ENHANCING SYSTEM CAPACITY FOR 2D SPECTRAL TEMPORAL OPTICAL CODE DIVISION MULTIPLE ACCESS SYSTEMS

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https://doi.org/10.26782/jmcms.2020.01.00022

Abstract

Spectral and spatial two-dimensional optical code division multiple access (2D-OCDMA) systems cannot support low cost passive optical networks (PON) due to the extensive use of optical fiber media. Consequently, spectral and temporal OCDMA systems are explored to provide the required system capacity. Maintaining an efficient cross correlation values between the adjacent codes is of primal importance to ensure required system capacity at relatively simple architecture. To develop such a system this paper focuses on the design of a 2D spectral and temporal OCDMA coding scheme. The proposed scheme mitigates the effect of interfering users by utilizing fixed in phase cross correlation code called diagonal eigenvalue unity (DEU) code along the spectral domain; whereas zero cross correlation (ZCC) code is adapted at the temporal domain. Analysis shows that the proposed combination significantly mitigates the contribution of interfering users and reduce the impact of cross correlation. This can lead to a system with relatively high transmission capacity and simple architecture for implementation at the cost sensitive access domain.

Keywords: Optical code division multiple access, two dimensional codes, diagonal eigenvalue unity code, zero cross correlation code.
I. Introduction

Deployment of bandwidth hungry applications and high capacity devices have significantly elevated the Internet traffic in the past two decades. In order to meet the ever-growing demand first mile section of the communication networks have adapted the optical fiber medium. However, the last mile section still thrives for an acceptable communication technology that can provide high capacity at low relatively costs. Fiber-to-the-home (FTTH) have provided a viable solution to the last mile bottleneck problem; however, a suitable access technology is still an open issue for use in passive optical networks (PON) at the access domain [I].

PON is a FTTH technology that provides an all fiber paths between the transmitters called optical line terminal (OLT) and subscribers premises called optical network terminal (ONT) as shown in Fig. 1. Several PON technologies have been proposed over the course of time; however, the inherent drawbacks of both technologies have limited their deployment as PON architecture [I,II].

![Figure 1: Passive optical network](image_url)

Optical code division multiple access (OCDMA) is another optical access technology that have attracted the attention of research community owing to several advantages like security, asynchronous communication, support for smooth upgradability, relatively modest network architecture, etc. OCDMA allow each subscriber to access the communication medium through a unique signature code that translates the overall capacity of the network. Numerous codes have been developed to support high capacity in terms of data, users, and reach of the network but spectral amplitude coding (SAC) family have gained more attention in comparison with the temporal and spatial coding family [I].

Nevertheless, the one-dimensional nature of SAC-OCDMA codes significantly limits their performance through several problems like (i) limited number of available frequency bins (ii) spectral width of the encoded chips (iii) limited number of users etc. Therefore, 2D codes have been introduced to overcome the mentioned problems. Several spectral/spatial 2D OCDMA coding schemes have been proposed to solve the bandwidth problem. Spectral/spatial systems essentially employees the combination of two coding schemes, where one is encoded in spectral domain and another is encoded using spatial domain respectively [III, IV].

Spectral/spatial OCDMA systems has been the center of research in OCDMA research community for over than a decade; however, a major problem have limited
the deployment of this system at the access domain. This problem deals with the employment of several optical fiber paths between the transmitter and receiver modules for the implementation of spatial encoding as shown in Fig. 2. This significantly elevates the complexity and cost of deployment for such systems. In order to overcome this problem, another family of 2D codes is proposed that replaces spatial encoding with temporal encoding to mitigate the extensive use of long span optical fiber media [V, VI].

Figure 2: Conventional spectral/ spatial OCDMA system

Spectral/ temporal coding schemes based OCDMA systems utilize the combination of spectral and time-based encoding, which significantly simplifies the system architecture. However, use of temporal encoding can limit the overall capacity of the network; therefore, it is of primal importance to utilize an efficient coding scheme that can offer desirable cross correlation by mitigating adjacent noise sources for high cardinality and transmission capacity.

