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Development and performance improvement of a novel zero cross-correlation code for SAC-OCDMA systems

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Abstract: In order to improve the performance of the Spectral Amplitude Coding-Optical Code Division Multiple Access (SAC-OCDMA) system, a zero cross-correlation (ZCC) code named double weight multi-diagonal (DW-MD) is proposed with constant weight (CW) or variable weight (VW). Mathematical results illustrate that it is feasible to reduce the number of filters without sacrificing system performance by using the CW DW-MD code instead of the multi-diagonal (MD) code. And for the VW DW-MD code, the supportable number of users for lower code weight W_L (3) at bit error rate (BER) of 10^{-3} (voice) is 43, medium code weight W_M (4) at BER of 10^{-9} (data) is 29, and higher code weight W_H (5) at BER of 10^{-12} (video) is 32. Finally, the analysis about the position of chips “1” is given, and the simulation setups show that the CW DW-MD code outperforms the MD code when Gaussian optical filter is used.

Keywords: double weight multi-diagonal (DW-MD) code; spectral amplitude coding-optical code division multiple access (SAC-OCDMA); variable weight code; zero cross-correlation (ZCC) code.

1 Introduction

Optical Code Division Multiple Access (OCDMA) is an attractive technology in the optical network due to the properties of asynchronous access to the entire channel and great capacity in bursty traffic [1]. In particular, Spectral Amplitude Coding-Optical Code Division Multiple

Access (SAC-OCDMA) techniques stand out because of the ability to eliminate multiple-access interference (MAI) [2–4]. And with light-emitting diodes (LEDs) as the light source, the SAC-OCDMA network is inexpensive and simple [5, 6]. The performance of the SAC-OCDMA system depends to a large extent on the choice of coding scheme, and many Spectral-Amplitude-Coding (SAC) codes have been reported, such as modified quadratic congruence (MQC) codes [3], double weight (DW) code family [7, 8], Khazani-Syed (KS) code [9], Random Diagonal (RD) code [10], Multi-Service (MS) code [11], Enhanced multi-diagonal (EMD) code [12], Zhang finite-difference (ZFD) code [13] and a code based on construction of parity check matrix of Low density parity check (LDPC) codes [14].

In addition to these codes designed with constant code weight (CW), the variable weight (VW) codes are also reported. And with the property of higher code weight representing better performance, they can be utilized to support multimedia service (e.g., voice, video, and data transmission) and provide different quality of service (QoS) for the various requirements in SAC-OCDMA network [15]. Some of them are VW KS code [9], VW RD code [10], VW MS code [16] and a VW code based on enhanced and modified DW codes [17].

All of the above CW and VW codes cannot avoid the impact of phase-induced intensity noise (PIIN). Thus, some zero cross-correlation (ZCC) codes along with the spectral direct detection (SDD) [18] technique has been reported to eliminate the PIIN for the SAC-OCDMA system. Such as ZCC code [19], Multi-Diagonal (MD) code based on the orthogonal matrix [20], new ZCC code with satisfactory code lengths [21], VW ZCC Code [22] and Zero Cross Correlation Code (ZCCC) with CW and VW [23].

There are also some two dimensional spectral/spatial codes have been proposed in order to improve the system capacity. Such as Two Dimensional-Single Weight Zero Cross Correlation (2D-SWZCC) code [24], two-dimensional hybrid ZCC/MD code [25], two-dimensional Fixed Right Shift (FRS) code [26] and two-dimensional Enhanced multi-diagonal (2D-EMD) Code [27]. Most of the two dimensional spectral/spatial codes are usually constructed on the basis of one-dimensional codes. Therefore, it is still very important to

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design one-dimensional SAC-OCDMA codes with excellent performance.

The code family for SAC-OCDMA system continues to grow, and the choice of an appropriate code with CW or VW is still an open issue. However, the position of chips “1” in the code sequences, one of the important factors affecting system performance, is not analyzed in the previous works. In this paper, a new ZCC code named double weight multi-diagonal (DW-MD) code is constructed based on the DW codes and MD code. In order to reduce the number of filters used in the system and make the SAC systems more cost-effective, the DW-MD code is designed with putting two chips “1” together compared to the MD code. And using the mapping technique, the DW-MD code with VW is given for supporting multimedia service. Furthermore, the effect of chips “1” position on system performance is qualitatively analyzed and evaluated by simulation in this paper.

