Flexible Variable Weight Zero Cross-Correlation (FVWZCC) investigations for multimedia applications

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https://doi.org/10.5937/vojtehg72-50521

FIELD: telecommunications, optical transmissions
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: In this paper, we propose a novel code construction method with the zero cross-correlation property, the Flexible Variable Weight Zero Cross-Correlation (FVWZCC). This method is simple and flexible, using different code weights to support different classes of users according to their transmission distance and the quality of services they require (data, audio, and video) in OCDMA systems. The use of higher code weights enables the support of higher-priority application networks, such as long-haul reach networks. The ZCC code structure does not have overlapping of bit '1' and can efficiently eliminates the MAI interference between users and PIIN noise, thus enhancing the system overall performance.

Methods: The shifting element position and the concatenation matrix process of the three basic matrices denoted as the Right vector, the basic matrix, and the Left vector were used for the construction of the proposed FVWZCC code. The mathematical analysis and simulations with Matlab and Optisystem software were used to evaluate the performance of the proposed FVWZCC method in SAC-OCDMA systems using the direct detection.

Results: The results show a significant improvement in the presented code compared to other existing codes in terms of simplicity, flexibility, and cost implementation. The method uses either constant or variable weight with *the Zero cross-correlation property. For a maximum acceptable BER of* 10^{-9} *, the simulation results of the SAC-OCDMA system using direct detection under OptiSystem software show better performance of the proposed code with four users of weight 6 at* $10\ Gb/s$*. Moreover, it can support up to 60 users simultaneously and reach a fibre distance of about 67 km. Consequently, the proposed FVWZCC code can be applied to support different Quality of Service (QOS) requirements with low cost and low complexity with a direct detection receiver.*

Conclusion: The findings of this study highlight the need for the FVWZCC code to support end-user QoS requirements. The new approach to code construction offers low-cost implementation, simplicity, and flexibility.

Key words: FVWZCC code, OCDMA, ZCC, Bit Error Rate BER.

Introduction

The unprecedented exponential growth in global mobile traffic and the huge development of smart devices such as the Internet of Things (IoT) expected for the future 5G/6G communication networks has increased the demand for a wide range of applications with substantial improvements to the data transfer rates, a huge amount of bandwidth and enhanced Quality of Services (QoS) requirements (Dat et al, 2018; Teli et al, 2018; Hakeem et al, 2022). Several multiple access techniques have been proposed for future applications with high bandwidth and high performance such as wavelength division multiple access (WDMA) (Dixit et al, 2013), time division multiple access (TDMA) (Osadola et al, 2011), and optical code division multiple access (OCDMA) (Mostafa et al, 2015). The optical OCDMA technique can be considered prominent and more suitable technology in the field of optical communication and computer networks due its high spectral efficiency, inherent security, low interference characteristics, scalability, multiplexing capability, and seamless integration with existing networks (Kaur & Sing, 2018; Lu et al, 2021; Pendeza Martinez et al, 2021). Furthermore, OCDMA is used in various optical network applications such as optical fiber sensors (Rahimian et al, 2019), metro networks (Zhang et al, 2019; Troia et al, 2020), passive optical networks (PONs) (Farghal, 2016; Zhang et al, 2019; Pendeza Martinez et al, 2021; Ahmed et al, 2022), and radio-of-fiber (RoF) (Ji & Chang, 2013; Kbashi et al, 2021).

In the spectral amplitude coding SAC-OCDMA system, asynchronous multiple users access the same channel medium simultaneously with a high level of security and flexibility. Each user is allocated a unique coding sequence which distinguishes the desired information from the other receiving sequences. However, it suffers from multiple access interference

(MAI) and phase-induced intensity noise (PIIN) phenomena at the receiver which reduces the maximum number of allowed optical codes (Huang et al, 2008; Kaur & Sing, 2018; Bensaad et al, 2019). A proper choice of codes with maximum auto-correlation and minimum cross-correlation known as Zero Cross-Correlation (ZCC) codes or using more sophisticated detection techniques can eliminate the MAI and the PIIN effects (Ahmed et al, 2022; El-Mottaleb et al, 2020; Abd et al, 2011).

In the literature, various codes with zero-cross correlation have been proposed for SAC-OCDMA such as random diagonal code (RD) (Fadhil et al, 2009a), multi-diagonal code (MD) (Imtiaz et al, 2020), and zero cross-correlation code (ZCC) (Bensaad et al, 2023; Anuar et al, 2009; Nisar et al, 2019). Other codes have been proposed that deal with the presence of PIIN effects at the receiver using suitable detection processes such as modified double weight code (MDW) (Upadhyay et al, 2020), Flexible Cross-Correlation code (FCC) (Rashidi et al, 2014), and diagonal Eigen Unity Code (DEU) (Ahmed & Nisar, 2013).

The above-reported codes were designed with constant code weight (CW) while variable code weight (VW) is used to support multimedia services such as voice, video, and image transmission at the physical layer with different bit rates (Nasaruddin & Tsujioka, 2008; Li et al, 2023). Physical layer QoS was made possible for the OCDMA system by varying the weight of the code, the length, or both the weight and the length. Higher quality services have been assigned more weights or more wavelengths corresponding to higher transmitted power sent by each code. A higher code length transports data information at a lower transmission rate (Li et al, 2020; Kumawatn & Maddila, 2017).

Variable code weights have been proposed by several researchers to provide different quality of service (QoS) requirements for the SAC-OCDMA network, among them: variable weight OOC codes for multimedia SAC-OCDMA systems (Nasaruddin & Tsujioka, 2008), Variable Weight Zero Cross-Correlation Code (VW-ZCCC) (Kumawat & Maddila, 2017), service differentiation using Khazani-Syed (KS) code (Anas et al, 2009), Variable Weight code for Multimedia Service (VW-MS) (Kumawat & Ravi Kumar, 2018), Variable code weight using Random Diagonal Code (RD) for Spectral Amplitude Coding OCDMA Systems (Fadhil et al, 2009b), Zero Cross-Correlation Magic Square Variable Weight Optical Orthogonal Code (ZMS-VWOOC) (Lu et al, 2021), Variable Weight Quadratic Congruence Code (VWQCC) (Feng et al, 2015), and variable weight Zero Cross-Correlation Code (VZCC) (Nisar et al, 2021).

In this paper, we proposed a new code construction design method for SAC-OCDMA systems which has the following properties:

- Zero Cross-Correlation ZCC property, which reduces significantly the MAI and PIIN noise effects, thus improving the performance of the system,
- The method offers a good flexibility in the choice of any number of users or code weight,
- It can be used with constant or variable code weight, and
- The mapping procedure of this method is simple and based on shifting a three elementary matrices which can reduce the cost and the system complexity.

The remainder of the manuscript is organized as follows: first, we present the need for the proposed FVWZCC code for multimedia applications and describe mathematically the code design construction. Then, the performance analysis of the code using Direct Detection (DD) is introduced followed by a theoretical analysis and performance comparison with other codes from the references to prove the efficiency of the proposed code. Next, the performance of the proposed FVWZCC code is validated by using simulations under Optisystem software Version 7.0. Finally, a conclusion is given to summarize the work.

