A New Spectral Code Allocation Design for Optical Multiple Access CDMA Networks to Cancel Multiple Access Interference (MAI)

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Abstract - The key objective of the spectral amplitude coding-optical code division multiple access (SAC-OCDMA) system is to maximize transmission capacity while lowering phase-induced intensity noise (PIIN). In this paper, a distinctive one-dimensional spectral flexible weight (1D-SFW) coding for non-coherent systems is given. The SFW is meant to overcome the limitations of one-dimensional codes such as multiple access interferences (MAI) and PIIN noise, as well as boost system capacity and support a high data rate. In terms of bit error rate (BER) and signal-to-noise ratio (SNR), the proposed code (1D-SFW) outperforms existing one-dimensional codes such as diagonal eigenvalue unity (DEU), flexible cross-correlation (FCC), multi-service (MS), and Fixed Right Shift (FRS) codes. The suggested code can enable a massive capacity that reaches 134 users with 2.7 Gbps of bit rate at a tolerable BER of 10^{-9}.

Keywords – BER, OCDMA, PIIN, SFW, SNR.

I. INTRODUCTION

Multiple access systems, such as Wavelength Division Multiple Access (WDMA), Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA), and Code Division Multiple Access (CDMA), have become indispensable approaches in most optical systems in recent years [1]. TDMA, WDMA, and FDMA enable multiple users to access the same channel at the same time by allocating a time slot, wavelength, or frequency to each user, respectively. Nonetheless, the fundamental drawbacks of these technologies include limited bandwidth for each user as the number of concurrent users increases [2,3]. Furthermore, the CDMA approach has become extensively used in optical communications networks to access the same channel and broadcast the data simultaneously without requiring a designated time slot or wavelength for each user [4]. The optical CDMA (OCDMA) multiplexing technique assigns each user a unique signature during transmission, providing good exploitation of bandwidth [5].

In OCDMA systems, multiple access interference (MAI) is primarily seen as a reason for system performance degradation when system capacity (the number of users) increases. For that, the MAI can be defined as the interferences that exist between chips of wavelengths that have the same location in the optical bandwidth, leading to phase-induced intensity noise (PIIN) at the receiver [5]. To prevent these constraints, a good selection of codes with high orthogonality is one of the critical stages in determining overall system performance. This technical word (orthogonality) is known as the zero cross-correlation (ZCC) property.

Spectral amplitude coding (SAC) is the most adopted encoding scheme in OCDMA due to the fact it provides an efficient solution for completely eliminating MAI and PIIN by applying codes with fixed in-phase cross-correlations. Various one-dimensional codes have been reported. In [6], new encoding for OCDMA systems has been examined. In [7] , Diagonal Eigenvalue Unity (DEU) code has been suggested for SAC-OCDMA. In [8], the Modified Double-Weight (MDW) Code is designed to support high capacity. In [9], a new code family for OCDMA named multi-service has been developed. In [10], Dynamic Cyclic Shift (DCS) code has been investigated to reduce PIIN noise. In [11], flexible cross-correlation (FCC) code has been proposed to minimize the MAI effect. In [12], a novel algorithm to build code sequences based using SAC encoding is constructed to reduce MAI and PIIN noise at the receiver level. All of these codes have substantial PIIN noise and necessitate the use of two photodetectors (2-PDs) at the receiver to extract the desired information, increasing the network's complexity.

The spectral flexible weight code (SFW) was established in this study for enhancing the optical efficiency of an incoherent SAC-OCDMA system. The designed code eliminates all PIIN noise and ignores MAI interferences. Further, when compared to earlier codes, the SFW code has a simple construction, adopts a flexible number of users and weights, supports a high bit rate, and employs direct detection using a single photodetector at the receiver due to the ZCC feature.

The rest of this work is organized as follows: the second section details the construction of a new one-dimensional spectral 1D-SFW code, the third section is devoted to discussion about 1D-SFW-OCDMA system, the fourth section provides a mathematical analysis in terms of SNR, BER, and error vector magnitude (EVM) expressions, and the fifth section discusses the performance of our proposed approach. Finally, in the sixth section, the conclusion relating to the effectiveness of our code is stated.

