Effect of SHIFTZCC codes for Optical CDMA system

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ABSTRACT

In this paper, we propose a novel SAC-OCDMA code called Shift Zero Cross Correlation (SHIFTZCC) code with zero cross correlation property to minimize the Multiple Access Interface (MAI), to be more scalable and secure compared to the other existing SAC-OCDMA codes. This SHIFTZCC code is constructed using address segment and data segment. In this work, the proposed SHIFTZCC code is implemented in an optical network using the Opti-System software for the spectral amplitude coded optical code division multiple access (SAC-OCDMA) scheme. The chief advantage of the proposed SHIFTZCC code is the zero cross correlation property, which reduces both the MAI and other noises improving the system performance. The proposed SHIFTZCC code provides flexibility in selecting the code parameters, supports a large number of users with higher data rate and longer fiber length. Simulation results prove that the optical code division multiple access system based on the proposed SHIFTZCC code supports maximum number of simultaneous users with higher transmission rate, lower bit error rates (BER) and longer travelling distance without any signal quality degradation, as compared to the former existing SAC-OCDMA codes.

Keywords: cross correlation (CC), optical code division multiple access (OCDMA), spectral amplitude coding optical code division multiple access (SAC-OCDMA), multiple access interference (MAI), shift zero cross correlation code (SHIFTZCC) and signal to noise ratio (SNR)

1. INTRODUCTION

Optical code division multiple access (OCDMA) is an advanced form of multiplexing technology for the latest optical networks which created a lot of attention due to its various features including better network flexibility, protocol transparency, asynchronous operation
and enhanced security for allowing dynamic resource sharing between multiple users in an effective way. But the crucial issue in OCDMA system is to find a coding system that can nullify the effects of co-channel interference, multiple access interference (MAI) and various noises. The easiest path to an efficient OCDMA system is to design an efficient code structure with zero cross correlation property which differentiates the target code sequence from other codes and minimizes the MAI and phase induced intensity noise (PIIN). The performance of the OCDMA system depends upon numerous parameters like data rate, number of active users, power of transmitter, bit error rate (BER), signal to noise ratio (SNR) at receiver and finally, code properties. In an OCDMA system, the codeword represents the unique code sequence assigned to each user which consists of either a bit ‘1’ representing the light pulse during that interval or the bit ‘0’ representing the absence of light pulse during that interval.

There are several one-dimensional (1-D) codes available in the literature, which spread either in time or in frequency domain such as Walsh Hadamard codes, optical orthogonal codes (OOC), zero cross-correlation (ZCC) codes, Random diagonal code (RD), Khazani Syed (KS) code, Dynamic cyclic code, multi diagonal code (MD), modified double weight code (MDW), enhanced double weight code (EDW) etc. [1-14]. However, these codes exhibit various limitations in their properties. Since, the cross correlation is not ideal for Walsh Hadamard code, it suffers from multiple access interference (MAI). The code construction is complicated for the OOC, the codes for the OOC and the prime code are too long with a high cross correlation value. The ZCC and MD codes have zero cross-correlation, however the long code length is a disadvantage since either very wide band sources or very narrow filter bandwidths are required [1-2]. EDW and MDW codes have too long code lengths and cross correlation values for these codes are fixed at one. Random diagonal code (RD) offers excellent code length as compared to that of other existing SAC-OCDMA codes. However, the drawback of this RD code is that it possesses variable cross correlation [1]. To overcome these problems in this work, a novel Shift Zero Cross Correlation (SHIFTZCC) code is suggested and compared with other existing SAC-OCDMA codes. The results are found to be suggesting better system performance than other codes in one dimensional OCDMA system.

This paper is organized as follows. The design and construction of the proposed SHIFTZCC code is described briefly in section 2. Section 3 describes the mathematical analysis and the system performance in terms of signal to noise ratio (SNR). Simulation using the opti-system software ver.14 and comparison of the proposed SHIFTZCC code with the other existing SAC-OCDMA codes are explained in section 4. Finally, conclusions are drawn in section 5.

2. THE PROPOSED SHIFTZCC CODE DESIGN

While designing the SHIFTZCC code, care has been taken to ensure the following points as mentioned here.