FVWZCC code for multimedia applications

The proposed FVWZCC code can support the diversity of multimedia services where a higher transmission rate is assigned to video applications, since a high video transmission rate provides high video quality, the medium data rate is assigned to audio transmission whereas data transmission such as image supports low data rate transmission. The FVWZCC code is characterized by the code weight W_i, the code length L_i, and the number of users K_i, where $i \in \{1, 2, 3\}$ denotes one of the three services: audio, video and data. For different quality of services, W_i represents the low-level weight dictated for data transmission with low quality of services, W_{i+1} represents the medium-level weight dictated for audio transmission with medium quality of services, and W_{i+2} represents the high-level weight dictated for video transmission with high quality of services. Let k_i^d, k_i^a, and k_i^v be constants for the i^{th} data, audio, and video services, respectively. The code length for each service can be expressed as:

$$L_d = k_i^d W_i \quad \text{for data transmission} \quad (1)$$

$$L_a = k_i^a W_{i+1} \quad \text{for audio transmission} \quad (2)$$

$$L_v = k_i^v W_{i+2} \quad \text{for video transmission} \quad (3)$$

For the code weight W_i, $i \in \{1, 2, 3\}$ denotes one of the three services: audio (W_1), video (W_2), and data (W_3). The subscript $(i+1)$ or $(i+2)$ denotes the code weight increment by one for video and data services, respectively.

$$\text{For } i = 1, W_i = W_1 = W \Rightarrow L_1 = L_d = k_i^d\, W_i = k_i^d\, W$$
$$i = 2, W_2 = W_{i+1} = W_i + 1 \Rightarrow L_2 = L_d = k_i^a\, W_{i+1} = k_i^a\,(W+1)$$
$$i = 3, W_3 = W_{i+2} = W_i + 2 \Rightarrow L_3 = L_d = k_i^v\, W_{i+2} = k_i^v\,(W+2)$$

The resulting matrix of the FVWZCC code can support two classes of users according to their transmission distance with different quality of services (data, audio, and video). The first class is the long-haul reach network of hundreds or thousands of kilometers and the second is the short-haul reach network with several tens of kilometers. Note that the weight assigned to each class of users or quality of services obeys some conditions such as:

$$W_{i+2} > W_{i+1} > W_i \tag{4}$$
$$W_{i,C_1} > W_{i+2,C_2} \tag{5}$$

where W_{i,C_1} and W_{i,C_2} denotes the code weight of the i^{th} transmission service (audio, data or video) used for the corresponding long-haul reach network class of the application zone and the short-haul reach network class of the application zone in the descending order of distance ($C_1 > C_2$), respectively. Figure 1 gives an example for two classes of networks length with a code weight of $W_i = 5$ and three transmission services.

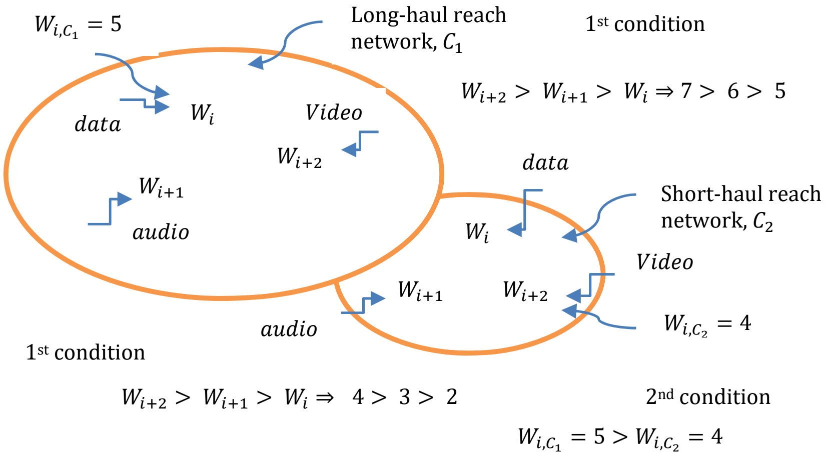


Figure 1 – Example of two classes: the long-haul reach network and the short-haul reach network

Construction method of the FVWZCC code

The process design construction of the proposed Flexible Variable Weight Zero Cross-Correlation matrix code FVWZCC is described by the following steps.

Step 1
Consider a basic matrix denoted by H_b of size $(K \times L)$ given by:

$$H_{b=1} = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix}_{(K \times L)}. \qquad (6)$$

where $K = 2$ rows represent the number of users, $L = 4$ columns represent the minimum code length, and the number of one element values $W = 2$ represents the code weight. Clearly, the cross-correlation of the proposed basic matrix is zero.

The basic matrix H_b is formed by the concatenation of three elementary basic compounds as:

the elementary matrix M_b of the size (2×2) denoted by: $M_b = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}_{(2 \times 2)}$,

the right vector $V_R = [1\ 0\ ]^T$ inserted in the right of the elementary matrix M_b, and

the left vector $V_L = [0\ \ 1\ ]^T$ inserted in the left of the elementary matrix M_b.

Step 2
Case 1: Consider a fixed number of users $K = 2$

To increase the code weight while maintaining the number of users fixed, the two elementary vectors V_R and V_L are inserted alternatively in the left and the right of the basic matrix H_b leading to a new matrix code characterized by:

a code weight: $W_N = W + W_v\ = 2 + W_v$ (7)
a code length: $L_N = L + 2W_v\ = 4 + 2W_v$ (8)

where W_v denotes the number of vectors inserted into the left or the right of the basic matrix H_b.

The resulting new matrix code of weight W_N is shown as:

$$H_N = [V_R\; V_L \ldots V_R\; V_L\; H_b\; V_R\; V_L \ldots V_R\; V_L] \tag{9}$$

For instance, the resulting new matrix of the code weight $W_N = 3$ is obtained as:

$$H_{N,W_N=4} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix}_{(K \times (L+2W_v))=(2 \times 6)} \tag{10}$$

Case 2: Consider a fixed code weight W of the basic matrix H_b

In this phase, the number of users can be further increased using a particular shifted process for the three elementary compounds of the basic matrix H_b. The right vector V_R is shifted to the right by some positions (or columns) equal to: $\left[0 : \left(\frac{K}{2} - 1\right)\right]$, where K denotes the number of users. The elementary matrix M_b is shifted to the right by some positions (or columns) equal to: $\left[\left(\frac{K}{2} - 1\right) : (K-2)\right]$, and the left vector V_L is shifted to the left by some positions equal to: $\left[(K-2) : \left(\frac{K}{2} - 1\right)\right]$, The number of shifted positions to the right side is filled with the same number of zeros. In the results, the total number of inserted zeros for the three elementary matrix and vector compounds is given below:

$$V_R \rightarrow \left[0 : \left(\frac{K}{2} - 1\right)\right]$$

$$M_b \rightarrow \left[\left(\frac{K}{2} - 1\right) : (K-2)\right] \cup \{V_R \text{ total number of zeros shifted positions}\}$$