II. SFW CODE DESIGN

A) One dimensional code

The spectral flexible weight (SFW) code is formed by joining three parameters (L, W, K), where "L" represents the spectral length of each sequence, "W" represents the number of "1" in each sequence (code weight), and "K" represents the number of users (number of codes). Hence, the stages of its construction are listed below:

1. Choose the number of users and the code weight (K, W).
2. Generate two matrices: even weight diagonal matrix (EWDM) and odd weight anti diagonal matrix (OWAM), where EWDM and OWAM are presented as follows:

$$EWDM = \begin{bmatrix} \overbrace{1 \dots 1}^{W\ even} & 0 & 0 \\ 0 & 1 \dots 1 & \vdots \\ \vdots & \vdots & 0 \\ 0 & 0 & 1 \dots 1 \end{bmatrix}_{K \times WK} \tag{1}$$

$$OWAM = \begin{bmatrix} \overbrace{0}^{C_1} & \overbrace{0}^{C_i} & \overbrace{1}^{C_K} \\ 0 & \iddots & 0 \\ \underbrace{1}_{W\ odd} & 0 & 0 \end{bmatrix}_{K \times K} \qquad i = 1,2, \dots ., K \tag{2}$$

3. When the weight is odd, perform the superposition of the two matrices as follows:

$$SFW_{W(Odd)} = \begin{bmatrix} 1 & \overbrace{0}^{C_1} & 1 & 0 & \overbrace{0}^{C_2} & 0 & \cdots & \overbrace{1}^{C_K} & 0 \\ 0 & \vdots & 0 & 1 & \vdots & 1 & \cdots & 0 & \vdots \\ \vdots & \vdots & \vdots & 0 & 0 & 0 & \cdots & \vdots & \vdots \\ \vdots & 0 & \vdots & \vdots & 1 & \vdots & \cdots & \vdots & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & \cdots & 0 & 1 \end{bmatrix} \tag{3}$$

4. When the weight is even, only EWDM is used as follows:

$$SFW_{W(Even)} = \begin{bmatrix} \overbrace{1 \dots 1}^{W} & 0 & 0 \\ 0 & 1 \dots 1 & \vdots \\ \vdots & \vdots & 0 \\ 0 & 0 & 1 \dots 1 \end{bmatrix}_{K \times WK} \tag{4}$$

5. Using the following formulae, determine the length of the SFW code and its auto/cross correlation property:

$$\begin{cases} L = K \times W \\ \sum_{i=1}^{K} C_i C_j = \begin{cases} \lambda_a = W & if \quad i = j \\ \lambda_c = 0 & if \quad i \neq j \end{cases} \end{cases} \quad (5)$$

Here λ_a and λ_c are autocorrelation and cross correlation, respectively. C_i, C_j are two sequences of SFW code. Table I gives an example of a one-dimensional SFW code (1D-SFW) for K=3 and W=2 and 3, respectively.

TABLE 1. 1D-SFW SPECTRAL CODE FOR 3 USERS.

	Even weight (K=3, W=2)
1D-SFW code	$\begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}$
	Odd weight (K=3, W=3)
1D-SFW code	$\begin{bmatrix} 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix}$

III. 2D-SFW-OCDMA MODEL

The schematic architecture of the spectral OCDMA model that employs SFW code through an optical channel is depicted in Fig. 1. The electrical signal of each user is modulated and converted into an optical signal thanks to an external modulator MZM (Mach-Zehnder modulator) using an optical source. Secondly, the resulting optical signals are sent to a one-dimensional OCDMA encoder to implement the spectral coding, wherein the optical signals are connected with a W-FBGs type spectral coder (fiber Bragg grating) to form the one-dimensional spectral coding according to the spectral sequence of SFW code as clarified in Fig. (1.a), in this point, the data is spectrally encoded according to the optical SFW code. Finally, the optical signals of all users are multiplexed into a composite optical signal and sent to the optical channel.

