonal Code

The 2D-MD code is described in Ref. 6, in which the authors had constructed the 2-D code using 1D-MD codes shown in Ref. 7. The main reason of choosing the 2D-MD code is its capability of cancelling MAI completely because it has zero cross-correlation feature. Also it is very simple to construct. Regardless of size of weight the code has, it requires only one wavelength to be detected at the decoder, hence it requires less hardware to construct compared to other codes. Table 1 from Ref. 12 provides a comparison among different codes, which gives a strong evidence of the superiority of MD codes.

Table 1 List of different OCDMA codes with their performance parameters.[12]

Codes	K	W	Code length	N	Cross-talk	λ_c	Implementation
MD	30	3	$K \times w$	90	None	0	Simple
RD	30	3	$K + 2w - 3$	33	Maximum	≥1	Moderate
EMD	30	3	$K + [K(w-2) + 1]$	61	Adjacent	1	Simple
DCS	30	3	K	30	Maximum	≥1	Moderate
DW	30	2	$\frac{3K}{2} + \frac{1}{2}\left[\sin \frac{K\pi}{2}\right]^2$	45	Adjacent	1	Complex
EDW	30	3	$2 \times K$	60	Adjacent	1	Complex
DDW	30	2	$K + 1$	31	Adjacent	1	Simple
DEU	30	4	$K(w-1) + 1$	91	Adjacent	1	Simple

The 2D-MD code is characterized by the following parameters (N, w, and λ_c), where N is the code length (number of total chips), w is the code weight (chips that have a value of 1), and λ_c is the in-phase cross correlation. For the code sequences $X = \{x_1, x_2, x_3, \dots, x_n\}$ and $Y = \{y_1, y_2, y_3, \dots, y_n\}$, the cross-correlation function can be represented by

$$\lambda_c = \sum_{i=1}^{N} x_i y_i. \tag{1}$$

When $\lambda_c = 0$, the code possesses zero cross-correlation properties. The MD code consists of a $K \times N$ matrix functionally depending on the value of the number of users (K) and code weight (w). The choice of the weight value is unrestricted and $N = K \times w$.

The combination of the diagonal matrices is used for the 1D-MD codes construction as a matrix of dimension $K \times N$, where each row in the matrix represents a single-code sequence:

$$\mathrm{MD} = \begin{bmatrix} T_{i,1} & \vdots & T_{i,2} & \vdots & \dots & \dots & \vdots & T_{i,w} \end{bmatrix}_{K\times N}, \tag{2}$$

$$\mathrm{MD} = \begin{bmatrix} d_{1,1} & d_{1,2} & \cdots & d_{1,N} \\ d_{2,1} & d_{2,2} & \cdots & d_{2,N} \\ d_{3,1} & d_{3,2} & \cdots & d_{3,N} \\ \vdots & \vdots & \dots & \vdots \\ d_{k,1} & d_{K,2} & \cdots & d_{K,N} \end{bmatrix}_{K\times N}. \tag{3}$$

Table 2 1D-MD code with ($K = 6$ and $w = 3$).

i	Code sequence
1	1 0 0 0 0 0 0 0 0 0 0 1 1 0 0 0 0 0
2	0 1 0 0 0 0 0 0 0 0 1 0 0 1 0 0 0 0
3	0 0 1 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0
4	0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 1 0 0
5	0 0 0 0 1 0 0 1 0 0 0 0 0 0 0 0 1 0
6	0 0 0 0 0 1 1 0 0 0 0 0 0 0 0 0 0 1

Table 3 2D-MD code with ($w_1 = 2$, $k_1 = 4$, $w_2 = 2$, and $k_2 = 3$).