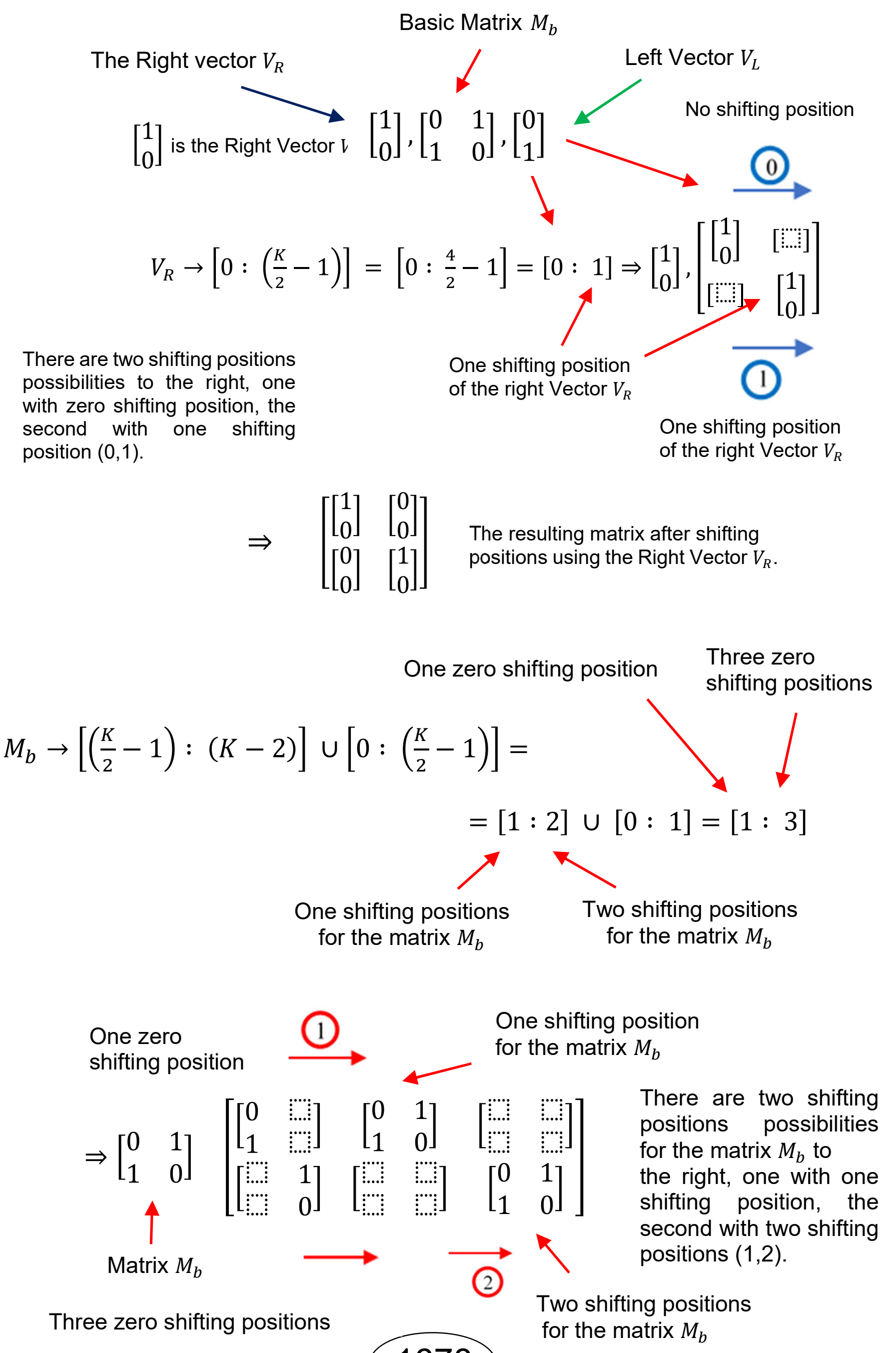
$$\Rightarrow M_b \rightarrow \left[\left(\frac{K}{2} - 1\right) : (K-2)\right] \cup \left[0 : \left(\frac{K}{2} - 1\right)\right]$$

$$V_L \rightarrow \left[(K-2) : \left(\frac{K}{2} - 1\right)\right] \cup \{M_b \text{ total number of zeros shifted positions}\}$$

$$\Rightarrow V_L \rightarrow \left[(K-2) : \left(\frac{K}{2} - 1\right)\right] \cup \left[\left(\frac{K}{2} - 1\right) : (K-2)\right] \cup \left[0 : \left(\frac{K}{2} - 1\right)\right]$$

For example, let the number of users $K = 4$, the weight $W = 2$, and the length code $L = 4$.

Following the above strategy, the resulting matrix code is given by:



The Right vector V_R

Basic Matrix M_b

Left Vector V_L

$\begin{bmatrix}1\\0\end{bmatrix}$ is the Right Vector V

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

No shifting position

⓪

$$V_R \rightarrow \left[0 : \left(\frac{K}{2}-1\right)\right] = \left[0 : \frac{4}{2}-1\right] = [0 : 1] \Rightarrow \begin{bmatrix}1\\0\end{bmatrix}, \begin{bmatrix}\begin{bmatrix}1\\0\end{bmatrix} & [\square] \\ [\square] & \begin{bmatrix}1\\0\end{bmatrix}\end{bmatrix}$$

There are two shifting positions possibilities to the right, one with zero shifting position, the second with one shifting position (0,1).

One shifting position of the right Vector V_R

①

One shifting position of the right Vector V_R

$$\Rightarrow \begin{bmatrix}\begin{bmatrix}1\\0\end{bmatrix} & \begin{bmatrix}0\\0\end{bmatrix}\\ \begin{bmatrix}0\\0\end{bmatrix} & \begin{bmatrix}1\\0\end{bmatrix}\end{bmatrix}$$

The resulting matrix after shifting positions using the Right Vector V_R.

One zero shifting position

Three zero shifting positions

$$M_b \rightarrow \left[\left(\frac{K}{2}-1\right) : (K-2)\right] \cup \left[0 : \left(\frac{K}{2}-1\right)\right] =$$

$$= [1 : 2] \cup [0 : 1] = [1 : 3]$$

One shifting positions for the matrix M_b

Two shifting positions for the matrix M_b

One zero shifting position

①

One shifting position for the matrix M_b

$$\Rightarrow \begin{bmatrix}0&1\\1&0\end{bmatrix} \begin{bmatrix}\begin{bmatrix}0&\square\\1&\square\end{bmatrix} & \begin{bmatrix}0&1\\1&0\end{bmatrix} & \begin{bmatrix}\square&\square\\\square&\square\end{bmatrix}\\ \begin{bmatrix}\square&1\\\square&0\end{bmatrix} & \begin{bmatrix}\square&\square\\\square&\square\end{bmatrix} & \begin{bmatrix}0&1\\1&0\end{bmatrix}\end{bmatrix}$$

There are two shifting positions possibilities for the matrix M_b to the right, one with one shifting position, the second with two shifting positions (1,2).

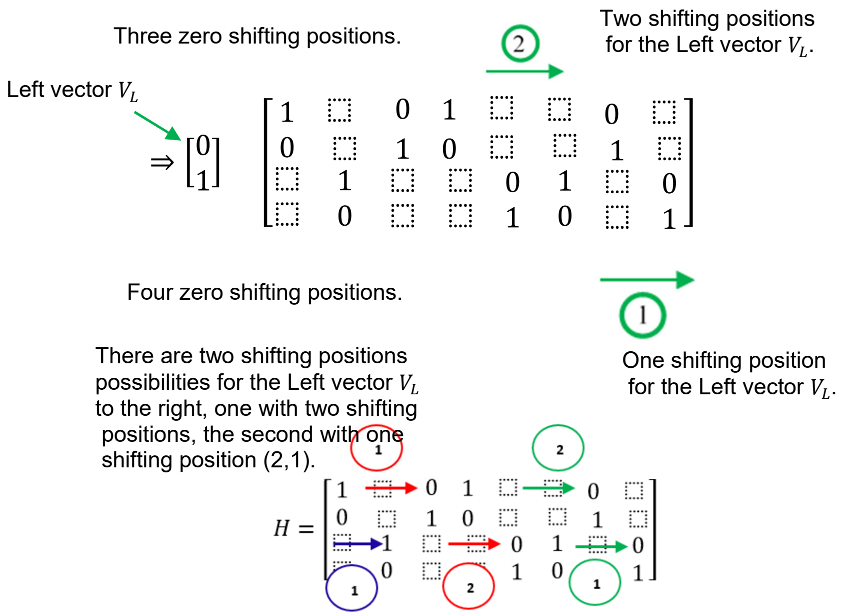
Matrix M_b

②

Two shifting positions for the matrix M_b

Three zero shifting positions

$$V_L \rightarrow \left[(K-2) : \left(\frac{K}{2}-1\right)\right] \cup \left[\left(\frac{K}{2}-1\right) : (K-2)\right] \cup \left[0 : \left(\frac{K}{2}-1\right)\right]$$
$$= [2 : 1] \cup [1 : 2] \ \cup [0 : 1] = [3 : 4]$$



$$\Rightarrow H = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}. \qquad (11)$$

where the shifted positions of each elementary matrix are: (0,1), (1,2) and (2,1), respectively.

