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A NEW CODE FOR OPTICAL CODE DIVISION MULTIPLE ACCESS SYSTEMS

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ABSTRACT

*A new code structure based on Double-Weight (DW) code families is proposed for Spectral-Amplitude-Coding Optical Code Division Multiple Access (OCDMA) system. The constraint of a constant weight of 2 for the DW code can be relaxed using a mapping technique. By using this technique, codes that have a larger number of weight can be developed. Modified Double-Weight (MDW) Code is another variation of a DW code family that can has a variable weight greater than two. The MDW code possesses ideal cross-correlation properties and exists for every natural number **n**. A much better performance can be provided by using the MDW code compared to the existing codes such as Hadamard and Modified Frequency-Hopping (MFH) codes. This has been demonstrated from the theoretical analysis and simulation.*

Keywords: ***OSCDMA, Cross-correlation, Double Weight (DW) Code, Modified Double Weight (MDW) Code***

1.0 INTRODUCTION

Optical Spectrum Code Division Multiple Access (OSCDMA) is a multiplexing technique adapted from CDMA system that was originally developed for Radio Frequency (RF) communication systems. The successful implementation of CDMA systems in wireless networks has motivated many researchers to take full advantages of fiber optics to establish an all Optical Code Division Multiple Access (OCDMA) communication systems. The system parameters of a great interest in OCDMA system are the code lengths, the number of weight, the number of users and stations that can be supported simultaneously and asynchronously and also the auto and cross-correlation performance of the codes.

In OSCDMA systems, each user is assigned with an address in a fashion of a code sequence. An Optical CDMA user modulates its code (or address) with each data bit and asynchronously initiates transmission. Hence, this modifies its spectrum appearance, in a way recognisable only by the intended receiver. Otherwise, only noise-like bursts are observed [1, 2]. The advantages of OSCDMA technique over other multiplexing techniques such as TDMA and FDMA are numerous [3, 4]. An OSCDMA technique requires neither time nor frequency management at its nodes compared to the TDMA and FDMA techniques.

Many codes have been proposed for OSCDMA [3], [5], [10], [11], [12]. Among the popular ones are Hadamard, Prime codes, and Optical Orthogonal codes. One of the latest codes proposed is MFH code [6]. However these codes suffer from various limitations one way or another. The codes constructions are either complicated (e.g. OOC and MFH codes), the cross-correlation are not ideal (e.g. Hadamard and Prime codes), or the code length is too long (e.g. OOC and Prime code). Long code lengths are considered disadvantageous in its implementation since either very wide band sources or very narrow filter bandwidths are required. Table 1 shows the code length required by the different codes to support only 30 users. For example, if the chip width (filter bandwidth) of 0.5 nm is used, the OOC code will require a spectrum width of 182nm and Prime code will require 480.5nm whereas MDW only requires 45nm. Hadamard and MFH codes show shorter code lengths than that of MDW and this will be discussed further in more detail in this paper. It will be shown that the transmission performance of MDW codes is significantly better than that of Hadamard and MFH codes. This is achieved through theoretical calculation and software simulation.

Table 1: Comparison between MDW, MFH, OOC, Hadamard and Prime Codes for same number of user ***K*** = 30

No	Codes	No Of User (*K*)	Weight	Code Length(*N*)
1	OOC	30	4	364
2	Prime Code	30	31	961
3	MDW code	30	4	90
4	Hadamard	30	16	32
5	MFH	30	7	42

2.0 CODE DESIGN

In [6], for code sequence $X = (x_1, x_2, ...x_N)$ and $Y = (y_1, y_2, ...y_N)$, the cross-correlation is given by $\lambda = \sum_{i=1}^{N} x_i y_i$. A code with length ***N***, weight *W* and cross-correlation λ can therefore be denoted by *(N, W,* λ). We can say that the code has an ideal in-phase cross-correlation when λ = 1, as this is a minimum value that can be achieved [6]. *W* and λ are two most important parameters as they directly affect the overall system signal to noise ratio (SNR) as expressed in equation (1):

$$\text{SNR} = \frac{2(\frac{W}{\lambda} - 1)\Delta v}{BK[\frac{K}{2} + \frac{W}{\lambda} - 2]} \tag{1}$$

where *B* is the noise equivalent electrical bandwidth of the receiver, Δv is the spectral width and *K* is the number of simultaneous users. Therefore for a given value of spectral width Δv , *B* and *K*, the SNR depends on $\frac{W}{\lambda}$ only. However, for DW and MDW codes, the cross correlation λ is always minimised at λ =1, thus, the performance of DW and MDW codes depends on code weight only, which is much easier to control.

2.1 DW Code Construction

The new proposed code families are referred to as DW codes. It can be constructed using the following steps.

Step 1:
The DW code can be represented by using a ***K*** x ***N*** matrix. In DW codes structures, the matrix ***K*** rows and ***N*** columns will represent the number of user and the minimum code length respectively. A basic DW code is given by a 2 x 3 matrix, as shown below:-

$$\begin{array}{cc} & \begin{array}{ccc} \mathbf{1} & \mathbf{2} & \mathbf{1} \\ \downarrow & \downarrow & \downarrow \end{array} \\ \mathrm{H}_1 = & \begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 0 \end{bmatrix} \end{array}$$

Notice that $\mathbf{H_1}$ has a chips combination sequence of 1, 2, 1 for the three columns (i.e. 0+1, 1+1, 1+0).