	$X_0 = [1\ 0\ 0\ 0\ 0\ 0\ 0\ 1]$	$X_1 = [0\ 1\ 0\ 0\ 0\ 0\ 1\ 0]$	$X_2 = [0\ 0\ 1\ 0\ 0\ 1\ 0\ 0]$	$X_3 = [0\ 0\ 0\ 1\ 1\ 0\ 0\ 0]$
$Y_0^T = \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$	$\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \end{bmatrix}$
$Y_1^T = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$
$Y_2^T = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$	$\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$

An example of the 1D-MD code family with $K = 6$ and $w = 3$ is presented in Table 2. The 2D-MD codes are extended from 1D-MD codes and constructed using two code sequences of the 1D-MD codes.

Let $X = \{x_0, x_1, x_2, \dots, x_{M-1}\}$ with code weight w_1 and $Y = \{y_0, y_1, y_2, \dots, y_{P-1}\}$ with the code weight w_2, represent two 1D-MD codes, which have the code sizes k_1 and k_2, respectively. So the code lengths of X and Y are $M = k_1 w_1$ and $P = k_2 w_2$, respectively. The code size of the 2D-MD is $K = k_1 k_2$. Let X_g and Y_h are the g'th and h'th code sequence of X and Y, respectively. The indices $g = 0, 1, \dots, k_1 - 1$ and $h = 0, 1, \dots, k_2 - 1$ represent the spectral and spatial codes sequence, respectively. The 2D-MD code can be expressed as $A_{g,h} = Y_h^{\mathrm{T}} X_g$. Let $a_{i,j}$ represent the elements of $A_{g,h}$, where $i = 0,1, \dots, P - 1$ and $j = 0,1, \dots, M - 1$. Then $A_{g,h}$ can be expressed as in Eq. (4). An example of the 2D-MD code sequences for ($w_1 = 2$, $k_1 = 4$, $w_2 = 2$, and $k_2 = 3$) is presented in Table 3:

$$A_{g,h} = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,M-1} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,M-1} \\ a_{2,0} & a_{2,1} & \cdots & a_{2,M-1} \\ \vdots & \vdots & \cdots & \vdots \\ a_{P-1,0} & a_{P-1,1} & \cdots & a_{P-1,M-1} \end{bmatrix}. \tag{4}$$

The cross correlation of $A_{0,0}^0$ and $A_{g,h}$ can be expressed as follows:

$$R^{(0)}(g,h) = \sum_{i=0}^{P-1} \sum_{j=0}^{M-1} a_{i,j}^{(0)} . a_{i,j}(g,h) = \begin{cases} w_1 w_2, & \text{for } g = 0,\ h = 0, \\ 0, & \text{otherwise.} \end{cases} \tag{5}$$

3 System Architecture of Proposed 2D-MD Code-based OCDMA PON

Figure 1 illustrates the architecture of 2D-MD code-based OCDMA PON system. The proposed architecture supports six users system. The system architecture is divided into four sections: the OLT, the backbone optical fibers, the RN, and the ONUs. The architecture supports a full duplex system. It addresses two-way communication between the service provider (OLT) and the users (ONUs); downstream as well as upstream communication. The OLT is mainly at the central office and the ONUs are at the customer premises. In a 2-D code-based OCDMA PON, the RN consists of X-couplers and optical combiners/splitters that deal with the decoding/encoding of spatial code. The spectral code is decoded/encoded inside the ONU and OLT, respectively. The number of transmitters (TX) and receivers (RX) modules depends on $K_1 \times K_2$. Each TX/RX pair has its own 2D-MD codeword $A_{g,h}$.

3.1 *Transmitter Module*

For downstream communication, the transmitter resides in the OLT, which is located at the central office, whereas for upstream communication the transmitter is placed inside every ONU, which is located at the customer premises. The 2-D encoding is a two-fold process: spectral coding and spatial coding. In spectral encoding, the binary 1's in X'th code sequence is converted into spectral representation. The transmitter module consists of continuous wave (CW) light sources, a wavelength division multiplexer, a nonreturn to zero (NRZ) pulse generator, and a Mack–Zander modulator (MZM) as shown in Fig. 1. The simulation-based structure of the transmitter module is shown in Fig. 2, where the wavelength of the CW laser represents a specific subscriber. Note that the number of CW lasers depends on the weight of the X code sequence (w_1) given in Table 3. CW lasers are used here instead of broadband sources because they give better performance in terms of bit error rate (BER) and support longer reach. The CW lasers are multiplexed and modulated using a pseudorandom bit sequence generator (PRBS) in the MZM. NRZ pulses are used to carry the data of the PRBS. The output of MZM is connected with power