Case 3: Consider a fixed number of users $K > 2$.

The code weight of the matrix code is increased using the following strategy:

Odd Code weight: The code weight of the basic matrix H_b is equal to $(W = 2)$. The code weight can be increased by using the elementary

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matrix compound M_b alternatively with the basic matrix H_b to get an odd code weight value W_o.

$$H_o = [H_b][M_b][H_b] \quad [H_b][H_b]. \tag{12}$$

Even Code weight: For an even code weight value, we choose one of the three possible configurations:

The basic matrix H_b is used in concatenation one with the other,

$$H_o = [H_b][H_b][H_b] \quad [H_b][H_b]. \tag{13}$$

We use the concatenation of the resulting odd code weight matrix codes H_o obtained from the precedent step.

$$H_o = [H_0][M_b][H_0][M_b] \quad [H_0]. \tag{14}$$

We can also use the concatenation of elementary matrix compounds M_b.

$$H_o = [M_b][M_b][M_b] \quad [M_b]. \tag{15}$$

Then, the size of the resulting matrix is $(K \times L)$, where $L = K * W$ represents the matrix code length. For two kinds of services with $K = 6, W = 4$ and $K = 3, W = 3$, the code matrix is given by:

$$H = \begin{bmatrix} \begin{bmatrix} 1&0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&1&0&0&0&0&0&0&0 \\ 0&0&0&1&0&0&0&0&0&1&0&0&0&0&0&1&0&0&0&0&0&1&0&0 \\ 0&1&0&0&0&0&1&0&0&0&0&0&0&1&0&0&0&0&1&0&0&0&0&0 \\ 0&0&0&0&0&1&0&0&0&0&1&0&0&0&0&0&0&1&0&0&0&0&1&0 \\ 0&0&1&0&0&0&0&0&1&0&0&0&0&0&1&0&0&0&0&0&1&0&0&0 \\ 0&0&0&0&0&0&0&1&0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&1 \end{bmatrix} & [0] \\ [0] & \begin{bmatrix} 1&1&0&0&1&0&0&0 \\ 0&0&1&0&0&1&0&0 \\ 0&0&0&1&0&0&1&1 \end{bmatrix} \end{bmatrix}$$

The total length of the matrix code is: $L = 6 \times 4 + 3 \times 3 = 33$.

Performance analysis using Direct Detection (DD)

In direct decoding (DD), a single input only is used at the receiver compared to other techniques which reduce the number of filters required for implementation. For a given user at the receiver using direct detection (DD), the number of FBGs that have bandwidths centered at the used wavelength is equal to the number of non-overlapping spectra $C_f(j)$ incident on the photodetector. The code correlation function using the DD technique of the FVWZCC can be written as:

$$\sum_{j=1}^{L_{Tot}} C_f\,(j)C_g(j) = \begin{cases} W_i & f = g, \text{ same user with similar weight} \\ 0 & f \neq g, \text{ other users with similar weight} \\ 0 & f \neq g, \text{ other users with distinct weight} \end{cases} \qquad (16)$$

where $C_f(j)$ represent the j^{th} component of the C^{th} proposed code sequence.

The variance of photocurrent due to the detection of an ideally unpolarized thermal light, which is generated by spontaneous emission, can be written as the sum of the Phase Induced Intensity Noise $\langle I_{piin}^2\rangle$, the shot noise $\langle I_{shot}^2\rangle$, and the thermal noise $\langle I_{thermal}^2\rangle$ (Ahmed et al, 2012; Shi & Gafouri-Shiraz, 2016; Kumawat & Maddila, 2017):

$$\langle i_{noise}^2\rangle = \langle I_{piin}^2\rangle + \langle I_{shot}^2\rangle + \langle I_{thermal}^2\rangle \qquad (17)$$

The thermal noise $\langle I_{thermal}^2\rangle$ is defined as (Ahmed et al, 2012):

$$\langle I_{thermal}^2\rangle = \frac{4k_bT_nB}{R_L} \qquad (18)$$

The shot noise $\langle I_{shot}^2\rangle$ is defined as (Ahmed et al, 2012):

$$\langle I_{shot}^2\rangle = 2eBI \qquad (19)$$

where e represents the electron charge, B the electrical bandwidth, I the average photocurrent, k_b the Constant Boltzmann, T_n the receiver noise temperature, R_L the receiver load, and the Phase Induced Intensity Noise $\langle I_{piin}^2\rangle$ is given as (Ahmed et al, 2012, 2019):

$$\langle I_{piin}^2\rangle = BI^2\tau_c \qquad (20)$$

The coherence time τ_c of the source can be expressed as (Ahmed & Nisar, 2013; Wei & Ghafouri-Shiraz, 2002):

$$\tau_c = \frac{\int_0^\infty G^2(v)dv}{\left[\int_0^\infty G(v)dv\right]^2} \tag{21}$$

where $G(v)$ denotes the single sideband power spectral density (PSD) of the source incident at the input of the photodiode.

For mathematical simplicity, the Gaussian approximation is used for all the noise distributions to analyze the system performance. Furthermore, the assumptions below are adopted for the transmitter and the receiver as follows:

- The light source is ideally unpolarized and its spectrum is flat for a given bandwidth $[v_0 - \Delta v/2, v_0 + \Delta v/2\,]$, where v_0 is the central optical frequency and Δv is the optical source bandwidth,
- The spectral width is the same for each frequency component,
- For each user, the bit stream is synchronized, and
- The same power is received by each user.

The power spectral density (PSD) of the received optical signals can be written as (Osadola et al, 2011; Mostafa et al, 2015):

$$r(v) = \frac{P_{sr}}{\Delta v} \sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i).rect(i) \tag{22}$$

where P_{sr} denotes the effective power, d_f the f^{th} user data bit, K_{Tot} is the total number of users and L_{Tot} is the total code length. The function $rect(.)$ is expressed as (Ahmed et al, 2012; Kumawat & Maddila, 2017):

$$rect(i) = u\left[v - v_0 - \frac{\Delta v}{2L_{Tot}}\left(-L_{Tot} + 2i - 2\right)\right] - u\left[v - v_0 - \frac{\Delta v}{2L_{Tot}}\left(-L_{Tot} + 2i\right)\right] = u\left[\frac{\Delta v}{L_{Tot}}\right] \tag{23}$$

where $u(v)$ is a step unit function defined as:

$$u(v) = \begin{cases} 1, & v \geq 0 \\ 0, & v < 0 \end{cases}$$

The total power at the f^{th} receiver of the proposed flexible variable weight

for one period is obtained based on Eq. 22, Eq. 23, and using the code correlation property of Eq. 16 as:

