Performance improvement of multi access OCDMA system based on a new zero cross correlation code

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Abstract. In this paper, a novel zero cross correlation (ZCC) code is proposed for spectral amplitude coding-optical code division multiple access (SAC-OCDMA) systems. The code construction method starts from the identity matrix and has several benefits summarized in both the code simplicity and flexibility. The proposed code presents also an adapted (or accepted) code length for SAC-OCDMA systems and a high SNR value that reaches respectively 3.18 and 1.84 times of the system capacity comparing to other existed codes such as modified quadratic congruence (MQC) and modified double weight (MDW) codes.

1. INTRODUCTION

Optical code division multiple access (OCDMA) technique is characterized by multiple advantages that make researchers more attracted to investigate its features comparing to time division multiple access (TDMA) or frequency division multiple access (FDMA). It employs orthogonal codes for securing the range of spectrum without overlapping it with the others [1]. It presents a spread spectrum technique that permits sharing the channel bandwidth between users by given each of them a specific code namely a sequence code [2]. However, OCDMA systems suffer always from different noises like: thermal noise, shot noise, dark current and multiple access interference (MAI) which leads to create a phase induced intensity noise (PIIN) [1,3]. Phase induced intensity noise (PIIN) is considered as one of the dominant factors of decreasing the system performance [4]. Accordingly, several codes such as: modified double weight [5], modified Quadratic Congruence (MQC) [6] and zero cross correlation [7] are proposed for OCDMA systems to outperform this issue. However, these codes suffer from many drawbacks such as: long code length, in-phase cross correlation which is always higher to one, non-null cross correlation value and complex construction steps [4].
Accordingly, this paper presents a novel ZCC code for OCDMA systems which compared other reported codes families of MDW, MQC codes.

This paper is structured as: Section II describes the steps of constructing the novel ZCC code, sections III and IV analyzes the system performance results and section V ended by a conclusion.

2. ZCC CODE CONSTRUCTION

Let take two different codes sequences:

\[ A_i = \{A_0, A_1, A_2, \ldots, A_N \} \] and \[ B_i = \{B_0, B_1, B_2, \ldots, B_N \} \], it can be define the auto and cross correlation as [8]:

\[
\lambda_a = \sum_{i=1}^{N} A_i \cdot A_{i+t} \quad (1) \\
\lambda_c = \sum_{i=1}^{N} A_i \cdot B_{i+t} \quad (2)
\]

The novel ZCC code can be defined by these parameters: \((L, w, C)\) where each of them presents code length, code weight and system capacity. It should to construct a novel code which high auto correlation and cross correlation null.

It can describe the method of ZCC code construction by the following steps:

A. **Step 1**

Create an identity matrix \(A_N\). For example \((N = 3)\), it gives the following matrix:

\[
A_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)
\]

B. **Step 2**

Starting from shifting of rows property and for an identity matrix with order \((N)\), the rule of required rotation number is \((N-1)\). After applying this rule, the rotations number is \((2)\). We will obtain a new matrix which also rotated by \((2)\). Consequently, we will obtain these matrices:

\[
A_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad A'_3 = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}, \quad A''_3 = \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \quad (4)
\]

C. **Step 3**

Write \(A_3\) matrix with the following form:

\[
A_3 = \begin{bmatrix} r_1(A_3) \\ r_2(A_3) \\ r_3(A_3) \end{bmatrix} \quad (5)
\]

Where \(r_1(A_3)\), \(r_2(A_3)\) and \(r_3(A_3)\): represent 1\(^{st}\) row, 2\(^{nd}\) row and 3\(^{rd}\) row of matrix \(A_3\) respectively. By using the method, both \(A'_3\) and \(A''_3\) can be written as:

\[
A'_3 = \begin{bmatrix} r_1(A'_3) \\ r_2(A'_3) \\ r_3(A'_3) \end{bmatrix} ; \quad A''_3 = \begin{bmatrix} r_1(A''_3) \\ r_2(A''_3) \\ r_3(A''_3) \end{bmatrix} \quad (6)
\]
D. Step 4
Reshape each of matrices $A_3$, $A'_3$ and $A''_3$ to row vector as:

\[
\begin{align*}
A_3 &= [r_1(A_3), r_2(A_3), r_3(A_3)] \rightarrow (A_3 = [1 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 1]) \\
A'_3 &= [r_1(A'_3), r_2(A'_3), r_3(A'_3)] \rightarrow (A'_3 = [0 \ 1 \ 0 \ 0 \ 1 \ 1 \ 0 \ 0]) \\
A''_3 &= [r_1(A''_3), r_2(A''_3), r_3(A''_3)] \rightarrow (A''_3 = [0 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 1 \ 0])
\end{align*}
\]

E. Step 5
Finally, by combining between these reshaped matrices, we will obtain the novel ZCC code as:

\[
ZCC_1 = [A_3 \ A'_3 \ A''_3] \rightarrow ZCC = [1 \ 0 \ 0 \ 0 \ 1 \ 0 \ 0 \ 0 \ 1] \\
\text{yielded} \rightarrow ZCC = [0 \ 1 \ 0 \ 0 \ 1 \ 1 \ 0 \ 0 \ 0 \ 1 \ 0]
\]

The relationship between code length (L) and number of user (K) of the code is given by:

\[
\begin{align*}
K &= N \\
L &= N^2 \rightarrow L = K^2
\end{align*}
\]

According to the above ZCC matrix, the codeword for each user would be:

\[
\text{codewords} = \begin{cases} 
\text{user} 1 \rightarrow \lambda_1, \lambda_5, \lambda_9 \\
\text{user} 2 \rightarrow \lambda_2, \lambda_6, \lambda_7 \\
\text{user} 3 \rightarrow \lambda_3, \lambda_4, \lambda_8
\end{cases}
\]

According to Eqs. (1) and (2), and features of our code, we can write:

\[
\begin{align*}
\lambda_a &= w \\
\lambda_c &= 0
\end{align*}
\]

| Code       | Code weight | Number of users | Code length | Cross correlation |
|------------|-------------|----------------|-------------|-------------------|
| MQC code   | 4           | 9              | 12          | $\geq 1$          |
| MDW code   | 4           | 4              | 18          | $\geq 1$          |
| Proposed   | 4           | 4              | 16          | 0                 |
| ZCC        |             |                |             |                   |

3. SYSTEM PERFORMANCE ANALYSIS
To make the system analysis easier, it take a consideration these following assumptions [9-11]:

1- Unpolarized light source ideally with flat spectrum over $[f_0 - \Delta f, f_0 + \Delta f]$ of bandwidth, where $f_0$ and $\Delta f$ are the central optical frequency and the optical source bandwidth respectively and it estimated in Hertz.

2- The same power for each transmitter.

3- An identical spectral for each component of power spectral.

4- Each bit stream from each user is synchronized.

To evaluate the SAC-OCDMA system with ZCC code, it takes a consideration the effect of shot and thermal noises and the PIIN is neglected due zero cross correlation property. The dark current noise can be written as [9, 11]:

\[
I_{\text{noise}}^2 = I_{\text{shot}}^2 + I_{\text{thermal}}^2 = 2eBId + \frac{4K_BT_aB}{R_l}
\]

(12)
Where \( e, B, I_{dd}, K_b, T_n \) and \( R_l \) present electron charge, electrical bandwidth, output of direct current, Boltzmann’s constant, absolute temperature and load resistor respectively. The output of direct current can be expressed [9-11]:

\[
I_{dd} = R \int_{0}^{\infty} r(v)dv = R \int_{0}^{\infty} \frac{P_{sr}}{\Delta f} \sum_{k=1}^{c} d(k) \sum_{j=1}^{L} C_F(j). C_F(j) \Pi(v, i)dv
\]

(13)