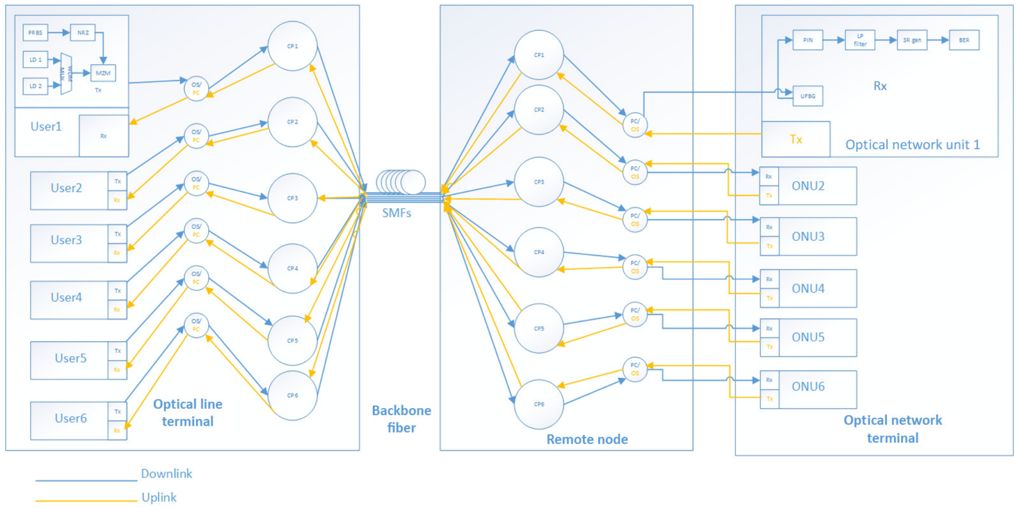

Fig. 1 Proposed system architecture of 2D-MD code-based OCDMA PON.