$$\int_0^{+\infty} G(v)\,dv = \int_0^{+\infty} \left[\frac{P_{sr}}{\Delta v}\sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i)c_g(i)\, rect(i)\right] dv$$

$$\Rightarrow \int_0^{+\infty} G(v)\,dv =$$

$$\left[\frac{P_{sr}}{\Delta v}\sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i)c_g(i)\right] \int_{v-v_0-\frac{\Delta v}{2L_{Tot}}(-L_{Tot}+2i-2)}^{v-v_0-\frac{\Delta v}{2L_{Tot}}(-L_{Tot}+2i)} rect(i)\,dv$$

$$\Rightarrow \int_0^{+\infty} G(v)\,dv = \frac{P_{sr}}{\Delta v}\frac{\Delta v}{L_{Tot}} \sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i)c_g(i)$$

$$\Rightarrow \int_0^{+\infty} G(v)\,dv =$$

$$\frac{P_{sr}}{L_{Tot}}\left[\sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i)c_g(i) + \sum_{f\neq 1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i)c_g(i)\right]$$

$$\Rightarrow \int_0^{+\infty} G(v)\,dv = \frac{P_{sr}}{L_{Tot}}\left[\sum_{f=1}^{K_{Tot}} d_f W_i + \sum_{f\neq 1}^{K_{Tot}} d_f \times 0\right]$$

Based on $\sum_{f=1}^{K_{Tot}} d_f = 1$, the total power at the f^{th} receiver is given by:

$$\Rightarrow \int_0^{+\infty} G(v)\,dv = \frac{P_{sr}\ W_i}{L_{Tot}} \tag{24}$$

Then, the resulting photocurrent due to the incident optical power I_{FVWZCC} is defined as (Kumawat & Maddila, 2017):

$$I_{FVWZCC} = \Re \int_0^{+\infty} G(v)\,dv = \Re\,\frac{P_{sr}\ W_i}{L_{Tot}} \tag{25}$$

where $\Re = {}^{\eta.e}/_{h.v_0}$ is the responsivity of the photodetectors, η denotes the quantum efficiency, *e* is the electron charge, and $h.v_0$ is the photon energy.

Substituting Eq. 25 in Eq. 19, the shot noise power is deduced as (Imtiaz et al, 2016; Kumawat & Maddila, 2017):

$$\langle I_{shot}^2\rangle = 2eB\Re\left[\int_0^{+\infty} G(v)\,dv\right] = 2eB\Re\left[\frac{P_{sr}\ W_i}{L_{Tot}}\right] \tag{26}$$

and the PIIN noise power is given by (Ahmed et al, 2012; Kumawat & Maddila, 2017):

$$\langle I_{piin}^2 \rangle = B\, I^2\, \tau_c = B\Re^2\left[\int_0^\infty G^2(v)\, dv\right] \tag{27}$$

When all active users are transmitting bit ‘1’, and using the average approximation, the code sequence C_k is given by:

$$\sum_{k=1}^{K_{Tot}} C_k(j) = \frac{1}{L_{Tot}} \sum_{i=1}^{W_{Tot}} K_{W_i}\, W_i \tag{28}$$

where $K_{Tot} = \sum_{i=1}^{W_{Tot}} K_{W_i}$ denotes the total number of active users with different weights, K_{W_i} is the number of users corresponding to the weight W_i, and W_{Tot} is the total number of weights.

Using Eq. 27, the variance of PIIN noise is determined as follows:

$$\langle I_{piin}^2 \rangle = B\Re^2\left[\int_0^\infty G^2(v)\, dv\right]$$

$$\Rightarrow \langle I_{piin}^2 \rangle = B\Re^2 \int_0^\infty \left[\frac{P_{sr}}{\Delta v}\sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i) c_g(i)\, rect(i)\right]^2 dv$$

$$\Rightarrow \langle I_{piin}^2 \rangle = B\Re^2 \left[\frac{P_{sr}}{\Delta v}\right]^2 \left[\frac{\Delta v}{L_{Tot}}\right] \left[\sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i) c_g(i)\right]^2$$

$$\Rightarrow \langle I_{piin}^2 \rangle = B\Re^2 \frac{{P_{sr}}^2}{L_{Tot}\, \Delta v} \left[\sum_{f=1}^{K_{Tot}} d_f \sum_{i=1}^{L_{Tot}} c_f(i) c_g(i)\right]^2$$

$$\Rightarrow \langle I_{piin}^2 \rangle = B\Re^2 \frac{{P_{sr}}^2}{L_{Tot}\, \Delta v} \sum_{i=1}^{L_{Tot}} \left\{ c_g(i) \left[\sum_{f=1}^{K_{Tot}} d_f\, c_f(i)\right] \left[\sum_{m=1}^{K_{Tot}} d_m\, c_m(i)\right] \right\}$$

Substituting Eq. 28, one obtains:

$$\langle I_{piin}^2 \rangle = B\Re^2 \frac{{P_{sr}}^2}{L_{Tot}\, \Delta v} \left[W_i\right] \left[\frac{1}{L_{Tot}} \sum_{i=1}^{W_{Tot}} K_{W_i}\, W_i\right] \tag{29}$$

As a result, the variance of PIIN noise is given by:

$$\langle I_{piin}^2 \rangle = \frac{B\Re^2\, P_{sr}^2}{L_{Tot}^2\, \Delta v} \left[\sum_{i=1}^{W_{Tot}} K_{W_i}\, W_i\right] W_i \tag{30}$$

For each user, the probability of transmitting bit ‘1’ and ‘0’ is the same at any time; then the photocurrent noise can be written as:

$$\langle i_{noise}^2 \rangle = \frac{B\Re^2 P_{sr}^2}{2L_{Tot}^2 \Delta v} \left[\sum_{i=1}^{W_{Tot}} K_{W_i} W_i \right] W_i + eB\Re\left[\frac{P_{sr} W_i}{L_{Tot}}\right] + \frac{4k_b T_n B}{R_L} \quad (31)$$

Since the probability of transmitting bit ‘1’ at any time for each user is half, then the average Signal to Noise Ratio SNR for a particular weight W_i used for evaluating the FVWZCC code in the SAC-OCDMA system can be expressed as (Shi & Ghafouri-Shiraz, 2016):

$$SNR = \frac{(I_{FVWZCC})^2}{\langle i_{noise}^2 \rangle} \quad (32)$$

Substituting Eq. 25 and Eq 30 in Eq. 31, the average SNR is deduced as:

$$SNR = \frac{\left(\Re \frac{\mathrm{P_{sr}} W_i}{L_{Tot}}\right)^2}{\frac{B\Re^2 P_{sr}^2}{2L_{Tot}^2 \Delta v}\left[\sum_{i=1}^{W_{Tot}} K_{W_i} W_i \right] W_i + \mathrm{eB}\Re\frac{\mathrm{P_{sr}} W_i}{\mathrm{L}_{Tot}} + \frac{4\,\mathrm{k_b T_n B}}{\mathrm{R_L}}} \quad (33)$$

Based on the Gaussian approximation, the Bit Error Rate BER or the probability of error $P_{e,i}$ of a particular weight W_i is calculated from the SNR as (Kaur & Singh, 2018; Wei et al, 2001):

$$\mathrm{BER} = P_{e,i} = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{SNR}{8}}\right) \quad (34)$$

Code comparison and discussions

In this section, simulations with the Matlab program were achieved for analysis and performance comparison between the proposed code and other reported codes.

The main parameters shown in Table I were fairly selected to provide a reasonable results comparison.