In quest to develop such a scheme, this paper utilizes the combination of diagonal eigenvalue unity (DEU) code along the spectral domain and zero cross correlation (ZCC) code along the temporal domain to develop a 2D code called 2D-DZ code. The proposed code is analyzed in terms of cross correlation properties in order to determine the improvement offered by the selected combination. Mitigation of cross correlation is of primal importance as it can reduce the contribution of interfering noise sources along with the simplification of network architecture that can facilitate the deployment as PON.

II. Design of 2D-DZ Coding Scheme

The proposed code utilizes a combination of of two 1D SAC-OCDMA coding scheme called DEU and ZCC codes respectively. Both codes are selected due to the efficient combination of their code length ($L$), hamming weight($\omega$), and auto-($\lambda_d$) and cross-correlation ($\lambda_c$) values between the intended and interfering
subscriber. Table 1 shows the 1D DEU code for 4 users with $w = 3$ and $L = [N_{DEU}(w_{DEU} - 1) + 1]$. Moreover, it can be observed from Table 1, the DEU code offers fixed in-phase $\lambda_c$ between the adjacent code sequences and that the value of $L$ increases at a relatively lower rate with increase in the number of users [III, VI].

Table 1: Construction and spectral allocation of 1D DEU code

| Users | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | $\lambda_5$ | $\lambda_6$ | $\lambda_7$ | $\lambda_8$ | $\lambda_9$ | PoS         |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| User 1| 1           | 1           | 1           | 0           | 0           | 0           | 0           | 0           | 0           | $PoS_1 = [1,2,3]$ |
| User 2| 0           | 0           | 1           | 1           | 0           | 0           | 0           | 0           | 0           | $PoS_1 = [3,4,5]$ |
| User 3| 0           | 0           | 0           | 1           | 1           | 0           | 0           | 0           | 0           | $PoS_1 = [5,6,7]$ |
| User 4| 0           | 0           | 0           | 0           | 0           | 1           | 1           | 0           | 0           | $PoS_1 = [7,8,9]$ |

Table 2 demonstrates the chips placement in the 1D ZCC codes with $w = 2$ and $L = [N_{ZCC} \times W_{ZCC}]$. Table 2 further demonstrates that zero cross correlation exists between all the codes of the ZCC matrix and a linear relation exists between the code length and the number of users.

Table 2: Construction and spectral allocation of 1D ZCC code

| Users | $\lambda_1$ | $\lambda_2$ | $\lambda_3$ | $\lambda_4$ | $\lambda_5$ | $\lambda_6$ | $\lambda_7$ | $\lambda_8$ | PoS         |
|-------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| User 1| 1           | 1           | 0           | 0           | 0           | 0           | 0           | 0           | $PoS_1 = [1,2]$ |
| User 2| 0           | 0           | 1           | 1           | 0           | 0           | 0           | 0           | $PoS_1 = [3,4]$ |
| User 3| 0           | 0           | 0           | 1           | 1           | 0           | 0           | 0           | $PoS_1 = [5,6]$ |
| User 4| 0           | 0           | 0           | 0           | 0           | 1           | 1           | 0           | $PoS_1 = [7,8]$ |

Consequently, the proposed 2D-DZ code is designed with DEU and ZCC code along the spectral domain and temporal domain. This arrangement is followed in order to mitigate the effect of reduction in the chip width with increases in the number of users by the application DEU code. Moreover, the deployment of ZCC code along the temporal domain mitigates the effect of added cross-correlation values along the y-axis. This significantly reduces the number of interfering users and facilitates the implementation of a corresponding network with relatively simple architecture.