- The code length should be as small as possible and it should not vary with the number of active users.
- The cross correlation should be zero to minimize MAI and the effect of PIIN.
- The code design procedure should be simple.
- The proposed codes should support large number of active users and high data rate, while achieving the minimum BER.
The novel Shift Zero Cross Correlation (SHIFTZCC) code is constructed by efficiently developing an identity matrix for suitable code length ($K$) and weight of the matrix ($W$) by suitably appending additional weight. In the proposed code, the number of users supported is the order of the matrix where the weight required is the number of 1’s in each row of the matrix.

In an OCDMA system, the signature sequence or the code sequence $C$ consists of unipolar $(0, 1)$ sequence. Generally, a code is denoted as $(N, W, \lambda_a, \lambda_c)$ where $N$ is the code length, $W$ is the code weight, $\lambda_a$ is the auto-correlation and $\lambda_c$ is the in-phase cross correlation. The cross correlation is defined as expressed in equation (1) [1].

$$\lambda_c = \sum_{i=1}^{N} X_i Y_i$$  \hspace{1cm} (1)

for any $X \neq Y \in C$ and any integer $i$.

Many OCDMA code strategies are proposed where the major limitations of designing the codes are to reduce the multiple access interference (MAI), code length and code weight. But in almost all the existing SAC-OCDMA codes, the code length increases with the increase in the number of users. As a result, the cross correlation becomes more than unity resulting in higher MAI. To reduce the MAI, the cross correlation should be as small as possible and auto-correlation should be higher. Therefore, in this work care has been taken to design a novel SAC-OCDMA code to reduce the code length, to keep the cross correlation zero and to keep the auto correlation maximum. In the proposed code, the central wavelength for each of the users can also be varied without altering the performance of the OCDMA system. The following steps describe the construction of SHIFTZCC code for various orders.

2.1. SHIFTZCC CODE CONSTRUCTION FOR VARIOUS VALUES OF $K$ AND $W$:-

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

Step 1: Generation of combined matrix

We have taken two matrices as the weight is considered to be two. First matrix is an identity matrix and the next matrix is a null matrix of same dimension as the identity matrix. Number of matrix taken equals to the weight value considered. The dimension of identity matrix is $3 \times 3$ as the number of users taken 3. Dimension of matrix equals to the number of active users.

Therefore, two $3 \times 3$ dimension matrixes are

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{and} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$
The two combined matrices together are shown as

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
\end{bmatrix}
\]

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

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

Last row shifting as per the above rule looks as

\[
[0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0] \rightarrow [0 \ 0 \ 0 \ 0 \ 1 \ 0]
\]

Middle row shifting as per the above rule looks as

\[
[0 \ 1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0] \rightarrow [0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 0]
\]

First row shifting as per the above rule looks as

\[
[1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0] \rightarrow [1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]
\]

Shifted matrix looks as shown below

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
\end{bmatrix}
\]

**Step 3: Replacing**

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

Last row replacing

\[
[0 \ 0 \ 0 \ 0 \ 1 \ 0] \rightarrow [0 \ 0 \ 0 \ 0 \ 1 \ 1]
\]
Middle row replacing

\[
\begin{bmatrix}
0 & 0 & 1 & 0 & 0 & 0
\end{bmatrix} \rightarrow \begin{bmatrix}
0 & 0 & 1 & 1 & 0 & 0
\end{bmatrix}.
\]

First row replacing

\[
\begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \rightarrow \begin{bmatrix}
1 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

The final SHIFTZCC code matrix is obtained as

\[
\begin{bmatrix}
1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 1
\end{bmatrix}
\]

Similarly, for the SHIFTZCC code for \(K=4, W=2\), is shown as

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

So, the code word for each user according to the above example would be:

\[
\text{Code word} = \begin{cases}
\text{user1} = \lambda_1, \lambda_2 \\
\text{user2} = \lambda_3, \lambda_4 \\
\text{user3} = \lambda_5, \lambda_6 \\
\text{user4} = \lambda_7, \lambda_8
\end{cases}
\]