Table 1 – Table of parameters

Symbol	Parameters	Values
$\mathcal{R}$	Responsivity of the photodiode	1
B	Electrical equivalent noise bandwidth of the receiver	$311\ MHz$
K_b	Boltzmann constant	$1.38\ \times 10^{-23}\ J/K$
R_L	Resistance load	$1030\ \Omega$
T_b	Temperature of noise at the receiver	$300\ K$
P_{rc}	Effective power at the receiver	$-10\ dBm$
e	Charge of electron	$1.6\ \times 10^{-19} C$

The BER curve variation as a function of the number of active users for each code weight service taking into account the PIIN effects is shown in Figure 2.

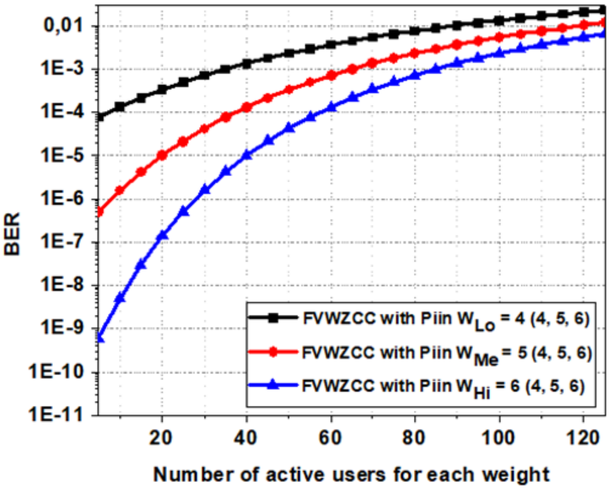


Figure 2 – BER as a function of the number of users for the three code weighs services ($W_{Lo} = 4$, $W_{Me} = 5$ and, $W_{Hi} = 6$)

The number of users is varied for each of the three code weights $W_{Lo} = 4\ (4, 5, 6)$, $W_{Me} = 5\ (4, 5, 6)$ and, $W_{Hi} = 6\ (4, 5, 6)$ assigned to video, audio and data services, respectively. The BER curve is plotted by varying the number of users for one code weight service while the other weights are kept constant to 40 users. The BER performance of the three code weights decreases as the total number of simultaneous users increases which can be referred to as the amount of noise level collected from an additional number of users leading to the degradation of the system performance. Moreover, up to the threshold value of 60 users, the total number of active users has fewer and low effects on the system performance for all weight codes. The BER performance of the system is better from high to low weight for some users fewer than 60 users and moderate up of this number of users which gives a good way for the choice of the range of the number of users with an appropriate quality of service in terms of the minimum desired bit error rate BER.

Figure 3 illustrates the BER performance comparison of the proposed FVWZCC code with and without PIIN consideration for the high-weight service $W_{Hi} = 6\ (4, 5, 6)$. The number of users of the high weight is set to $K_{Hi} = 15, 25, \text{and } 30$ while it is kept constant to 40 users for low and medium weights services $(K_{Lo} = K_{Me} = 40)$. As it can be concluded, the BER performance of the system is better with neglecting the term of PIIN effects and increases as the number of users for the high-weight service decreases which decreases the code length. Meanwhile, taking as reference the number of accommodated users with and without the PIIN term effects at the maximum acceptable BER (10^{-9}), the difference is large enough $(13\ users)$ to consider the hypothesis of neglecting the PIIN term effects may be worst. For example, with $K_{Hi} = 15$, the number of accommodated users is 50 users without the PIIN term effects while it is only 37 with them.

Consequently, the performance comparison of the codes in the case presented in this work will be done by taking into account the PIIN term effects. Moreover, the BER performance of the system experiences the same behavior when the number of users of the low and medium weights exceeds approximately 80 users with a high BER value.

The performance comparison between the proposed flexible constant weight FCWZCC code and other reported codes with PIIN consideration such as MQC, MFH, Hadamard, CWZCCC, and RD versus the number of active users is plotted in Figure 4. The proposed FCWZCC code gives the best and the same BER performance as the reported CWZCCC code while it outperforms all the other reported codes. The BER performance is better although with a lower code weight value $(W = 4)$ compared to others codes with code weight values $(W = 7, 12)$ taking into account the PIIN effects. Given two code sequences $X = (x_1, x_2, \dots, x_N)$ and $Y = (y_1, y_2, \dots, y_N)$, the cross-correlation is defined as $\lambda = \sum_{i=1}^{N} x_i y_i$. When $\lambda = 0$, the code is said to the have zero cross-correlation property. It is obvious that since the FCWZCC code has the property of zero cross-correlation $(\lambda = 0)$, the MAI and PIIN interference effects, which are the major sources of performance degradation, can be eliminated effectively. For a maximum acceptable BER of 10^{-9}, the number of accommodated users for the proposed FCWZCC is 71 users which is the same number of users as the reported CWZCCC code, 53 for the RD code, 40 for the MQC code, 27 for the MFH code and 19 for the Hadamard code, respectively.

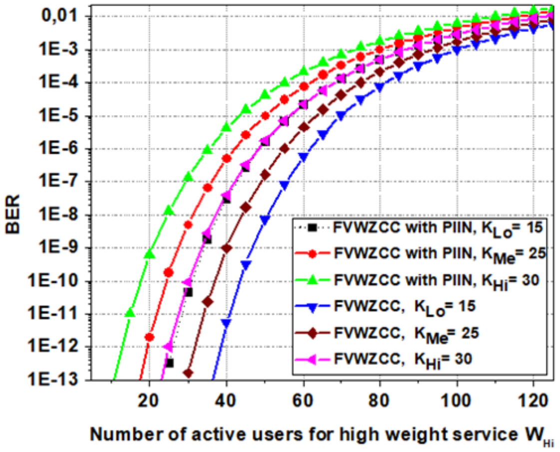


Figure 3 – BER performance comparison of the proposed FVWZCC code with and without PIIN consideration as a function of the number of active users of the high-weight service

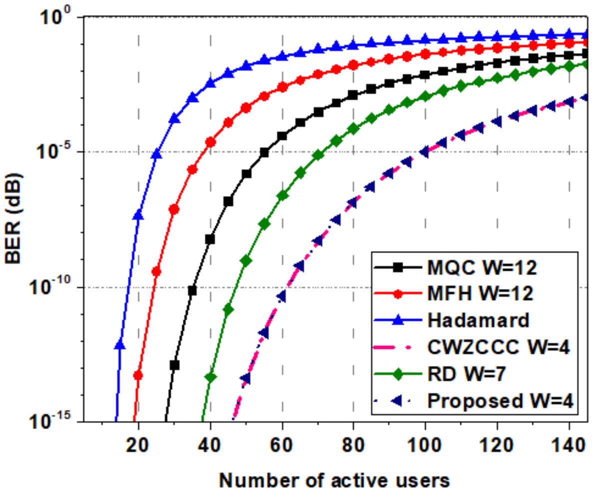


Figure 4 – BER as a function of the number of users for different codes in the SAC-OCDMA system

Figure 4 shows the BER performance system comparison of the proposed FVWZCC code with other published variable weight codes such as VWQCC, VWZCCC, and VWKS. The BER curve is plotted as a function of the number of users for medium and high weights $(W = 4, 6)$ while varying the high-weight users from 0 to 100. The number of users for the medium weight is set to 30 users. The proposed code's BER performance is better than that of the reported VWZCCC code and outperforms all the remainder reported codes.