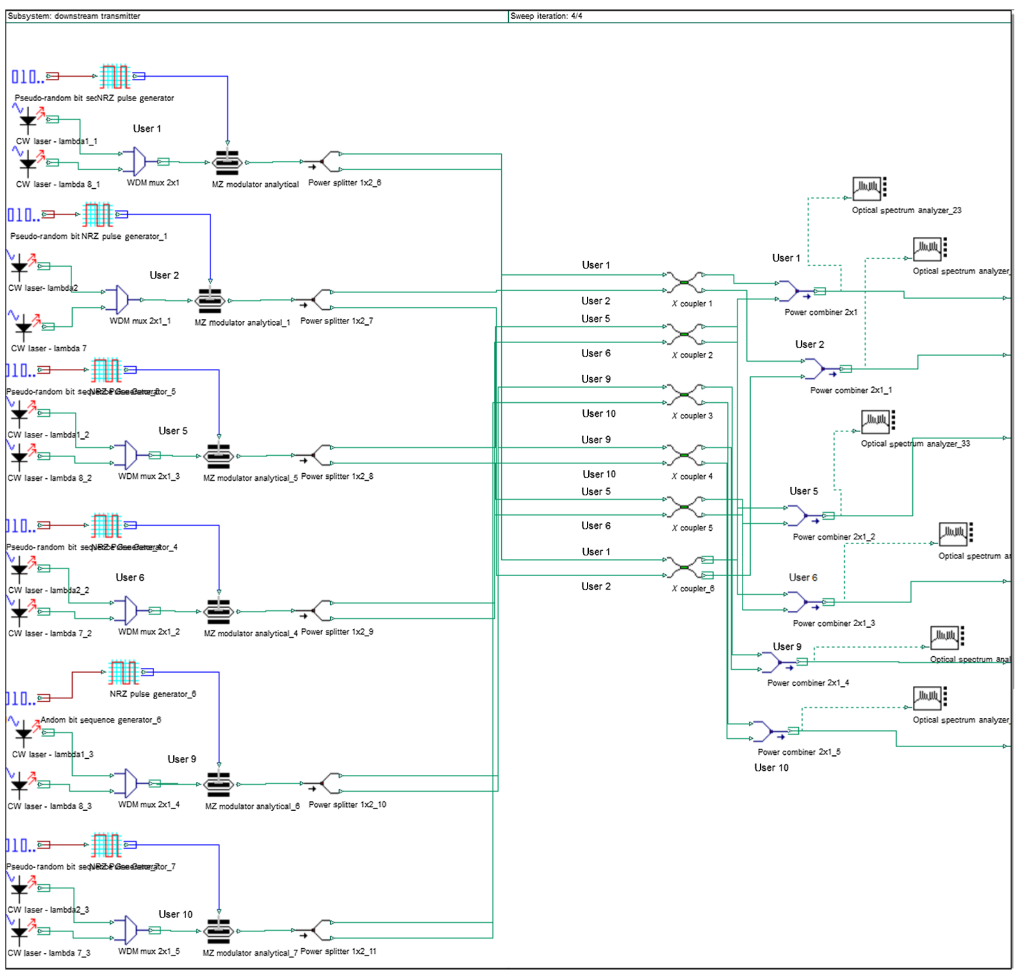

Fig. 2 Transmitter design with spectral plus spatial coding.

splitters that split the signal into w_2 portions to create the spectral coding, where w_2 is the weight of the Y code sequence.

The spatial encoding is performed using the splitters and x-couplers. The number of x-couplers equals the length of the Y'th code sequence. Selection of the x-couplers for each user is based on the 2-D code for that user. When the Y'th code is 1, the spectral code is sent from the respective coupler as described in Table 3 for user1 as an example, where the used wavelengths λ_1 and λ_8 are passed through coupler CP1 and CP6. User 1 data are then sent to the power combiners as shown in Fig. 2. Each power combiner represents individual user data, which is then fed to the SMF. Note that in spatial coding multiple SMFs are used. The quantity of SMF cables depends upon the length of the 2-D code. Hence, a six user PON system will have six single mode fibers.

3.2 *Receiver Module*

For downstream communication, the receiver resides inside the customer premises (ONU); whereas for the upstream communication, the receiver is located at the OLT. The decoding process is composed of two operations: (i) spatial decoding and (ii) spectral decoding. The decoding