In the receiver part, the inverse operations of the transmitter are applied as shown in Fig. (1.b). Firstly, the arrived pulse is attached by FBGs to implement spectral decoding by following the spectral SFW code sequence, in this case, the pulses are decoded spectrally. Secondly, the resulting pulses are directly spotted by a single photo-detector (PD) due to the ZCC property of our code and converted into the electrical domain, thereafter, the resulting electrical signal is filtered by a low pass Bessel filter (LPBF) for elimination unwanted signals and recover the original information.

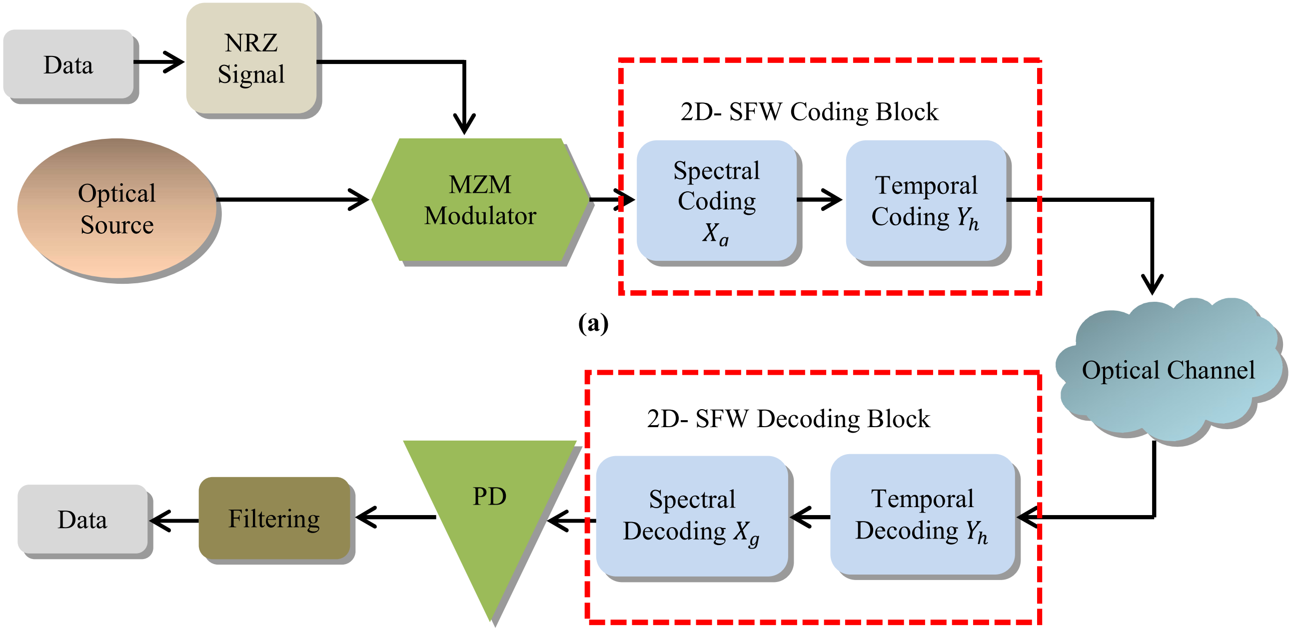
IV. MATHEMATICAL ANALYSIS

Some hypotheses are presented in order to facilitate the analysis of the 1D-SFW-OCDMA system [13,14]: Firstly, the spectral spread of an unpolarized optical source is flat and broadband over the interval $[v_0 - \Delta v/2 \,, v_0 + \Delta v/2\,]$, where v_0 is the central frequency and Δv is the light source's bandwidth. Second, all of the data sent by each user to the receivers comes at the same time. Third and fourth, the power and spectrum width of each transmitter's spectral components are identical.

Since there is no superposition between independent users' spectrums, the MAI influence has been entirely abolished. As a result, we take into consideration the effect of thermal noise $< I_{th}^2 >$ and shot noise $< I_{sh}^2 >$ to estimate the noise variance of the photocurrent produced by direct detection, where phase-induced intensity noise (PIIN) is omitted due to the advantage given by the used code (ZCC property). The photocurrent variance noise is stated as follows [15,16]:

$$<I_{noise}^2> = < I_{sh}^2 > + < I_{th}^2 > = 2eB_r I_r + \frac{4K_b B_r T_n}{R_l} \quad (6)$$

Where e refers to the electron charge, B_r refers to the electrical bandwidth, I_r refers to the average photo direct current, K_b refers to Boltzmann's constant, T_n refers to the absolute temperature and R_l refers to the load.