The improvement in the system performed of the proposed code derives from the good correlation property and a shorter code length which is the same as the reported VWZCCC code while it is large compared to other codes. The VWKS code experiences the same system performance as the code proposed in this work when the total number of users exceeds 60 users corresponding to a bit error rate of approximately $\approx 10^{-7}$.

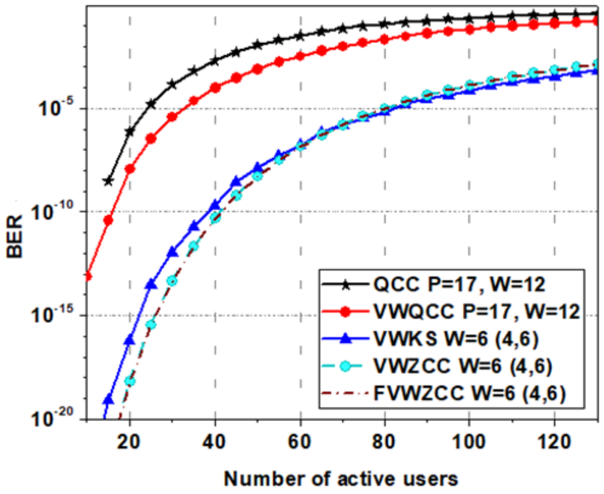


Figure 5 – BER as a function of the number of users for different variable weight codes in the SAC-OCDMA system

System description and the simulation results

The simulation of the proposed FVWZCC code design was carried out using Optisystem version 7.0. The block diagram with 5 users and the code weight value $W = 6$ is shown in Figure 6. In the transmission part, a series of W number of laser light sources were used each of them with a power of $0.417\ mW$. Multiplexers and Demultiplexers for encoding optical signals, a pseudo-random bit sequence (PRBS) generator, and a non-return-zero (NRZ) pulse generator are used to generate the data signal. Then, the electric data of each user is modulated by the external intensity modulator Mach–Zehnder. The bit rate of $10\,Gbps$ was adopted for simulations over a fiber optic distance varying in the range of $20\,km$ to $90\,km$. The ITU-T G.652 standard single mode optical fiber with all the non-linearity effects was considered, attenuation of $0.2\ dB/km$, dispersion of $16.75ps/nm/km$ and a spectral width of 0.8 nm for each chip were also adopted.

At the receiver part, Fiber Bragg grating FBGs corresponding to a unique wavelength from a specified code sequence followed by photo-detectors PDs were used to decode the signal. Finally, the detected signal is passed through a low-pass filter to remove the remaining noise. The performance of the system was analyzed using the BER and the eye patterns.

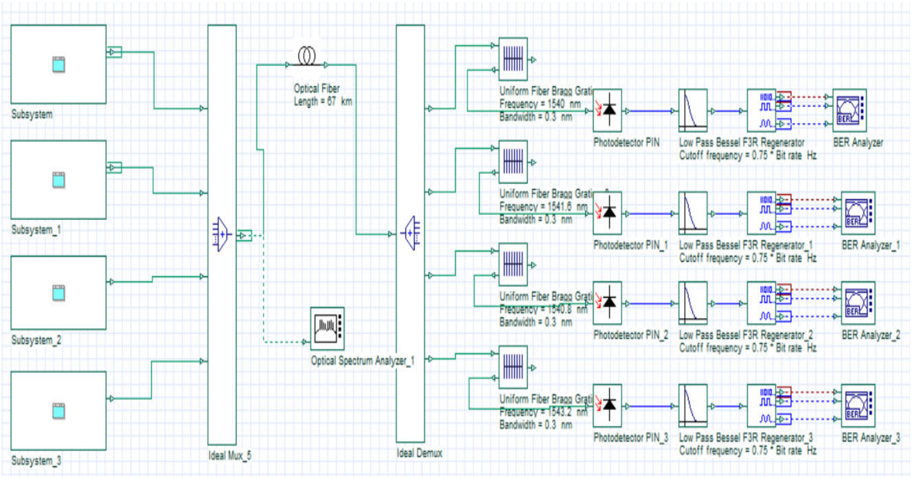
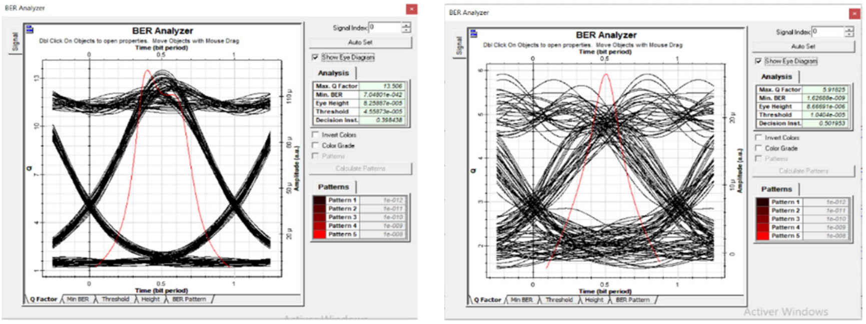


Figure 6 – Simulation design of the proposed VFWZCC scheme for 4 users of code weight 6

Figures 7 a) and 7 b) show the eye diagram and the BER values of the proposed FVWZCC code in the OCDMA system at $10\ GBps$ data rates through two different optical fiber distance lengths $(30\ km, \text{and } 67\ km)$, respectively. As it can be seen, the eye diagram clearly illustrates that the proposed code gives better performance for fiber distance length shorter than $67\ km$ corresponding to the basic required bit error rate value for acceptable system performance (10^{-9}). A shorter fiber distance provides low attenuation and dispersion which decreases the bit error rate and thus improve the performance of the system. The more the eye closes, the more difficult it is to distinguish between ones and zeros in the signal which can be deduced from Figures 6 a) and 6 b). The height of the eye-opening at the specified sampling time shows the noise margin or immunity to noise. The BER value of 1.62×10^{-9} was obtained for a fiber distance of $67\ km$ while it is about 7×10^{-42} for $30\ km$ which is much better and prove the feasibility of the code for optical applications with a data rate of $10\ GBps$.



Max. Q Factor	13.506
Min. BER	7.04801e-042
Eye Height	8.25887e-005
Threshold	4.55873e-005
Decision Inst.	0.398438

Max. Q Factor	5.91825
Min. BER	1.62688e-009
Eye Height	8.66691e-006
Threshold	1.0404e-005
Decision Inst.	0.501953

Figure 7 – Eye diagram for the proposed FVWZCC code at $10\ GBps$ for two optical fiber distances a) $30\ km$, and b) $50\ km$, respectively

Conclusion

A new FVWZCC code design is proposed for multimedia applications in SAC-OCDMA systems. The design procedure is flexible and can be used for any constant or variable code weight number with any number of users based on an appropriate shifting manner of three elementary matrices. The cross-correlation property of value zero between any pairs of users reduces the PIIN interference effects leading to the improvement of the system performance. The performance comparison shows that the proposed code with a good correlation property and a shorter code length which is the same as the reported VWZCCC gives better performance over other constant or variable reported weight codes. Moreover, the good simulation results obtained in terms of the BER and eye diagram of the proposed code design for OCDMA systems at $10\ Gb/s$ with direct detection clearly depict a strong possibility to be used for multimedia applications diversity. The proposed code gives better performance until the fiber distance length value of $67\ km$ corresponds to the basic required bit error rate for the acceptable system performance (10^{-9}). On the other hand, changing code weights (CW or VW) provides better BER from high to low weight for several users fewer than 60 users and moderate up of this amount of users which gives a good way for the choice of the range of number of users with an appropriate quality of service in terms of the minimum desired bit error rate BER. The low complexity and the low-cost design of the receiver using direct detection is another important factor for the implementation of the proposed FVWZCC code.