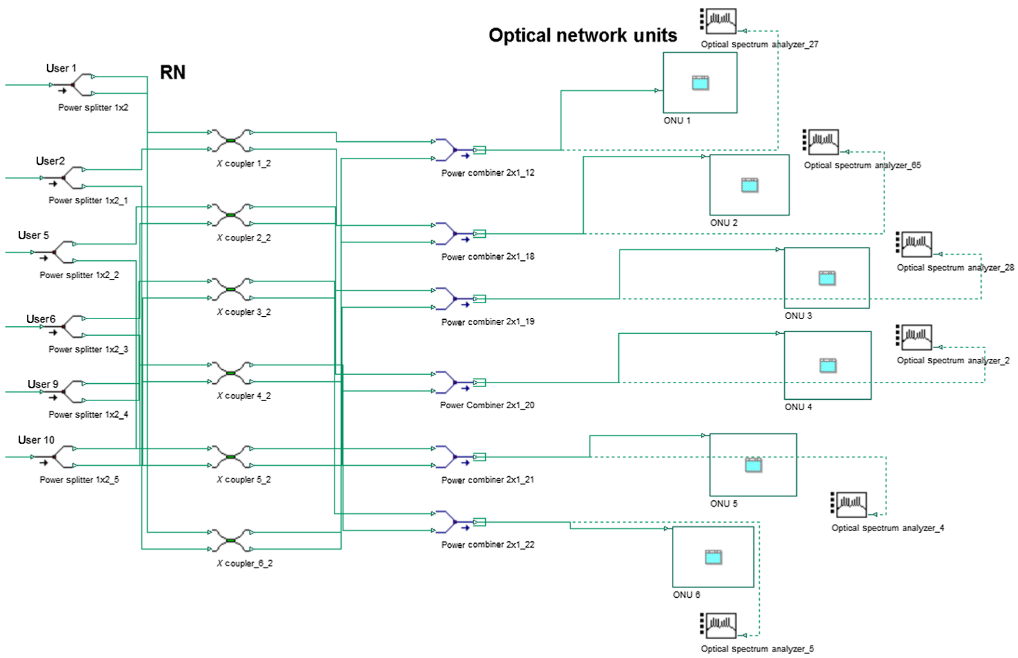

Fig. 3 RN design for 2D-MD code-based OCDMA PON.

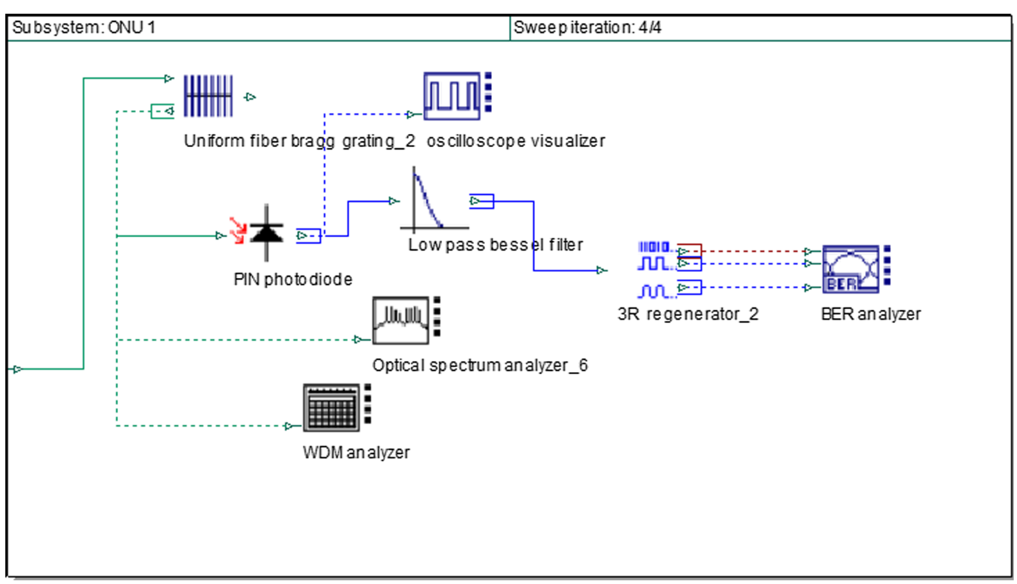

Fig. 4 Receiver design for 2D-MD code-based OCDMA PON.

process starts at the RN, where spatial decoding is performed using the couplers. The decoding process is just opposite to the encoding process, therefore, the connectivity to the couplers will be the exact same as in the encoder. As shown in Fig. 3, the SMFs outputs are connected to the splitters to split the user data into the x-couplers to achieve spatial decoding. For example, the outputs of coupler CP1 and CP6 will then be combined using power combiner and sent to its respective end user, in this case ONU1.

Spectral code is decoded using uniform fiber Bragg grating (UFBG). Every receiver module consists of a single UFBG, a PIN photodiode, an LP filter, a 3R generator, and a BER analyzer. As MD codes have zero cross correlation, detection of any wavelength for each user data is sufficient to decode the spectral code, hence, only one UFBG is required. The structure of receiver module is shown in Fig. 4. The reflected wavelength from the UFBG is then passed to a PIN photodetector, which converts the light signal to electrical signal. Then the output signal is filtered and connected to a 3R regenerator for recovering the data, which is analyzed in the BER analyzer.