This paper is organized as follows. In Section 2, construction of the DW-MD code with CW and VW are presented. In Section 3, mathematical and analysis results for evaluating the performance of the DW-MD code are given. Analysis of chips “1” position and simulation setup is given in section 4. Finally, conclusions are drawn in Section 5.

2 Construction of DW-MD code

2.1 Introduction of MD and DW codes

Construction of the DW-MD code is based on the DW codes and MD code.

As reported in [20], the MD code is constructed by using V alternating M -dimensional unit diagonal matrices and anti-angle matrices (V is code weight and M is the number of users):

$$\left[\begin{array}{c} \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{M \times M}, \begin{bmatrix} 0 & \cdots & 0 & 1 \\ 0 & \cdots & 1 & 0 \\ \vdots & \cdots & \ddots & \vdots \\ 1 & \cdots & 0 & 0 \end{bmatrix}_{M \times M}, \cdots, \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{M \times M} \end{array} \right] \quad (1)$$

number of the matrices is V

The DW codes are designed with the property that chip “1” occurs in pairs [7, 8]. Therefore, when the DW codes are used in SAC-OCDMA systems, the number of filters can be reduced by almost half. The principle of reducing the number of filters is shown in Figure 1. Here, the one filter with a bandwidth of $2\Delta f$ (central wavelength of $f_c = (f_1 + f_2)/$

Figure 1: Schematic diagram for reducing the number of filters.

2) can be used to replace the two filters with a bandwidth of Δf (central wavelength of f_1 and f_2 , respectively).

2.2 Construction of DW-MD code with constant weight

Construction steps of the DW-MD with CW code are as follows.

Step 1: Defining the code weight W and the number of users N , where W and N are positive integer numbers. And the code length L is given as $L = N \times W$.

Step 2: Constructing a sequence of matrices S_w ($w = 1, 2, 3, \dots, w_{\max}$) with only elements “1” and “0” according to W and N , and the $S_w(i, j)$ ($i = 1, 2, 3, \dots, N$) represents the element of the i th row and the j th column of each matrix respectively.

(a)

When W is an odd number, the value of $w_{\max}$ is $(W + 1)/2$. S_1 is a matrix with $N \times N$ dimensions, and S_w ($w = 2, 3, \dots, w_{\max}$) are matrices of power $N \times 2N$, the position of elements “1” in S_w is determined by

$$\begin{cases} S_{w=1}(i, j) = 1, & \text{for } j = i \\ S_{w=\text{odd number}, w \neq 1}(i, j) = 1, & \text{for } j = 2i - 1, 2i \\ S_{w=\text{even number}}(i, j) = 1, & \text{for } j = 2(N + 1 - i) - 1, 2(N + 1 - i) \end{cases} \quad (2)$$

where, i is varied from one to N , and

$$\begin{aligned}
S_1 &= \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}_{N \times N}, \\
S_2 &= \begin{bmatrix} 0 & 0 & \cdots & \cdots & 0 & 0 & 1 & 1 \\ 0 & 0 & \cdots & \cdots & 1 & 1 & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 1 & 1 & \cdots & \cdots & 0 & 0 & 0 & 0 \end{bmatrix}_{N \times 2N}, \\
S_3 &= \begin{bmatrix} 1 & 1 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \cdots & 1 & 1 \end{bmatrix}_{N \times 2N}, \dots, S_{(W+1)/2}
\end{aligned} \quad (3)$$

(b)

When W is the even number, the value of $w_{\max}$ is $W/2$. S_w ($w = 1, 2, 3, \dots, w_{\max}$) are matrices of $N \times 2N$, the position of elements “1” in S_w is determined by

$$\begin{cases} S_{w=\text{odd number}}(i, j) = 1, & \text{for } j = 2i - 1, 2i \\ S_{w=\text{even number}}(i, j) = 1, & \text{for } j = 2(N + 1 - i) - 1, 2(N + 1 - i) \end{cases} \quad (4)$$