Similarly, the SHIFTZCC code word for \(K=4\) and \(W=3\) is shown as

\[
\text{Code word} = \begin{cases}
\text{user1} = \lambda_1, \lambda_2, \lambda_3 \\
\text{user2} = \lambda_4, \lambda_5, \lambda_6 \\
\text{user3} = \lambda_7, \lambda_8, \lambda_9 \\
\text{user4} = \lambda_{10}, \lambda_{11}, \lambda_{12}
\end{cases}
\]
If the same pattern is followed the SHIFTZCC code for K=5, W=3 will be as

$$A_1 = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 \ \end{bmatrix}$$

Similarly other codes can be constructed for K no of users by using the basic code $C_B = [1 \ 1 \ \cdots \ \ W+1]$. Therefore, to support large no of subscribers (K) with a fixed value of code weight (W), the basic code block ($C_B$) is repeated K times to produce the following SHIFTZCC matrix:

$$A_{K-1} = \begin{bmatrix} C_B & 0 & 0 & 0 & 0 \ 0 & C_B & 0 & 0 & 0 \ 0 & 0 & C_B & 0 & 0 \ \cdots & \ \cdots & \ \cdots & \ \cdots \ 0 & 0 & 0 & 0 & C_B \ \end{bmatrix}$$

Here, the code length (N) = Code weight (W) X Number of user (K) = $W \times K$. The final code is designed as below.

$$Z = [D \quad C]$$ where $D$ is the Data segment & $C$ is the Code segment.

The Novel SHIFTZCC code sequence for W=3, K=5 and N=15 will be:

$$D = \begin{bmatrix} 1 & 1 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ \end{bmatrix}, \quad C = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 \ \end{bmatrix}$$

So, the novel code becomes

$$Z = [D \quad C] = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 \ \end{bmatrix}_{5 \times 15}$$

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The SHIFTZCC code family is constructed based on the following conditions

(a) \( N \leq K \) and \( W = C_B \) (code block) for data segment \( (D) \)

(b) \( N > K \) and \( W = C_B \) (code block) for code segment \( (C) \)

**Fig. 1.** Flow chart for the novel SHIFTZCC code family construction.

Figure 1 shows the flow chart step of the novel SHIFTZCC code family Construction. So, the code word for each user according to the above example would be:

\[
\text{Code word} = \begin{cases} 
\text{user1} = \lambda_1, \lambda_2, \lambda_3 \\
\text{user2} = \lambda_4, \lambda_5, \lambda_6 \\
\text{user3} = \lambda_7, \lambda_8, \lambda_9 \\
\text{user4} = \lambda_{10}, \lambda_{11}, \lambda_{12} \\
\text{user5} = \lambda_{13}, \lambda_{14}, \lambda_{15} 
\end{cases}
\]

The novel SHIFTZCC code design represents those changing matrices elements resulting in a constant property of zero cross correlation and improving auto correlation resulting in cancellation of MAI. The novel SHIFTZCC code provides more flexibility in choosing \( W \) and \( K \) parameters for its design to supply a large number of users compared to the other codes. The code length of the proposed novel SHIFTZCC code depends on the weight \( (W) \) of the code.
Fig. 2. RTL Schematic for the novel SHIFTZCC code family construction for 3 users with weight 2 (TOP view).
Fig. 3. RTL Schematic for the novel SHIFTZCC code family construction for 3 users with weight 2.
**Fig. 4.** Code generation logic for the novel SHIFTZCC code family construction using Xilinx 9.2i for 3 users with weight 2.
Fig. 5. SHIFTZCC code output family construction for 3 users with weight 2 using Xilinx 9.2i.
The proposed SHIFTZCC code is generated using Xilinx version 9.2i and the RTL schematics are shown in figures 2 & 3, code generation logic in figure 4 and the output SHIFTZCC code obtained is shown in Figure 5. For simplicity, the RTL schematics and the output codes are shown for 3 numbers of active users with weight 2.

Table 1 shows the code length (N), Weight (W) and Cross Correlation value (\( \lambda_c \)) that is required for different existing codes to support 30 users. It is shown that the proposed SHIFTZCC exhibits the least code length as compared to the other existing codes for 30 numbers of active users with zero cross correlation.

**Table 1.** Comparison of different properties of proposed SHIFTZCC and other codes

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Code</th>
<th>No. of users</th>
<th>Weight</th>
<th>Code length</th>
<th>Cross correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MD</td>
<td>30</td>
<td>2</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>OOC</td>
<td>30</td>
<td>4</td>
<td>364</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Prime Code</td>
<td>30</td>
<td>31</td>
<td>961</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>EDW</td>
<td>30</td>
<td>3</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>MDW</td>
<td>30</td>
<td>4</td>
<td>90</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>SHIFT ZCC</td>
<td>30</td>
<td>2</td>
<td>60</td>
<td>0</td>
</tr>
</tbody>
</table>

3. SYSTEM PERFORMANCE ANALYSIS (GAUSSIAN APPROXIMATION)

For the analysis of our system, Gaussian approximation is used for the calculation of BER as SHIFTZCC code exhibits zero cross correlation property and hence, there is no overlapping in the spectra of different users minimizing various types of noises. In this work, for the SHIFTZCC code, thermal noise (\( \sigma_t \)), phase induced intensity noise (\( \sigma_{PIN} \)) and shot noise (\( \sigma_{sh} \)) in the photo detector is considered.