Table 4 Simulation parameters.

Parameters	Values
Data rate	622 Mbps, 1 Gbps, 2.5 Gbps, 5 Gbps, 10 Gbps, 12 Gbps, and 15 Gbps
Backbone fiber length	25 km
Attenuation	0.22 dB/km for downstream and 0.5 dB/km for upstream
Dispersion	16.75 ps/nm/km
CW laser input power	5 dBm
Wavelength	1546 nm (downstream) 1310 (upstream) with 0.3 nm spacing
Spreading code	2D-MD code
Number of ONUs	06
Nonlinear properties	Enabled
Dark current	2 nA
Thermal noise	1.8×10^{-23} W/Hz
Responsivity	1 A/W

Table 5 BER and Q factor at various data rates.

	Downstream link		Upstream link	
Date rate	Bit error rate	Quality factor	Bit error rate	Quality factor
622 Mbps	0	493.585	0	120.639
1 Gbps	0	439.986	0	97.0651
2.5 Gbps	4.74274×10^{-38}	12.8424	1.70827×10^{-37}	12.7427
5 Gbps	5.74762×10^{-34}	12.0928	3.82374×10^{-23}	9.8378
10 Gbps	3.03785×10^{-22}	9.6255	7.94812×10^{-20}	9.0366
12 Gbps	1.82052×10^{-20}	9.19525	3.88089×10^{-13}	7.15583
15 Gbps	4.4139×10^{-12}	6.82113	4.88543×10^{-9}	5.73177

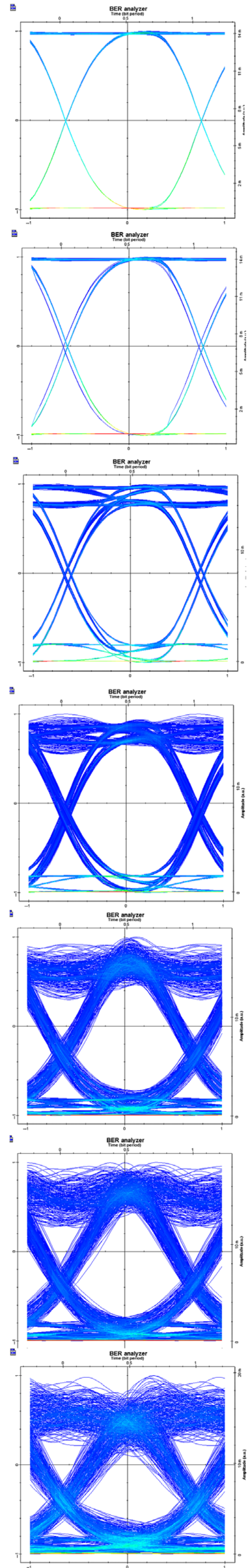

Fig. 5 Eye diagrams at (a) 622 Mbps/user, (b) 1 Gbps/user, (c) 2.5 Gbps/user, (d) 5 Gbps/user, (e) 10 Gbps/user, (f) 12 Gbps, and (g) 15 Gbps.

4 Simulation Results and Discussion

A commercial software has been used to simulate the 2D-MD-based OCDMA PON. The proposed architecture shown in Fig. 1 for six users and 2D-MD codes given in Table 3 is simulated and analyzed for different data rates per user. Users 1, 2, 5, 6, 9, and 10 are being simulated. The parameters used in the proposed design are summarized in Table 4. Four downstream wavelengths in the C-band in the range of 1546 to 1548.1 nm and four upstream wavelengths in the O-band in the range of 1310 to 1312.1 nm are used in the system with 0.3 nm spacing. Although the simulation is done for six users, it can be easily extended to more users. A 25-km standard single-mode optical fiber is used in downlink and uplink with attenuation of 0.22 and 0.5 dB/km, respectively, and constant dispersion of 16.75 ps/nm/km in the C-band is used. Table 5 illustrates the BER performance and quality factor (Q) of the downstream and upstream links at different data rates. It is clear that due to using 2-D codes, the performance of PON has improved significantly, such that it can support very high data rate. The downlink BER and Q factor for 15 Gbps/user (90 Gbps downlink and 90 Gbps uplink; 180 Gbps system) are 4.4139×10^{-12} and 7, respectively. Whereas the BER is 4.88543×10^{-9}, the Q factor is 5.73 for the uplink communication.