where, i is varied from one to N , thus

$$\begin{aligned}
S_1 &= \begin{bmatrix} 1 & 1 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \cdots & 1 & 1 \end{bmatrix}_{N \times 2N}, \\
S_2 &= \begin{bmatrix} 0 & 0 & \cdots & \cdots & 0 & 0 & 1 & 1 \\ 0 & 0 & \cdots & \cdots & 1 & 1 & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots & \vdots & \vdots & \vdots \\ 1 & 1 & \cdots & \cdots & 0 & 0 & 0 & 0 \end{bmatrix}_{N \times 2N}, \\
S_3 &= \begin{bmatrix} 1 & 1 & 0 & 0 & \cdots & \cdots & 0 & 0 \\ 0 & 0 & 1 & 1 & \cdots & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & \cdots & \cdots & 1 & 1 \end{bmatrix}_{N \times 2N}, \dots, S_{W/2}
\end{aligned} \quad (5)$$

For example, to construct a DW-MD code with $W = 3$ and $N = 3$ according to the previous steps.

Therefore, $L = N \times W = 9$, W is an odd number and $w_{\max} = 2$. For $i = 1, 2, 3$, the matrices S_w ($w = 1, 2$) can be expressed as:

$$S_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}_{3 \times 3}, S_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}_{3 \times 6} \quad (7)$$

and the DW-MD code will be:

$$\begin{aligned}
\text{DW-MD}(3) &= [S_1 \quad S_2]_{3 \times 9} \\
&= \begin{bmatrix} 1 & 0 & 0 & \vdots & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & \vdots & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & \vdots & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}_{3 \times 9}
\end{aligned} \quad (8)$$

The DW-MD code concentrates on the advantages of MD and DW codes. On the one hand, MAI can be fully eliminated and the PIIN can be suppressed due to the property of ZCC (same as MD code). On the other hand, the number of filters and the complexity of the system can be reduced because the two chips “1” are adjacent (same as DW code). Besides, the DW-MD code can be generated easily and efficiently with any code weight and the number of users.

2.3 Construction of DW-MD code with variable weight

Construction of DW-MD code with VW for supporting multimedia service with different QoS in SAC-OCMA network is described here. It consists of several CW DW-MD code matrices by using the mapping technique and each code weight can be chosen independently to satisfy the required service quality. The VW code with J number of service classes is described as

$$\text{DW-MD}_v = \begin{bmatrix} \text{DW-MD}_{N_1}(W_1) & 0 & 0 & 0 \\ 0 & \text{DW-MD}_{N_2}(W_2) & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & \text{DW-MD}_{N_J}(W_J) \end{bmatrix}_{N_v \times L_v} \quad (9)$$

Step 3: The total combination of the S_w ($w = 1, 2, 3, \dots, w_{\max}$) in matrices (3) or (5) represents the DW-MD code as a matrix of power $N \times L$.

$$\text{DW-MD}(W) = [S_1 \quad S_2 \quad \cdots \quad S_{w_{\max}}]_{N \times L} \quad (6)$$

where, N_j is the number of users of the j th CW code matrix whose code weight is W_j , and $W_1 > W_2 > \cdots > W_J$.

Thus, the total number of users N_v is expressed as

$$N_v = \sum_{j=1}^J N_j \quad (10)$$

Figure 3: Schematic diagram of SAC-OCMA system for CW DW-MD code.

Figure 4: Schematic diagram of SAC-OCMA system for VW DW-MD code.

$$G(v) = \frac{P_{sr}}{\Delta v} \sum_{n=1}^N d_n \sum_{i=1}^L C_n(i) \cdot \text{rec}(i) \quad (13)$$

where, P_{sr} represents the effective power at the receiver, N is the active users, L is the DW-MD code length, d_n is the data bit of the n th user that is “1” or “0”, $\text{rec}(i)$ in Eq. (13) is explained as

$$\begin{aligned} \text{rec}(i) &= u \left[v - v_0 - \frac{\Delta v}{2L} (-L + 2i - 2) \right] - u \left[v - v_0 - \frac{\Delta v}{2L} (-L + 2i) \right] \\ &= u \left[\frac{\Delta v}{L} \right] \end{aligned} \quad (14)$$

and $u(v)$ is the unit step function expressed as

$$u(v) = \begin{cases} 1, & v \geq 0 \\ 0, & v \leq 0 \end{cases} \quad (15)$$

Let $C_n(i)$ be the i th element of n th CW DW-MD code

sequence and according to the correlation properties, the SDD technique for the DW-MD code can be represented as

$$\sum_{i=1}^L C_n(i) \cdot C_l(i) = \begin{cases} W, & n = l \\ 0, & n \neq l \end{cases} \quad (16)$$