Now the proposed 2D-DZ coding scheme is designed by combining the 1D DEU and DW-ZCC X-axis and Y-axis respectively. Thus, the 1D-DEU code shows the spectral code sequence, which will be referred to as the $X^{th}$ code sequence, while the 1D-ZCC code demonstrates the temporal code sequence and will be referred to as the $Y^{th}$
code sequence due to its placement along the Y axis. Below Table 3 shows an example of both code sequences

Table 3. Spectral and temporal code sequences for the proposed 2D-DZ code

| $X^\text{th}$ code sequences | $Y^\text{th}$ code sequences |
|------------------------------|------------------------------|
| $X_1 = \{11100\}$          | $Y_1 = \{1100\}$          |
| $X_2 = \{00111\}$          | $Y_2 = \{0011\}$          |

Assume that $X_g$ and $Y_h$ are the $g^{th}$ and $h^{th}$ code sequences of the $X$ and $Y$ codes respectively, where $g = 0, 1, \ldots, N_1 - 1$ and $h = 0, 1, \ldots, N_2 - 1$. Then, the proposed 2D-DZ code can be expressed as the combination of $X_g$ and $Y_h^T$, where $Y_h^T$ represents the transpose of $Y_h$ code respectively. Now the resulting code with length $L_{DZ} = L_{DEU} \times L_{ZCC}$ can be expressed as

$$D_{g,h} = Y_h^T X_g$$ (1)

The proposed 2D-DZ codes from the combination of $X$ and $Y$ code sequences are shown in Table 4

Table 4: Code matrices for the proposed 2D-DZ coding scheme

| $A_{g,h} = Y_h^T X_g$ | $X_1 = \{11100\}$ | $X_2 = \{00111\}$ |
|-----------------------|-------------------|-------------------|
| $Y_1^T$              | 11 1100           | 11 1100 00 0000 00 0000 |
|                      | 10 0000           | 11 1100 00 0000 00 0000 |
|                      | 00 0000           | 00 0000 00 0000 00 0000 |
| $Y_2^T$              | 00 0000           | 00 0000 00 0000 00 0000 |
|                      | 00 1110           | 00 0000 00 0000 00 0000 |
|                      | 00 1110           | 00 0000 00 0000 00 0000 |

III. CROSS CORRELATION VALUES FOR 2D-DZ CODE:

It is of primal importance to determine the cross-correlation properties of the proposed code in order to determine its suitability for the support of high transmission capacity through the mitigation of noise from interfering subscribers. Moreover, it will also help to design a suitable encoder and decoder to ensure an efficient operation of the system. Thus, four characteristic matrices are be identified to determine the $\lambda_c$ values for the proposed 2D-DZ code encoded spectrum after recovery at the PIN photodiode. The four matrices are developed by undertaking all possible arrangement of $X_g$ and $Y_h$ codes sequences, which can be written as
\[
E_{g,h}^{(0)} = Y_h^T X_g \\
E_{g,h}^{(1)} = Y_h^T \overline{X}_g \\
E_{g,h}^{(2)} = Y_h^T X_g \\
E_{g,h}^{(3)} = \overline{Y}_h^T X_g
\]  

(2)

Now \(X_g^\perp\) and \(Y_h^\perp\) in Eq. 2 demonstrate the complementary codes of spectral and temporal code sequences respectively. Consequently, the resulting \(\lambda_c\) between \(E^d\) and \(E_{g,h}\) for the proposed 2D-DZ code based on the characteristic matrices can be expressed as

\[
C^{(d)}(g,h) = \sum_{i=1}^{\ell_{ZCC}} \sum_{j=1}^{\ell_{DEU}} e^{(d)}_{(i,j)} e_{(i,j)}(g,h)
\]  

(3)

Where \(e^{(d)}_{(i,j)}\) and \(e_{(i,j)}\) demonstrates the elements from characteristic matrix \(E^d\) and \(E_{g,h}\) respectively. Now, the \(\lambda_c\) values for the proposed 2D-DZcodes are listed in Table 5.