(a)

(b) Receiver

Fig. 1. Schematic architecture of the spectral SFW OCDMA model.

Following the aforementioned hypotheses, the power spectral density (PSD) of the received signal is written as follows [17]:

$$r(v) = \frac{P_{sr}}{\Delta v} \sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_K(i) C_l(i) \prod(v,i)\, dv \tag{7}$$

Where P_{sr} denotes the effective power of the source at receiver, K denotes the number of simultaneous users, L denotes the code length and d_k denotes the data bit of k^{th} user (i.e., ''0'' or ''1''). As well, $\prod(v,i)$ can be defined as [18]:

$$\prod(v,i)\, dv = \left\{ u\left[v - v_0 - \frac{\Delta v}{2L}(-L+2i) \right] - \left[v - v_0 - u\frac{\Delta v}{2L}(-L+2i+2) \right] \right\} \tag{8}$$

Where $u(v)$ is the unit step function, which is stated as follows :

$$u(v) = \begin{cases} 1 & v \geq 0 \\ 0 & else \end{cases} \tag{9}$$

The output of photocurrent through direct detection at the receiver can be mentioned as:

$$I_r = \Re \int_0^{\infty} r(v) dv = \frac{\Re P_{sr}}{\Delta v}\left(1 \times W \times \frac{\Delta v}{L} + 1 \times 0 \times \frac{\Delta v}{L} \right) = \frac{\Re P_{sr} W}{L} \tag{10}$$

Where $\Re$ is the PD response expressed as: $\Re = \frac{\eta . e}{h . v_0}$

η, h, v_0 are denoted as the quantum efficiency, Plank's constant, and central frequency of the broad-band optical pulse, respectively.

Using (10), the shot noise I_{sh}^2 become as:

$$I_{sh}^2 = 2eB_r I = 2eB_r \frac{\Re P_{sr} W}{L} \tag{11}$$

Thus, following the results of (6), (10), and (11), the SNR expression can be provided as:

$$SNR = \frac{I_r^2}{<I_{noise}^2>} = \frac{\left[\frac{\Re P_{sr} W}{L}\right]^2}{2eB_r \frac{\Re P_{sr} W}{L} + \frac{4K_b T n B_r}{R_l}} \tag{12}$$

Considering that the probability of transmitting "0" and "1" is equal to (0.5), hence, (12) becomes:

$$SNR = \frac{\left[\frac{\Re P_{sr} W}{L}\right]^2}{eB_r \frac{\Re P_{sr} W}{L} + \frac{4K_b T n B_r}{R_l}} \tag{13}$$

The BER is determined from the SNR using the Gaussian approximation as follows [19, 20]:

$$BER = \frac{1}{2} erfc \sqrt{\frac{SNR}{8}} = \frac{1}{2} erfc \sqrt{\frac{1}{8} \times \frac{\left[\frac{\Re P_{sr} W}{L}\right]^2}{eB_r \frac{\Re P_{sr} W}{L} + \frac{4K_b T n B_r}{R_l}}} \tag{14}$$

According to the BER formula, the EVM (%) can be stated as:

$$EVM(\%) = \sqrt{\left(\frac{1}{SNR}\right)} \times 100 \tag{15}$$

V. RESULTS AND DISCUSSION

This section addresses the evaluation of our proposed SFW-OCDMA system under the impact of various parameters including the number of users, effective power, and data rate on BER and SNR factors, as well as comparison to other systems using diagonal eigenvalue unity (DEU), flexible cross-correlation (FCC), multi service (MS), Fixed Right Shift (FRS) codes which are studied in [7,9,11,12] with taking into consideration both shot noise and thermal noise during simulation, where the PIIN noise has been totally neglected due to ZCC advantage. Further, the parameters chosen for the simulation using the MATLAB software can be found in Table II.