From the Eqs. (13) and (16), the PSD at the photo-detector of the l th receiver during one period can be written as:

$$G(v) = \frac{P_{sr}}{\Delta v} \sum_{n=1}^N d_n \sum_{i=1}^L C_n(i) C_l(i) \cdot u \left(\frac{\Delta v}{L} \right) \quad (17)$$

and then

$$\begin{aligned} \int_0^\infty G(v) dv &= \int_0^\infty \frac{P_{sr}}{\Delta v} \sum_{n=1}^N d_n \sum_{i=1}^L C_n(i) C_l(i) \cdot u \left(\frac{\Delta v}{L} \right) dv \\ &= \frac{P_{sr}}{\Delta v} \cdot \frac{\Delta v}{L} \cdot \sum_{n=1}^N d_n \sum_{i=1}^L C_n(i) C_l(i) \\ &= P_{sr} \frac{W}{L} \end{aligned} \quad (18)$$

The photocurrent I can be found as

$$I = \Re \int_0^\infty G(\nu) d\nu = \Re P_{sr} \frac{W}{L} \quad (19)$$

where, $\Re$ is the responsivity of the photo-detectors given by $\Re = \mu e / (h\nu c)$, μ is the quantum efficiency, h is Planck's constant, and ν_c is the central frequency of the original broad-band optical pulse.

Substituting Eq. (19) in Eq. (12), it can be obtained that

$$\sigma^2 = \frac{2eB\Re P_{sr} W}{L} + \frac{4K_b T_n B}{R_L} \quad (20)$$

Noting that the probability of sending bit “1” at any time for each user is $1/2$, Eq. (17) becomes

$$\sigma^2 = \frac{eB\Re P_{sr} W}{L} + \frac{4K_b T_n B}{R_L} \quad (21)$$

Thus, for users with code weight W , the average Signal to Noise Ratio (SNR) can be calculated as

$$SNR = \frac{(\Re P_{sr} W / L)^2}{eB\Re P_{sr} W / L + 4K_b T_n B / R_L} \quad (22)$$

Using Gaussian approximation, the BER can be expressed as

$$P_e = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{SNR}{8}} \quad (23)$$

And for VW DW-MD code, the Eq. (16) can be expressed as

$$\sum_{i=1}^{L_v} C_n(i) \cdot C_l(i) = \begin{cases} W_j, & n = l \\ 0, & n \neq l \end{cases} \quad (24)$$

By the similar derivation to CW DW-MD code, the average SNR_j for VW DW-MD code with code weight W_j can be calculated as

$$SNR_j = \frac{(\Re P_{sr} W_j / L_v)^2}{eB\Re P_{sr} W_j / L_v + 4K_b T_n B / R_L} \quad (25)$$

Using Gaussian approximation, the BER_j can be also expressed:

$$P_{ej} = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{SNR_j}{8}} \quad (26)$$

3.3 Mathematical results and discussion

The parameters used in the numerical analysis are listed in Table 1. Comparison of the number of filters used at the encoder/decoder between the CW DW-MD and MD codes is given in Figure 5. For the same number of users and code weight, fewer filters are used with the DW-MD

Table 1: System parameters description and specifications.

Symbol	Parameter	Value
E	Electron charge	1.6×10^{-19} C
B	Electrical bandwidth	311 MHz
K_b	Boltzmann's constant	1.38×10^{-23} J/K
T_n	Received noise temperature	300 K
R_L	Received load resistor	1030 Ω
M	Photodetector quantum efficiency	0.6
$\Delta\nu$	Linewidth of broadband source	3.7 THz
λ_0	Operating wavelength	1550 nm
P_{sr}	Received optical power	-10 dBm
H	Planck's constant	6.626×10^{-34} J s

Figure 5: Comparison of number of filters used at the encoder/decoder between MD and DW-MD codes.

Figure 6: Comparison of the BER performance between DW-MD code and other codes.

Figure 7: Variation of BER against number of each weight users with $W_L = 3$, $W_M = 4$ and $W_H = 5$.