The performance of an optical receiver depends on the signal to noise ratio (SNR). The SNR of an electrical signal is defined as the average signal power to noise power (SNR= \( \frac{I^2}{\sigma^2} \)) where, \( \sigma^2 \) is defined as the variance of different noise sources, I is the average photo current and \( I^2 \) is the power of I. For SHIFTZCC coding

\[
\sigma^2 = \sigma_{sh} + \sigma_t + \sigma_{PIN} = 2eIB + \frac{4K_B T_n B}{R_L} + I_{PIN}^2 Bt_c \tag{2}
\]
where $e$ represents the electronic charge, $B$ is the noise equivalent of the electrical bandwidth of the receiver, $k_B$ is the Boltzmann’s constant, $T_{n}$ is the absolute receiver temperature, $R_L$ is the receiver load resistance, $t_c$ is the coherent time for light incident onto the photo diode and $I_{PHN}$ is PIIN photo noise current.

$C_k(i)$ represents the $i$-th element of the $k$-th SHIFTZCC code sequence. According to the properties of SHIFTZCC code, the direct detection technique is expressed as:

$$
\sum_{i=1}^{N} C_k(i)C_l(i) = \begin{cases} 
W(k = l) & \\
0 & \text{(otherwise)}
\end{cases} 
$$

(3)

Since shot noise and thermal noise obey negative binomial distribution, the following assumptions are used to analyze the system with transmitter and receiver without much difficulty and for mathematical straightforwardness [10]

The assumptions are:

- Individual light sources ideally unpolarized and their spectrum is flat over the bandwidth $\left[ v_0 - \frac{\Delta v}{2}, v_0 + \frac{\Delta v}{2} \right]$ where $v_0$ represents the central optical frequency and $\Delta v$ represents the optical bandwidth in Hz.
- Power spectral component have identical spectral width.
- Every user has equal transmitted power and synchronized bit stream.

Using these assumptions, the performance of the system is analyzed using Gaussian approximation. The power spectral density (PSD) of the received optical signal is described as [11]:

$$
r(v) = \frac{P_s}{\Delta v} \sum_{k=1}^{k} b_k \sum_{i=1}^{N} c_k(i)rect(i,v)
$$

(4)

where, $P_s$ is the effective power of a broadband source at the receiver, $k$ is the number of active users, $N$ is the SHIFTZCC code length, $b_k$ is the data bit of the $k$-th user.

The $rect(i,v)$ function in (4) can be expressed as .

$$
rect(i,v) = u \left[ v - v_0 - \frac{\Delta v}{2N} (-N + 2i - 2) \right] - u \left[ v - v_0 - \frac{\Delta v}{2N} (-N + 2i) \right]
$$

(5)

where $u(v)$ represents the unit step function.

When a broadband pulse is source input to a group of fiber Bragg gratings, the incoherent light fields are mixed and applied to the photo detector, and the phase noise of the fields appear in the photo detector output. The coherence time of the thermal source ($t_c$) is expressed as:
\[ t_c = \frac{\int_{0}^{\infty} G^2(v) dv}{\left[ \int_{0}^{\infty} G(v) dv \right]^2} \]  

(6)

where, \( G(v) \) is the single sideband power spectral density (PSD) of the source.