| \(E_{g,h}\) | \(C^{(0)}(g,h)\) | \(C^{(1)}(g,h)\) | \(C^{(2)}(g,h)\) | \(C^{(3)}(g,h)\) |
|---------|--------|--------|--------|--------|
| \(g = 0, h = 0\) | \(w_{ZCC} w_{DEU}\) | 0 | 0 | 0 |
| \(g \neq 0, h = 0\) | \(w_{ZCC}\) | 0 | \(w_{ZCC}(w_{DEU} - 1)\) | 0 |
| \(g = 0, h \neq 0\) | 0 | \(w_{ZCC} w_{DEU}\) | 0 | 0 |
| \(g \neq 0, h \neq 0\) | 0 | \(w_{ZCC}\) | 0 | \((w_{DEU} - 1)w_{ZCC}\) |

Now Table 5 shows that \(\lambda_c\) only exists along the \(X^{th}\) code sequences, so the four characteristic matrices can be rearranged into two new groups constructed as

\[
C_{g,h}^{(0-2)} = \{C_{g,h}^{(0)}, C_{g,h}^{(2)}\}
\]  

(4)

\[
C_{g,h}^{(1-3)} = \{C_{g,h}^{(1)}, C_{g,h}^{(3)}\}
\]  

(5)

Based on the relations of \(C_{g,h}^{(0-2)}\), and \(C_{g,h}^{(1-3)}\), it is observed that \(C_{g,h}^{(1-3)}\) has no use for the new correlation function, which makes the MAI elimination process easier and a single balanced detector can be adapted to recover the intended spectrum. Hence the expression of new cross correlation function from the previous table is given as follows.

\[
C_{g,h}^{(0)} = \frac{C_{g,h}^{(2)}}{w_{DEU} - 1} = \begin{cases} w_{DEU} w_{ZCC} & \text{for } g = h = 0 \\ 0 & \text{otherwise} \end{cases}
\]  

(6)

Table 5: Cross correlation properties of the proposed 2D-DZ code
IV. Discussion

Equation 6 demonstrates the $\lambda_c$ values for the proposed 2D-DZ coding scheme that will be encountered at the receiving photodiode. It can be observed that the proposed scheme offer maximum values of $\lambda_a$ and zero values for $\lambda_c$ at the reciving end. Such values are highly desirable as they ensure high transmission capacity by mitigating the noise sources from interfering users through $\lambda_c = 0$. Moreover, it also helps in maintaining high values of the signalt to noise ratio with $\lambda_a = w_{DEU}w_{ZCC}$.

Furthermore, Eq. 4 and 5 also demonstrates that the application of ZCC temporal coding schemes mitigates the contribution of $Y^{th}$ interfering sequences. This property of the proposed code significantly simplifies the system architecture by utilizing $C_g^{(0-2)}$ function that requires a single balanced detector at the receiving node unlike the conventional spectral/ spatial schemes based OCMDA systems that require 2 balanced detector to detect and recover the intended spectrum. Thus, the proposed 2D-DZ coding scheme offers desirable correlation values by the efficient combination of DEU and ZCC along the spectral and temporal domain that leads to a system with relatively high transmission capacity and simple implementation architecture. Conseuqently, the proposef 2D-DZ code can be adataped as a viable candidate for the deployment of next generation PONs at the access domain.

V. Conclusion

This paper provides the design of a new coding scheme called 2D-DZ code for OCDMA based PONs. The proposed code is designed by the combination of 1D DEU and ZCC codes along the spectral and temporal domain. Analysis of the proposed arrangement demonstrates that the 2D-DZ code significantly reduces the contribution of interfering users by mitigating the effect of the cross-correlation functions at the receiving end. This results in an output current that is proportional to $w_{ZCC}w_{DEU}$ at $g = 0, h = 0$ and 0 otherwise. This can not only elevate the transmission capacity of the system but also helps in simplifying the overall architecture of the 2D-DZ based OCDMA system making it more feasible for implementation at the low-cost PONs.

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Mansoor Qadir et al
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