TABLE 2. ADOPTED PARAMETERS FOR NUMERICAL CALCULATION.

Parameters	Value
Photo detector responsivity ($\mathscr{R}$)	0.75
Data rate ($\boldsymbol{R_b}$)	622 Mbps
Electric bandwidth ($\boldsymbol{B_r}$)	$0.5 \times \boldsymbol{R_b}$MHz
Receiver Load resistor ($\boldsymbol{R_l}$)	1030Ω
Spectral width of light (Δv)	3.75 THz
Effective source power ($\boldsymbol{P_{sr}}$)	-10 dBm
Receiver noise Temperature ($\boldsymbol{T_n}$)	300 K
Electron charge ($\boldsymbol{e}$)	$1.6 \times \boldsymbol{10^{-19}}$c
Boltzmann's constant ($\boldsymbol{K_b}$)	$1.38 \times \boldsymbol{10^{-23}}$J/K
Code weight (W)	4

When the effective source power and bit rate are -10 dBm and 622 Mb/s, respectively, and all codes have the same weight, Fig.2 depicts the BER versus the number of subscribers. Our 1D-SFW code achieves 200 simultaneous users with an admissible $BER = 10^{-9}$, whereas the 1D-DEU, 1D-FCC, 1D-MS, and 1D-FRS codes can reach 80, 100, and 146 users, respectively. Thus, cardinality raises 1D-DEU codes 2.5 times, 1D-FCC codes 2 times, 1D-MS codes 2.29 times, and 1D-FRS codes 1.36 times, respectively in comparison to our 1D-SFW code. The ZCC feature of our code explains this efficacy, which removes multiple access interference (MAI) and makes the system more suitable for a large number of users. As a result, the measured improvement cardinality using (14) is stated as:

$$\begin{aligned}
&C_{SFW/DEU}\frac{134-61}{61} \times 100 = 114.75\ \% \\
&C_{SFW/FCC}\frac{134-47}{47} \times 100 = 185.1\ \% \\
&C_{SFW/MS}\frac{134-38}{38} \times 100 = 252.63\ \% \\
&C_{SFW/FRS}\frac{134-113}{113} \times 100 = 18.58\ \%
\end{aligned} \tag{16}$$

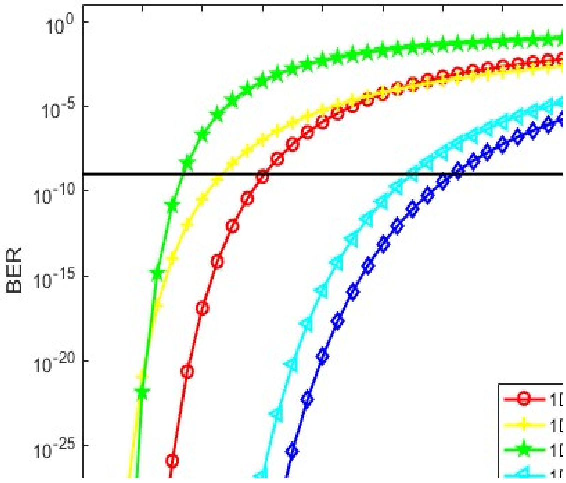


Fig. 2. measure BER against the number of active users.

Figure 3 depicts the BER efficacy as a function of speed rate at -10 dBm transmitter power and 60 active users. As observed, our 1D-SFW code has a diminished BER value than other codes; it can support an excellent data rate of 2.7 Gbps at a sufficient BER value, whereas other codes DEU, FCC, MS, and FRS can support limited data rates within 0.79 Gbps, 0.52 Gbps, 0.41 Gbps, and 2 Gbps, respectively. Nevertheless of the high transmission rate, our code achieves better levels of efficiency due to reduced length and ease of construction and raises system performance when considering the requirements of optical communication systems.