From (6), the sum of power spectral density at the photo detector of the \( i \)-th receiver during one period can be found by

\[ \int_{0}^{\infty} G(v) dv = \left[ \int_{0}^{\infty} \frac{P_r}{\Delta v} \sum_{k=1}^{k} b_k \sum_{i=1}^{N} c_k(i)c_i(i) \text{rect}(i,v) \right] dv \]  

(7)

Substituting (5) in (4), we get (8) and it is expressed as:

\[ \int_{0}^{\infty} G(v) dv = \frac{P_r}{\Delta v} \left[ \sum_{k=1}^{k} b_k W \frac{\Delta v}{N} \right] \]  

(8)

where, \( b_k \) is the Data Bit of the \( k \)-th user and that takes the value of either one or zero. When all users transmit bit ‘1’, then

\[ \left[ \sum_{k=1}^{k} b_k \right] = [b_1 + b_2 + b_3 + \cdots + b_k] = W \]  

(9)

Therefore (8) is simplified and written as:

\[ \int_{0}^{\infty} G(v) dv = \frac{P_r W^2}{N} \]  

(10)

The photo current ‘I’ is described as in (11)

\[ I = \Re \int_{0}^{\infty} G(v) dv = \frac{\Re P_r W^2}{N} \]  

(11)

where \( \Re \) is the Responsivity of the photo detector.

The average power of signal is represented as

\[ I^2 = \left( \frac{\Re P_r W^2}{N} \right)^2 \]  

(12)
The phase induced intensity noise (PIIN) power for SHIFTZCC code for various weight parameters ($W$) can be expressed as [12]

\[ I_{PIIN}^2 = \frac{P_{WBR}^2}{\Delta v} \]  

(13)

Substituting (11) and (13) in (2), the noise power is found and is expressed as:

\[ \sigma^2 = \frac{2eBP_r\mathfrak{R}W^2}{N} + \frac{4K_B BT_n}{R_L} + \frac{P_{WBR}^2}{\Delta v} \]  

(14)

Since the probability of sending bit ‘1’ is 0.5, (14) becomes

\[ \sigma^2 = \frac{eBP_r\mathfrak{R}W^2}{N} + \frac{2K_B BT_n}{R_L} + \frac{P_{WBR}^2}{2\Delta v} \]  

(15)

From (12) and (15), the average SNR is calculated as [9]:

\[
\text{SNR} = \frac{I^2}{\sigma^2} = \left[ \frac{\left( \frac{\mathfrak{R}P_r W^2}{N} \right)^2}{\frac{eBP_r\mathfrak{R}W^2}{N} + \frac{2K_B BT_n}{R_L} + \frac{P_{WBR}^2}{2\Delta v}} \right]
\]  

(16)

The probability of error ($P_e$) or the bit error rate (BER) is estimated using gaussian approximation [14]:

\[ P_e = BER = \frac{1}{2} erfc \left( \sqrt{\frac{\text{SNR}}{8}} \right) \]  

(17)

The $\text{SNR}$ represents the signal to noise ratio and “$erfc$” is the error complimentary function.

4. SIMULATION AND OBSERVATION

4.1. SIMULATION SETUP

The developed SHIFTZCC codes are validated using an OCDMA trans-receiver circuit. The receiver in the circuit employs a direct detection receiving technique. This OCDMA trans-receiver circuit simulated using opti-system v12.0 software. Figure 6 presents the simulation circuit for 3 users [1].

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Fig. 6. A simulation circuit for 3 users.
As shown in the Figure 6, in the encoder side continuous wave (CW) lasers are used as optical source with the input power varying from 0 dBm to -10 dBm, which produces pulses with a repetition rate equal to the bit rate of the system. The code chips for different users are given as input through the user defined bit sequence generators and are encoded to the equivalent non return to zero (NRZ) signals. A Mach-Zehnder modulator modulates the signals/data.

The modulated signals are multiplexed in a WDM multiplexer or may be combined in a power combiner and then are transmitted through a standard single mode optical fiber with the natural channel parameters as specified in Table 2. In the receiver side, a demultiplexer is used to transmit the data to three different receivers. For each receiver, a uniform fiber Bragg grating (FBG) is allocated that acts as a band pass filter used to filter the received signal corresponding to the transmitted wavelength at the source. A PIN photo diode detector is used to convert optical data to electrical signal which is then transmitted through a low pass Gaussian filter to recover the data and regenerators. A visualizer (eye diagram analyzer) is connected at the end to analyze the received signal.

The table 2 depicts the parameters used in the simulation.