Figure 5 shows the eye diagrams at the output of the receiver modules of the proposed system for various data rates per user. The achieved BER and Q factor for the different data rates per user for downstream and upstream link are shown in Figs. 6 and 7, respectively. It is clear that the performance of the proposed system is satisfactory. It can support high data rates per user over long distances, and the cardinality of the system has also increased significantly, which can be seen by the fact that the 2-D code reuses the same wavelength for multiple users as compared to the 1-D codes where a set of individual wavelengths for each user is required. This provides a firm ground for using 2D-MD codes in OCDMA PONs.

The effect of the link length on the performance of the proposed system at 5-Gbps data rate is summarized in Table 6. Figure 8 shows the BER performance of the system for the upstream and downstream links at 5 Gbps. Satisfactory BER of 5.60203×10^{-24} for downlink and 1.82802×10^{-11} for uplink are achieved till 40-km distance while utilizing 2D-OCDMA code (2D-MD code). It can be observed that performance of the proposed PON system is reliable at long distances too.

Referring to the previous similar work done in Ref. 12, Table 7 points out the significant contribution and differences in this work. It must be noted that the design of this work is much simpler in construction as it requires less number of components then those given in Ref. 12. Another significance is the data rate, which is up to 15 Gbps/user, whereas maximum data rate in Ref. 12 is 1 Gbps.

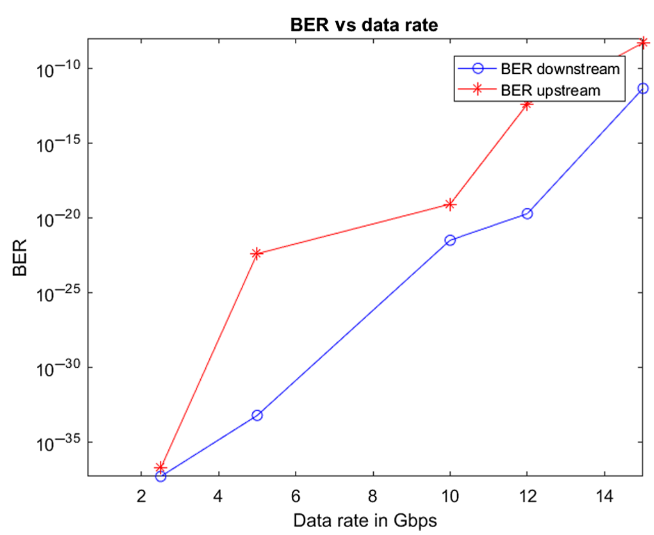

Fig. 6 BER versus data rate per user.

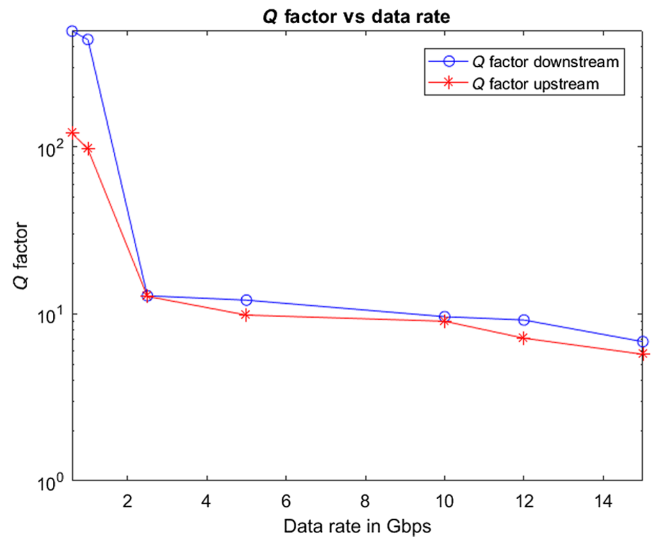

Fig. 7 *Q*-factor versus data rate per user.