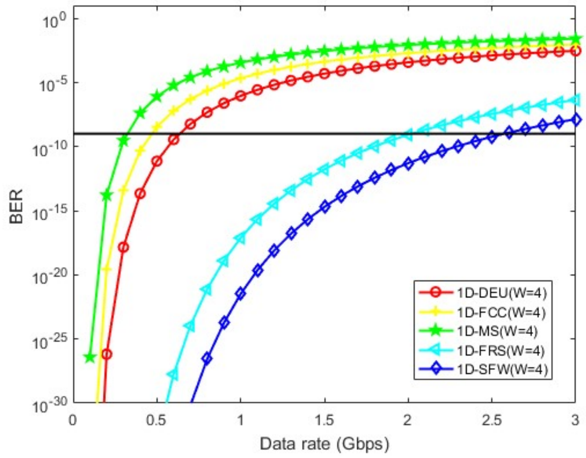


Fig. 3. BER performance against bit rate.

Through the overlapping of wavelengths of different users, PIIN is closely associated with MAI. Fig. 4 displays the PIIN graph against the received power for SFW, DEU, FCC, MS, and FRS codes regarding the following parameters: W = 4, K = 120, and the input bit rate is 622 Mbps. The graphic indicates that as the received power gets higher, the PIIN noise increases linearly for all codes except our code, which remains constant at zero. The value of PIIN noise varies depending on the code employed due to the degrees of interference between users and the value of correlation as indicated in the DEU, FCC, MS, and FRS codes. The SFW code, on the other hand, absolutely suppresses PIIN noise due to the ZCC feature, which ignores any MAI interferences.

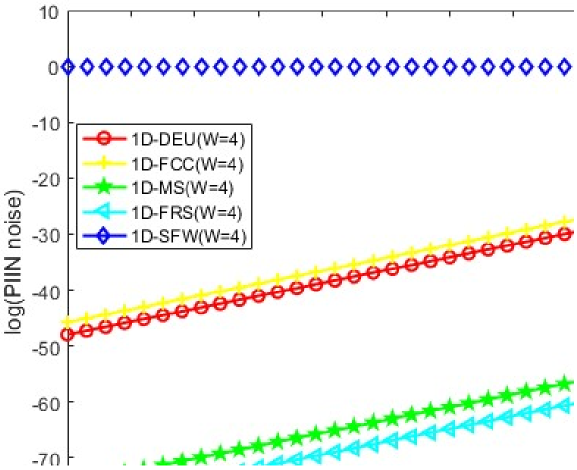


Fig. 4. PIIN noise regarding received power.

Figure 5 exhibits the influence of received power on photocurrent noise when the bit rate is set to 622 Mb/s and the number of available subscribers is set to 60. The noise current obviously increases proportionally to the received power. We can see that when $\boldsymbol{P_{sr}}$ is less than -20 dBm, all codes have nearly the same noise photocurrent. Meanwhile, when $\boldsymbol{P_{sr}}$ exceeds -20 dBm, we clearly detect a significant increase in noise photocurrent, notably for the 1D-DEU, 1D-FCC, 1D-MS, and 1D-FRS codes, due to the substantial influence of PIIN noise especially, as well as shot noise at the receiver. Additionally, despite the high power, we observe a tiny increase in noise photocurrent in our code 1D-SFW due to a very low cross-correlation value between users (ZCC=0), which deletes successfully all PIIN noise effects and makes the system much less susceptible to thermal noise and shot noise.

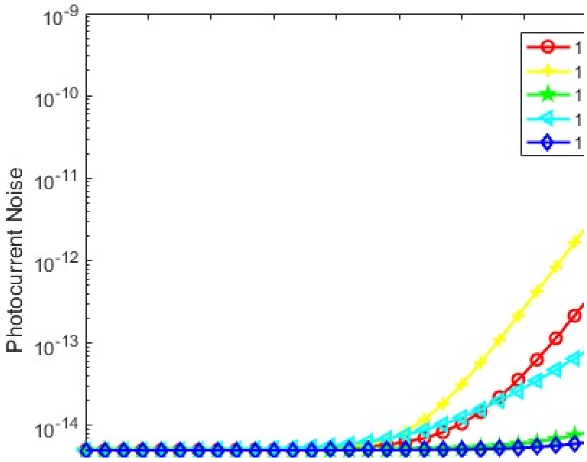


Fig. 5. Photocurrent noise versus received power.