Table 2. System parameters used in the simulation.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>PARAMETERS</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Line encoding</td>
<td>NRZ</td>
</tr>
<tr>
<td>2</td>
<td>Effective Power source</td>
<td>0 to -10 dBm</td>
</tr>
<tr>
<td>3</td>
<td>Number of users</td>
<td>20 to 120</td>
</tr>
<tr>
<td>4</td>
<td>Operating Wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>5</td>
<td>Fiber length</td>
<td>10 to 50 km</td>
</tr>
<tr>
<td>6</td>
<td>Data rate</td>
<td>622 Mbps to 1 Gbps</td>
</tr>
<tr>
<td>7</td>
<td>Received power</td>
<td>0 to -35 dBm</td>
</tr>
<tr>
<td>8</td>
<td>Fiber attenuation</td>
<td>0.2 dB/km</td>
</tr>
<tr>
<td>9</td>
<td>Dispersion</td>
<td>16.75 ps/nm/km</td>
</tr>
<tr>
<td>10</td>
<td>PMD coefficient</td>
<td>0.5 ps/sqrt(km)</td>
</tr>
<tr>
<td>11</td>
<td>Filter cutoff frequency</td>
<td>0.75*Bit Rate</td>
</tr>
</tbody>
</table>
4.2. SIMULATION RESULT AND OBSERVATION

To test the efficiency of the proposed SHIFTZCC code various simulation tests are carried out and compared with the performance of recently developed codes addressed in the literature.

Figure 7 compares the proposed SHIFTZCC code with different existing SAC-OCDMA codes in terms of bit error rate (BER) for different numbers of active users. It is observed from the figure 7 that the SHIFTZCC exhibits least BER compared to the existing SAC-OCDMA codes such as FFH, MQC, and WALSH HADAMARD codes for almost different number of active users. This experiment proves that the proposed codes can be used for more than 60 active users while maintaining a low BER and are better compared to the other codes at a data rate of 1Gbps [17].

![Figure 7. Comparison of BER (log) versus the active number of users for the proposed SHIFTZCC code with the other existing SAC-OCDMA codes [17].](image)

Figure 8 compares the proposed SHIFTZCC code with a multi service code (MS) in terms of BER for different numbers of active users. It is observed from the figure that the proposed SHIFTZCC code exhibits lower BER compared to the MS code for almost different number of active users. This experiment is simulated at a data rate of 622Mbps and the input power was kept fixed at -10 dBm. It is observed from the results that the proposed codes can accommodate more than 80 simultaneous active users while maintaining a low BER [15]. When the number of active users are fixed at 80, the BER of the proposed SHIFTZCC code levels at $10^{-18}$ well below the threshold value of $10^{-12}$. This simulation experiment reveals that the proposed SHIFTZCC code can accommodate more than 80 numbers of active users.

Figure 9 compares the proposed SHIFTZCC code with other existing SAC-OCDMA codes such as MS and ZCC codes in terms of code length for different numbers of active users. It is observed from the figure that the proposed SHIFTZCC code exhibits minimum code length compared to the other existing SAC-OCDMA codes for almost different number of active users when the weight of the code is kept fixed at two. However, it is also observed
that the proposed SHIFTZCC code requires the least code length compared to that of the MS code and the code length exactly matches to that of the ZCC code when the weight of the code equals to four [15].

Fig. 8. Comparison of BER (log) versus the active number of users for the proposed SHIFTZCC code with the multi service (MS) SAC-OCDMA codes [15].

Fig. 9. Comparison of code length versus the active number of users for the proposed SHIFTZCC code with the other existing SAC-OCDMA codes [15].

Figure 10 compares the proposed SHIFTZCC code with a variable cross correlation (VCC) code in terms of BER for different fiber lengths at two different data rates 622 Mbps and 2.5 Gbps for a fixed value of active users. It is observed from the figure that the proposed SHIFTZCC code exhibits lesser BER compared to the VCC code for different fiber lengths at respective 622 Mbps and 2.5 Gbps data rates when the numbers of active users are kept fixed.
at six. The pattern observed is similar for both the codes. For example, the BER for a particular code say, the proposed SHIFTZCC code at a distance of 30 km at 622 Mbps is less compared to that of BER for the SHIFTZCC code at 30 km at 2.5 Gbps. Since Data rate and BER are inversely proportional to each other, this experiment clearly indicates that both the proposed SHIFTZCC codes at different data rates are suitable for a fiber distance of more than 35 km while maintaining the threshold value of BER. On other hand, the variable cross correlation code is suitable only for 20-25 km [16].