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Investigaciones de correlación flexible cruzada cero de peso variable (FVWZCC) para aplicaciones multimedia

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CAMPO: telecomunicaciones, transmisiones ópticas
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: En este artículo, proponemos un método novedoso de construcción de código con la propiedad de correlación cruzada cero, la correlación cruzada cero de peso variable flexible (FVWZCC). Este método es simple y flexible, utiliza diferentes pesos de código para soportar diferentes clases de usuarios según su distancia de transmisión y la calidad de los servicios que requieren (datos, audio y video) en sistemas OCDMA. El uso de pesos de código más altos permite el soporte de redes de aplicaciones de mayor prioridad, como redes de largo alcance. La estructura del código ZCC no tiene superposición del bit '1' y puede eliminar eficientemente la interferencia MAI entre usuarios y el ruido PIIN, mejorando así el rendimiento general del sistema.

Métodos: Para la construcción del código FVWZCC propuesto se utilizó la posición cambiante del elemento y el proceso de matriz de concatenación de las tres matrices básicas denominadas vector derecho, matriz básica y vector izquierdo. El análisis matemático y las simulaciones con los software Matlab y Optisystem se utilizaron para evaluar el desempeño del método FVWZCC propuesto en sistemas SAC-OCDMA utilizando la detección directa.

Resultados: Los resultados muestran una mejora significativa en el código presentado en comparación con otros códigos existentes en términos de simplicidad, flexibilidad y costo de implementación. El método utiliza un peso constante o variable con la propiedad de correlación cruzada cero. Para una BER máxima aceptable de 10^{-9}, los resultados de la simulación del sistema SAC-OCDMA que utiliza detección directa bajo el software OptiSystem muestran un mejor rendimiento del código propuesto con cuatro usuarios de peso 6 a 10 Gb/s. Además, puede admitir hasta 60 usuarios simultáneamente y alcanzar una distancia de fibra de unos 67 km. En consecuencia, el código FVWZCC propuesto se puede aplicar para soportar diferentes requisitos de Calidad de Servicio (QOS) con bajo costo y baja complejidad con un receptor de detección directa.

Conclusión: Los hallazgos de este estudio resaltan la necesidad de que el código FVWZCC admita los requisitos de QoS del usuario final. El nuevo enfoque para la construcción de código ofrece implementación de bajo costo, simplicidad y flexibilidad.

Palabras claves: código FVWZCC, OCDMA, ZCC, tasa de error de bits BER.

Исследование нулевой взаимной корреляции с гибкими переменными весами (FVWZCC) для мультимедийных приложений

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РУБРИКА ГРНТИ: 49.40.00 Системы передачи движущихся изображений,
49.33.29 Сети связи
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье представлен новый метод разработки кода со свойством нулевой взаимной корреляции (Flexible Variable Weight Zero Cross-Correlation - FVWZCC). Это простой и гибкий метод, использующий различные веса кода для поддержки разных классов пользователей в зависимости от расстояния передачи и качества требуемых им услуг (передачи данных, аудио и видео) в системах OCDMA. Использование более высокого веса кода обеспечивает поддержку сетей приложений с более высоким приоритетом, таких как сети дальней связи. Структура кода ZCC не перекрывает бит "1" и может эффективно устранять помехи MAI между пользователями и шум PIIN, тем самым повышая общую производительность системы.

Методы: Для разработки предлагаемого кода FVWZCC были использованы сдвиг положения элемента и матричный процесс конкатенации трех базовых матриц, обозначенных как правый вектор, базовая матрица и левый вектор. Математический анализ и моделирование с помощью программного обеспечения Matlab и Optisystem были использованы для оценки *эффективности предложенного метода FVWZCC в системах SAC-OCDMA, использующих прямую детекцию.*

Результаты: Результаты показывают значительное улучшение представленного кода по сравнению с другими существующими кодами с точки зрения простоты, гибкости и стоимости внедрения. В методе используется постоянные или переменные веса со свойством нулевой взаимной корреляции. При удельном значении BER, равном 10-9, результаты моделирования системы SAC-OCDMA с использованием прямого обнаружения в программном обеспечении OptiSystem показывают лучшую производительность предложенного кода с четырьмя пользователями весом 6 со скоростью 10 Гбит/с. Помимо того, он может поддерживать до 60 пользователей одновременно и обеспечивать волоконно-оптическую связь на расстоянии до 67 км. Следовательно, предлагаемый код FVWZCC можно применять для поддержки различных требований к качеству обслуживания (QoS) при низкой стоимости и низкой сложности в использовании детекторного приемника.

Вывод: Результаты данного исследования подчеркивают необходимость в коде FVWZCC для поддержки требований QoS конечного пользователя. Новый подход к разработке кода обеспечивает низкую стоимость внедрения, простоту и гибкость.

Ключевые слова: FVWZCC-код, OCDMA, ZCC, частота ошибок в битах BER.

Испитивање нулте унакрсне корелације флексибилне променљиве тежине (FVWZCC) за примену у различитим медијима

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ОБЛАСТ: телекомуникације, оптички преноси
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У раду се предлаже нова метода за конструисање кода са својством нулте унакрсне корелације (Flexible Variable Weight Zero Cross-Correlation – FVWZCC). Метода је једноставна, флексибилна и користи различите тежине кода да подржи различите класе *корисника зависно од њихове даљине преноса и квалитета услуга које су им потребне (подаци, аудио или видео) у системима OCDMA. Коришћењем тежина вишег кода омогућава се подршка мрежним апликацијама вишег приоритета као што су мреже великог домета. Структура кода ZCC се не преклапа са битом ‘1’ и може ефикасно да елиминише интерференцију MAI међу корисницима, као и PIIN шум, повећавајући тако укупне перформансе система.*

Методе:За конструкцију предложеног кода FVWZCC коришћени су позиција елемента померања и процес конкатенације матрице три основне матрице означен као десни вектор, основна матрица, као и леви вектор. Математичка анализа и симулације помоћу софтверских програма Matlab и OptiSystem коришћене су за евалуацију перформансе предложене методе FVWZCC у системима SAC-OCDMA директном детекцијом.

Резултати: Резултати показују значајан напредак у представљеном коду у поређењу са осталим постојећим кодовима, што се огледа у једноставности, флексибилности и цени имплементације. Метода користи или константну или променљиву тежину са својством нулте унакрсне корелације. За максимално прихватљив BER од 10^{-9}*, резултати симулације система SAC-OCDMA коришћењем директне детекције у софтверу OptiSystem показују боље перформансе од предложеног кода са четири корисника тежине 6 при 10* Gb/s*. Штавише, може да подржава до 60 корисника истовремено и да достигне дужину влакна од око 67 km. Зато предложени код FVWZCC може да подржава захтеве за различит квалитет услуге (QoS), уз ниску цену и једноставну примену са пријемником директне детекције.*

Закључак: Налази ове студије наглашавају потребу за кодом FVWZCC ради подршке захтевима QoS крајњих корисника. Нови приступ конструкцији кода обезбеђује ниску цену имплементације, једноставност и флексибилност.

Кључне речи: код FVWZCC, OCDMA, ZCC, BER (Bit Error Rate).

Paper received on: 18.04.2024.
Manuscript corrections submitted on: 16.11.2024.
Paper accepted for publishing on: 18.11.2024.