Assuming that all codes have the same code weight and that the effective source power and data rate are -10 dBm and 622 Mb/s, respectively, Fig. 7 shows the EVM alteration in relation to the number of active users. Our 1D-SFW model is able to accommodate 160 simultaneous users at a normalized EVM(%) value in the communication requirement (10%), while the 1D-DEU, 1D-FCC, 1D-MS, and 1D-FRS codes can support 77, 64, 43, and 138 simultaneous users, respectively. Thus, this advantage can be explained by the zero cross-correlation feature of the SFW code, which limits multiple access interference (MAI) and boosts the system's suitability for a high cardinality in addition to its short spectrum length.

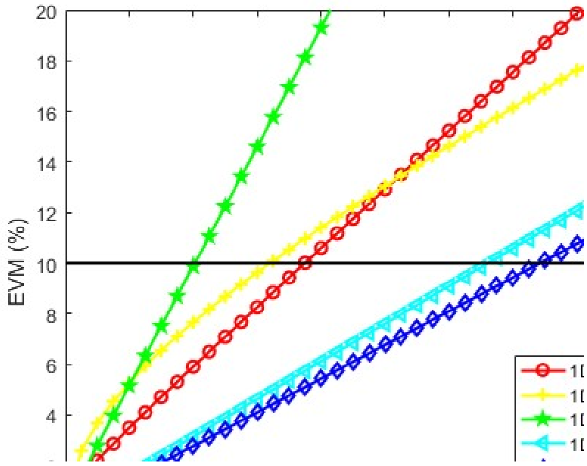


Fig. 7. EVM (%) regarding active users.

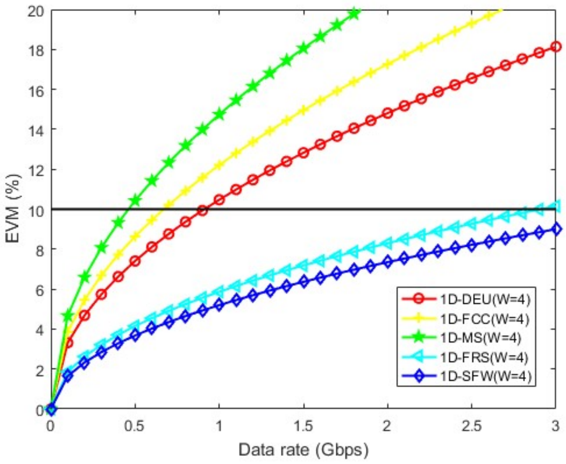


Fig. 8. EVM(%) regarding data rate.

The EVM(%) curve can be seen in Fig. 8 versus data rate alteration, where all codes have the same weight and the effective source power and number of active users are set to 60 and -10 dBm, respectively. The suggested 1D-SFW-OCDMA system can handle a high data rate of more than 3 Gb/s at 10% of optical needs, while the low data rates of 0.42, 0.75, 0.94, and 2.96 Gb/s are provided by the 1D-MS, 1D-FCC, 1D-DEU, and 1D-FRS codes. This means that the suggested 1D-SFW approach outperforms the others and operates in systems capable of processing with high data rates. Hence, the ZCC feature's strong ability to negate PIIN and MAI interferences and accommodate high data rate explains this effectiveness.

VI. CONCLUSION

A new code known as spectral flexible weight (SFW) code for incoherent SAC-OCDMA systems has been designed in this study. The performance of our system has been examined numerically in terms of BER and SNR under the influence of various parameters. During the evaluation process, the effect of shot noise and thermal noise sources was taken into account after the PIIN noise was completely eliminated.

The outcomes demonstrate that our code outperformed the DEU, FCC, MS, and FRS codes. It supports 134 users with a high bit rate of up to 2.7Gbps. Thus, this dominance can be summarized as follows: (1) short code length; (2) ZCC feature; (3) absence of PIIN noise; (4) flexibility of W and K; (5) large capacity; and (6) high bit rate.

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