Figure 8: Performance of the VW DW-MD code on varying the value of W_L or W_H .

code due to the property that chip ‘1’ occurs in pairs, and half number of filters can be reduced when the code weight is an even number (e.g., $W = 4$). It is noted that the same number of filters (two filters per encoder) are required for the DW-MD code with $W = 4$ and $W = 3$, but both filters are double bandwidth for $W = 4$ while only one for $W = 3$.

As shown in Figure 6, the performance of DW-MD code ($W = 4$), MD code ($W = 4$) [20], KS code ($W = 6$) [10] and MS code ($W = 4$ and $N_B = 3$) [12] are investigated as log of BER against the total number of active users operating at P_{sr} of -10 dBm. Due to the same ZCC and no PIIN, the DW-MD code and MD code have almost the same BER performance and are superior to other codes. This further indicates that it

Figure 9: BER against the number of active users with $N_L = 10$, 20, and 30.

Figure 10: Theoretical model of Gaussian Optical Filters used at encoder/decoder.

is feasible to reduce the number of filters without sacrificing system performance by using the DW-MD code instead of the MD code.

Figure 7 illustrates the variations of the BER against the number of users (each weight of VW DW-MD code). For supporting multimedia service, the lower code weight W_L , medium code weight W_M , and higher code weight W_H are set as 3, 4 and 5, respectively. The Supportable number of users for W_L at BER of 10^{-3} (voice) is 43, W_M at BER of 10^{-9} (data) is 29, and W_H at BER of 10^{-12} (video) is 32.

Figure 8 depicts BER versus the number of users (each weight) for VW code by varying the W_L or W_H and keeping another code weight fixed. The combinations of two code weights (W_L, W_H) are taken as (3, 4), (3, 5) and (4, 5). On one hand, increasing the W_H from four to five and keeping the W_L fixed at three leads to the worse BER for W_L users and better performance for W_H users. On the other hand, the

Figure 11: Simulation setup of SAC-OCDMA using CW DW-MD code with code weight of 4.

Table 2: Mapping of DW-MD code ($W = 4$) and wavelength (1542.8~1558 nm) for each user.

nm	1542.8	1543.6	1544.4	1545.2	1546	1546.8	1547.6	1548.4	1549.2	1550
User 1	1	1	0	0	0	0	0	0	0	0
User 2	0	0	1	1	0	0	0	0	0	0
User 3	0	0	0	0	1	1	0	0	0	0
User 4	0	0	0	0	0	0	1	1	0	0
User 5	0	0	0	0	0	0	0	0	1	1

nm	1550.8	1551.6	1552.4	1553.2	1554	1554.8	1555.6	1556.4	1557.2	1558
User 1	0	0	0	0	0	0	0	0	1	1
User 2	0	0	0	0	0	0	1	1	0	0
User 3	0	0	0	0	1	1	0	0	0	0
User 4	0	0	1	1	0	0	0	0	0	0
User 5	1	1	0	0	0	0	0	0	0	0

BER for W_L users and W_H users decreased and increased respectively when the W_H is fixed at five and W_L increases from three to four Eq. (11) indicates whether it is to increase W_L or W_H , the total code length L_v should be increased. And it is obvious that the BER performance becomes worse for the fixed code weight (W_L or W_H) as the increase of L_v according to the Eq. (26).

In Figure 9, BER is plotted against the number of simultaneous users with the number of lower code weight users (N_L) being 10, 20, and 30, respectively. As the N_L increases, both the W_L and W_H users have a better BER performance. Thus, the higher the proportion of users with W_L , the better the system performance. This is because increasing the N_L can decrease the total code length L_v and provide a lower BER for the whole system according to the Eqs. (11) and (26).

4 Simulations

4.1 Analysis of interference between two adjacent “1”s

The above mathematical analysis and discussion are based on the assumption that there is no interference between two adjacent chips “1”. However, filters used at the encoder/decoder in SAC-OCDMA systems are not ideal filters in real scenario, and there is indeed interference between the two adjacent wavelength channels. Take the Gaussian Optical Filter commonly used in SAC-OCDMA systems as an example, and its theoretical model is shown in Figure 10 (theoretical model of ideal filter can be obtained from Figure 1). According to Figure 10 where the interference is represented as ΔS , it can be concluded that

Figure 12: Simulation setup of SAC-OCDMA using MD code with code weight of 4.

the construction with two discrete “1” (MD code) has more interference than two adjacent “1”s (DW-MD) ($4\Delta S$ for the former and $2\Delta S$ for the latter when the code weight is 2). If there is only one chip “1” needed at the decoder in the SDD technique, the filter with a bandwidth of Δf and the central wavelength of f_c can be the optimal choice.