![Graph comparing BER (log) versus the active number of users for the proposed SHIFTZCC code with the VCC codes at different data rates](image)

**Fig. 10.** Comparison of BER (log) versus the active number of users for the proposed SHIFTZCC code with the VCC codes at different data rates [16].

Figure 11 compares the multi service (MS) code with the proposed SHIFTZCC code. It is found from the plot that the proposed SHIFTZCC code exhibits a BER value of $10^{-20}$ and that is well below the threshold value of $10^{-12}$ even when the received power at the receiver is -12 dBm. The graph shows simulation for 30 numbers of active users, keeping the weight of the proposed SHIFTZCC code at 4. The performance of the proposed SHIFTZCC code matches with that of the MS (NB=2) code when the received power is at -12 dBm and falls below -12 dBm. However, when the received power is above -12 dBm, the performance of the proposed SHIFTZCC code is better compared to that of MS (NB=2) code, MS (NB=4) code exhibits the least performance and MS (NB=3) exhibits moderate performance where NB represents different number of users in the basic code matrix [15].

Figure 12 exhibits the plot of comparison of the received power (dBm) versus the fiber length (km) for the proposed SHIFTZCC code (N=30, W=4) with the other existing SAC-OCDMA codes such as OOC, WALSH, ZCC. It is observed from the plot that the received power is decreasing uniformly with the increase in fiber length. But, the proposed SHIFTZCC code has the maximum received power representing better signal quality and is simulated using NRZ modulation format, while other codes such as OOC, WALSH, and ZCC are simulated using NRZ raised cosine modulation format [19].
Fig. 11. Comparison of BER (log) versus the received power (dBm) for the SHIFTZCC code (N=30, W=4) with the multi service (MS) code for different values of NB [15].

Fig. 12. Comparison of received power (dBm) versus the fiber length (km) for the proposed SHIFTZCC code (N=30, W=4) with the other existing SAC-OCDMA codes such as OOC, WALSH, ZCC [19].

Figures 13 and 14 represent the eye diagrams of the proposed SHIFTZCC code at 622 Mbps while keeping the fiber length fixed at 40 km and the number of active users are kept fixed at ten and five respectively.
Fig. 13. Eye diagram indicating performance of ten users with a weight of four, using the proposed SHIFTZCC code.

Fig. 14. Eye diagram indicating performance of five users with a weight of four, using the proposed SHIFTZCC code.
It is found that the BER is lesser than many other existing SAC-OCDMA codes such as ZCC code and MD code as addressed by the authors recently [3,18]. All other simulation parameters are kept identical to that of MD code. The MD code exhibits a BER of $10^{-13}$ for ten numbers of active users and the proposed SHIFTZCC code exhibits a BER of $10^{-36}$ for the same numbers of active users.

5. CONCLUSIONS

A novel code, referred in this work as SHIFTZCC code with zero cross correlation property for SAC-OCDMA system is successfully designed and simulated. The new code family shows better system performance as compared to the former SAC-OCDMA codes with the same system complexity. The SHIFTZCC code offers several advantages such as zero cross correlation, minimum BER, more flexibility and simple code construction as compared to that of other existing SAC-OCDMA codes. Also, this code features better flexibility in choosing the code parameters (e.g., number of users, distance of the fiber, the code weight and cross correlation) and the number of users can be increased without much increase in the code weight and code complexity. In the absence of multiple access interference and phase induced intensity noise, the OCDMA system shows excellent performance. Unlike the other existing SAC-OCDMA codes, for the proposed SHIFTZCC code, the code length is minimum when the weight is fixed at two without altering the performance of the system. Finally, simplicity in the code construction, flexibility in cross correlation control and minimum bit error rate during transmission has made this code suitable for future OCDMA applications. It is observed from the simulation experiments that the proposed SHIFTZCC code supports 80-100 active users at 622 Mbps, 60 simultaneous active users at 1 Gbps respectively. The proposed code can accommodate a fiber distance of 35-40 km with an acceptable level of BER at different data rates. This implies that the code is suitable for FTTH (fiber to the home) applications at a data rate of 622 Mbps to 10 Gbps. The proposed SHIFTZCC code maintains the BER well below the threshold value of $10^{-12}$ even when the received power is below -12 dBm. It is also observed that the proposed SHIFTZCC code exhibits maximum received power as compared to that of OOC, WALSH HADAMARD AND ZCC code, while the fiber length is varied from 0 km to 25 km.

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