Table 6 BER and *Q* factor for different link lengths at 5 Gbps data rate.

	Downstream link		Upstream link	
Distance	Bit error rate	Quality factor	Bit error rate	Quality factor
10 km	1.98234×10^{-37}	12.7311	6.13461×10^{-36}	12.4603
20 km	1.99714×10^{-36}	12.5496	9.21267×10^{-31}	11.4709
30 km	9.73347×10^{-29}	11.0605	6.71738×10^{-28}	10.8858
40 km	5.60203×10^{-24}	10.0304	1.82802×10^{-11}	6.61693

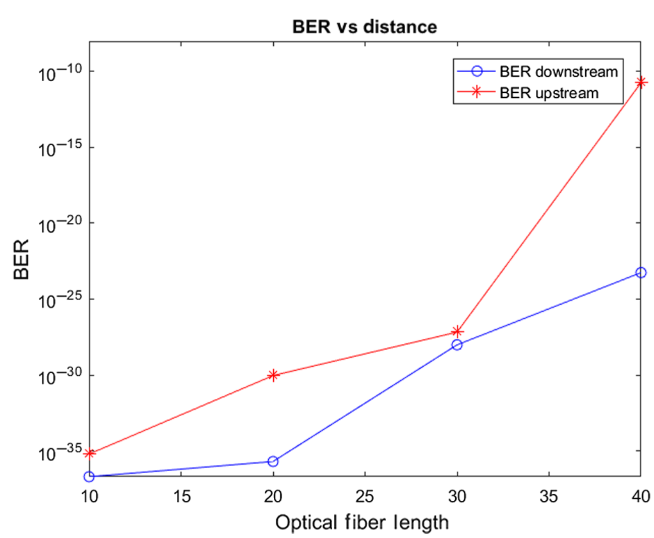

Fig. 8 BER versus distance at 5 Gbps.

Table 7 Comparison of proposed design with similar work done in Ref. 12

Ref. 12	This work
2D-EMD code	2D-MD code
LED 20 nm	LASER 5-dBm power
SMF fiber 25 km	SMF fiber 25 km
Data rate 622 Mbps and 1 Gbps	Data rate from 622 Mbps up to 15 Gbps
Transmitter requires two fiber Bragg gratings	Transmitter requires no fiber Bragg grating
Complex structure, two balanced detectors are required, each having four fiber Bragg gratings	Very simple structure, only one fiber Bragg grating is required

5 Conclusions

A 2D-MD code is used for an OCDMA-based PON. The 2D-MD code is chosen because it is simple, flexible, and easy to implement. It has zero cross correlation, which completely eliminates MAI. The performance of a duplex OCDMA PON that uses 2D-MD code is evaluated at various data rates per user. The performance is quantified via BER, Q factor, and eye diagrams. It is shown that an OCDMA PON that uses a 2D-MD code can support up to 15 Gbps/user over 25 km of SMF distance. The downlink BER and Q factor for 15 Gbps/user (90-Gbps downlink and 90-Gbps uplink; 180-Gbps system) is 4.4139×10^{-12} and 7, respectively, whereas the BER is 4.88543×10^{-9} and the Q factor is 5.73 for the uplink communication. Satisfactory BER of 5.60203×10^{-24} for downlink and 1.82802×10^{-11} for uplink are achieved till 40-km distance at 5 Gbps while utilizing 2D-OCDMA code (2D MD code).

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