4.2 Simulation setup

The simulation setup for the CW DW-MD code is shown in Figure 11. There are five users in the SAC-OCDMA system, and the data rate is set as 1.25 Gbps. The a.u. value of Bias Generator (d.c. source) is set as one. The spectral width is set as 0.8 nm for each chip and the mapping of DW-MD

code ($W = 4$) and wavelength for each user is given in Table 2.

At the transmitter, the LED is utilized as a broadband light source whose parameters are set as the wavelength of 1550 nm and bandwidth of 3.75 THz (30 nm), WDM Demux and Mux are used for encoding the optical spectra, a pseudo-random bit sequence (PRBS) generator and a non-return-zero (NRZ) pulse generator are used to generate the data signal for each user, and the Mach-Zehnder Modulator is utilized as external intensity modulator. According to ITU-T G.652 standard, the 20 km standard single mode optical fiber (SMF) with the dispersion of 16.75 ps/nm/km and attenuation of 0.2 dB/km is chosen to connect the transmitter and receiver.

Table 3: Mapping of MD code ($W = 4$) and wavelength (1542.8–1558 nm) for each user.

nm	1542.8	1543.6	1544.4	1545.2	1546	1546.8	1547.6	1548.4	1549.2	1550
User 1	1	0	0	0	0	0	0	0	0	1
User 2	0	1	0	0	0	0	0	0	1	0
User 3	0	0	1	0	0	0	0	1	0	0
User 4	0	0	0	1	0	0	1	0	0	0
User 5	0	0	0	0	1	1	0	0	0	0
nm	1550.8	1551.6	1552.4	1553.2	1554	1554.8	1555.6	1556.4	1557.2	1558
User 1	1	0	0	0	0	0	0	0	0	1
User 2	0	1	0	0	0	0	0	0	1	0
User 3	0	0	1	0	0	0	0	1	0	0
User 4	0	0	0	1	0	0	1	0	0	0
User 5	0	0	0	0	1	1	0	0	0	0

Figure 13: Eye diagram for one user of SAC-OCDMA system with (a) DW-MD code and (b) MD code when using Gaussian Optical Filter.

And at the receiver, the SDD technique is applied to detect signals. The Gaussian Optical Filter with the bandwidth of 0.8 nm is utilized to filter the unique wavelength chips for each user, and the photo-detector with dark current value being 5 nA and 0.75 GHz. Low Pass Bessel Filter is applied for recovering the original electrical signal. It is noted that the channel bandwidth of WDM Demux and Mux

are set as 1.6 nm (represent two “1” s with the bandwidth of 0.8 nm) for reducing the number of filters at the encoder. And the wavelength of Gaussian Optical Filter is set as the center of two adjacent wavelengths for mitigating interference from other users.

The simulation setup for MD code is shown in Figure 12, and all the parameters are the same as that shown in Figure 11 except for the encoder and decoder corresponding to the code sequence. The mapping of MD code ($W = 4$) and wavelength for each user is given in Table 3.

4.3 Simulation results and discussion

4.3.1 Simulation with Gaussian Optical Filter

Performance of the system with the DW-MD and the MD codes is characterized in terms of the BER and eye pattern. As shown in Figure 13, eye patterns of one user using (a) DW-MD and (b) MD code clearly depict that the DW-MD code gives a more open eye and a better BER. Furthermore, Table 4 lists the BER values of the five users in the simulation systems using the DW-MD and MD codes, and the BER values of the two codes differ by 8~14 orders of magnitude. This is because the DW-MD code can reduce the interference by the structure of two adjacent “1” s (analysis of the Figure 10).

In order to further analyze the performance of DW-MD and MD codes, the fiber length between the transmitter and receiver is changed from 10 to 50 km. And the BER of the two codes versus fiber length is observed at two different data rates (622 Mbps and 1.25 Gbps). Figure 14 shows that BER increases with increasing SMF length, which can be attributed to the increasing attenuation and dispersion of SMF.