Where \( R \) and \( P_{sr} \) present the photo-diode responsivity and received power respectively. \( d(k) \) is the data bit which can be ‘’0’’ or ‘’1’’. The \( \Pi(v, i) \) function can be defined as:

\[
\Pi(v, i) = u \left\{ f - f_0 - \frac{\Delta f}{2L} (-L + 2i - 2) \right\} - u \left\{ f - f_0 - \frac{\Delta f}{2L} (-L + 2i) \right\} = u \left( \frac{\Delta f}{L} \right)
\]

(14)

Where \( u(f) \) present the unit step function defined as:

\[
u(f) = \begin{cases} 1 & f \geq 0 \\ 0 & f < 0 \end{cases}
\]

(15)

Let \( C_F(j) \) presents the \( j^{th} \) element of \( C^{th} \) user and according to our proposed ZCC code, the cross correlation of direct detection can be written as:

\[
\sum_{j=1}^{L} C_F(j). C_F(j) = \begin{cases} w & \text{for } E = F \\ 0 & \text{else} \end{cases}
\]

(16)

Substituting Eqs. (14) and (16), Eq. (13) of output photo-current will be:

\[
I_{dd} = R P_{sr} C
\]

(17)

Based on Eq. (17) and with take account the probability of transmitting ‘’0’’ or ‘’1’’ is the same and equal to (0.5) Eq. will write as:

\[
I_{noise}^2 = eBR P_{sr} C + \frac{4K_bT_nB}{R_l}
\]

(18)

The average signal to noise ratio can be given as:

\[
SNR = \frac{I_{dd}^2}{I_{noise}^2}
\]

(19)

Using the Gaussian approximation, the bit error rate (BER) is given by [2, 9, 10, 11]:

\[
BER = \frac{1}{2} erf \frac{1}{2} \sqrt{SNR/8}
\]

(20)

4. RESULT DISCUSSION:

This section explain the s SAC-OCDMA system performance with a novel ZCC code in two terms: signal to noise ratio (SNR) and bit error rate (BER) against number of simultaneous users. Used parameters for numerical analysis are listed in table 2.
Table 2. Used parameters in numerical analysis.

| Parameter                              | Value                |
|----------------------------------------|----------------------|
| Photo-diode responsivity (R)           | 0.6                  |
| Effective source power ($P_{sr}$)      | -10 dBm              |
| Data rate ($R_b$)                      | 622 Mb/s             |
| Electron charge (e)                    | $1.6 \times 10^{-19}$ c |
| Receiver noise temperature ($T_n$)     | 300 K                |
| Boltzmann’s constant ($K_b$)           | $1.38 \times 10^{-23}$ J s$^{-1}$ |
| Receiver load resistor ($R_L$)         | 1030 ohm             |
| Spectral width (Δν)                    | 3.75 Thz             |

Figure 1 shows the SNR variation as function of number of active users for effective power of $-10 \, dBm$ and 622 Mb/s of data rate. It seems that our code has higher power and that’s due to zero cross correlation property which has been canceled the PIIN effect and increased from desired signal power comparing to noise power.

In figure 2, it shows the BER variation as function of number of active users for the same code weight which equal to (4). It seems that our code has minor BER and can support higher number of users. For the same acceptable BER, the system can support 22, 38 and 70 of number users for MQC, MDW and ZCC codes. Thus system capacity has been enhanced up to 3.18 and 1.84 times comparing with MQC and MDW codes respectively.
Finally, figure 3 shows the BER variation as function of power source at receiver level for 50 of number of active user. It seems that our proposed system needs minor power at receiver reaches around $-12.6 \text{ dBm}$ comparing to other systems using MQC and MDW codes where SAC-OCDMA using MQC code does not reach an acceptable BER and using MDW code, the received power reaches around $-6.4 \text{ dBm}$ which is about half the energy of our system.

5. CONCLUSION

In this paper, a novel ZCC code is developed for SAC-OCDMA systems based on shifting rule property. The codes provides several advantages presented in its weight simplicity and flexibility, an efficient zero cross correlation property that permits a large MAI and PIIN minimization, a high auto-correlation and a short code length. In addition to OCDMA system employing the new ZCC code can support a high cardinality and signal power in terms of acceptable BER comparing to MQC and MDW codes.
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