Moreover, it is observed that the performance advantages of DW-MD code are obvious. In the range of 10–40 km, the SAC-OCDMA system with DW-MD code transmitted at higher rate (1.25 Gbps) performs better than that with MD code transmitted at lower rate (622 Mbps). And for lengths of up to 40 km, the

Table 4: BER values of five users with the DW-MD and MD codes when using Gaussian Optical Filters.

BER value of	User 1	User 2	User 3	User 4	User 5
DW-MD	2.293×10^{-17}	2.559×10^{-17}	4.670×10^{-19}	6.095×10^{-16}	5.068×10^{-18}
MD	5.218×10^{-9}	4.254×10^{-5}	1.414×10^{-5}	2.459×10^{-5}	4.555×10^{-10}

Figure 14: BER of DW-MD and MD codes versus Fiber Length at two different data rates.

proposed DW-MD has the ability to provide nominal performance for an acceptable BER of 10^{-9} at 1.25 Gbps of data.

4.3.2 Simulation with rectangle optical filter

In the next simulation, the Rectangle Optical Filters are utilized to replace the Gaussian Optical Filters at the encoder and decoder and other settings and parameters remain unchanged. The BER values of the five users in the SAC-OCDA systems using the DW-MD and MD codes are given in Table 5, and the BER difference between two corresponding users does not exceed two orders of magnitude. Furthermore, as a sample, the eye diagrams for one user using DW-MD code and MD code are shown in Figure 15 (a) and (b), respectively. Obviously, the two users have a very close eye quality. This is because when using the Rectangle Optical Filters, there is no interference between adjacent filter channels and the effect of chips “1” position on system performance does not exist (theoretical model of ideal Rectangle Optical Filter is shown in Figure 1).

(a)

(b)

Figure 15: Eye diagram for one user of SAC-OCDA system with (a) DW-MD code and (b) MD code when using Rectangle Optical Filters.

From the above analysis, it can be easy to conclude that the DW-MD and MD codes have a similar performance when the ideal Rectangle Optical Filters are utilized, which indirectly reveal that the effect of chips “1” position on system performance cannot be ignored when the non-ideal optical filter (e.g., Gaussian Optical Filter) is used at the encoder/decoder in the real scenario.

Table 5: BER values of five users with the DW-MD and MD codes when using Rectangle Optical Filters.

BER value of	User 1	User 2	User 3	User 4	User 5
DW-MD	2.293×10^{-17}	3.771×10^{-21}	5.488×10^{-17}	1.186×10^{-18}	1.656×10^{-17}
MD	4.604×10^{-18}	2.033×10^{-19}	1.783×10^{-17}	2.991×10^{-17}	5.163×10^{-19}

5 Conclusions

A new ZCC code named DW-MD code has been developed to reduce the number of filters used in the SAC-OCDMA system with the feature of two adjacent chips “1”. And the DW-MD code with variable weight is also constructed to support multimedia in SAC-OCDMA system by associating several different CW code matrices and using the mapping technique. The VW DW-MD code can be chosen independently for each code weight to satisfy the required service quality. Theoretical analysis shows that the DW-MD code can be used instead of the MD code to reduce the number of filters without sacrificing system performance under the ideal conditions. Here, one filter with a larger bandwidth (doubled) can be used instead of using two filters (represent two distinct chips ‘1’). The ability of VW DW-MD code to support multimedia service is also verified, and results indicate that the users with lower code weight W_L , medium code weight W_M , and higher code weight W_H have the higher BER, medium BER and lower BER, respectively. In terms of changing the W_L or W_H and keeping another code weight fixed, increasing W_L or W_H results in an increase in the total code length L_v , and the performance for the fixed code weight (W_H or W_L) deteriorates. In addition, the number of lower code weight users (N_L) with different values (i.e., 10, 20 and 30) are set for the VW code with the combination of (3, 5). It is shown that increasing the N_L decreases the total code length and provides better performance for both the W_L and W_H . Finally, the performance comparison of the MD code and proposed CW code is given through qualitative analysis and simulation setups. The proposed code provides a significant performance improvement compared with the MD code when the Gaussian Optical Filters are used. In summary, the overall results demonstrate that the DW-MD code can be a code candidate that makes the SAC-OCDMA system more cost-effective, and the VW DW-MD code is suitable for supporting multimedia service in optical networks.

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