Step 2:
A simple mapping technique is used to increase the number of codes as shown below:-

$$H_2 = \left|\begin{array}{ccc|ccc} 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ \hline 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \end{array}\right| = \begin{vmatrix} 0 & H_1 \\ H_1 & 0 \end{vmatrix}$$

Note that as the number of user, ***K*** increases, the code length, ***N*** also increases. The relationship between the two parameters, ***K*** and ***N*** is given by equation (2):

When K is even (i.e ***K***= 2, 4, 6,…..)

$$N = 3K.$$

But if ***K*** is odd (***K*** = 1,3,5…..)

$$N = \frac{3K}{2} + \frac{1}{2}$$

For (***K*** = 1,2, 3……)

$$N = \frac{3K}{2} + \frac{1}{2}\left[\sin\left(\frac{K\pi}{2}\right)\right]^2 \tag{2}$$

The purpose of $\left[\sin\left(\frac{K\pi}{2}\right)\right]^2$ term is used to simplify the equation.

Some DW code sequences are listed in Table 2 below.

Table 2: Example of DW Code sequences

Kth	**C_6**	**C_5**	**C_4**	**C_3**	**C_2**	**C_1**
1	0	0	0	0	1	1
2	0	0	0	1	1	0
3	0	1	1	0	0	0
4	1	1	0	0	0	0

Note that C_i is the column number of the codes which also represents the spectral position of the chips where i is 1, 2, 3……N. In DW code sequence construction, the spectral positions of the two weights, $C_{1,K}$ for the first weight and $C_{2,K}$ for the second weight for the *K*th user are given by:

$$C_{2,K} = C_N \tag{3}$$

and

$$C_{1,K} = C_{N-1} \tag{4}$$

where ***N*** is as in Equation (2). Notice that the spectral position of the second weight $C_{2,K}$ is always the same as the minimum code length, N (also shown in Table 1) while the 1st weight, $C_{1,K}$ is always one position before. This makes the DW code construction simple. For instance, if $K = 4$, the minimum code length, N is equivalent to 6 using Equation (2), and the spectral positions $C_{1,4}$ and $C_{2,4}$ are C_5 and C_6 as obtained using Equations (3) and (4) respectively. It is important that the weight positions are maintained in pairs, so that less number of filters can be used in the encoder and decoder. This way, a filter with the bandwidth twice of the chip width can be used, instead of two different filters, making the systems easier and less costly to implement.

2.2 MDW Code Construction.

MDW is the modified version of DW code. The MDW code weight can be any even number that is greater than 2. MDW codes can also be represented by using the ***K x N*** matrix. The basic MDW can be developed by using the following steps:-

Step 1:
The basic matrix for MDW codes also consists of a ***K x N*** matrix depending on the value of code weight. The general form of matrix for a MDW code is shown below.

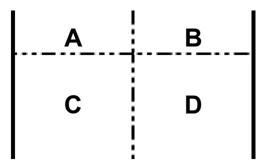

Fig. 1: General form of MDW code

From Fig. 1, the elements in each section are given by:-

1. A consists of a $1 \times 3\sum_{j=1}^{\frac{W}{2}-1} j$ matrix of zeros.
2. B consists of a 1 x 3***n*** matrix containing the basic matrix of [X_2] for every 3 columns. (i.e. a 1 x 3***n*** matrix which is n repetition of [X_2])
3. C is the basic code matrix for the next smaller weight, W = 2(***n***-1).
4. D is a matrix ***n*** x ***n*** consisting of basic matrix of [X_3] arranged as shown in Fig. 2.

$$\begin{bmatrix} 000 & 000 & [X_3] \\ 000 & [X_3] & 000 \\ [X_3] & 000 & 000 \end{bmatrix}$$

Fig. 2: A matrix ***n*** x ***n*** consisting of basic matrix of [X_3]

And $n = \frac{W}{2}$, $W = 2,4,6.....R$

where X_1 , X_2 and X_3 are the [1 x 3] matrix.

and it consists of

$$X_2 = \begin{bmatrix} 0 & 1 & 1 \end{bmatrix}$$
$$X_3 = \begin{bmatrix} 1 & 1 & 0 \end{bmatrix}$$
$$X_1 = \begin{bmatrix} 0 & 0 & 0 \end{bmatrix}$$

Step 2

There two basic components in basic matrix for MDW codes are:-

Code length, $$N_B = 3\sum_{j=1}^{\frac{W}{2}} j \qquad (5)$$

Number of user, $$K_B = \frac{W}{2} + 1 \qquad (6)$$

Equation (5) and (6) represent the basic matrix for MDW code, where N_B is the column (i.e. its represent basic code length) and K_B is the row (its represents basic number of user). The MDW matrix is consisting of ($K_B \times N_B$).

In this paper, the MDW with the weight of 4 is used as an example.

For ***W*** = 4, therefore, from Equation (5)

$$N_B = 3\sum_{j=1}^{\frac{W}{2}} j = 9$$

And from Equation (6)

$$K_B = \tfrac{W}{2} + 1 = 3$$

Now, MDW ***4*** consists of [3 x 9] matrix.

Element in each section is depend on value of ***n*** and for MDW 4, n =2. The elements in each section are given by:

1. A consists of a $1 \times 3\sum_{j=1}^{\frac{W}{2}-1} j$ matrix of zeros. A = [X_1] = [0 0 0]
2. B consists of a 1 x 3***n*** matrix which is n repetition of [X_2] , B = [[X_2],[X_2]] = [0 1 1 0 1 1]
3. C consists of MDW matrix of ***W*** = 2(***n***-1) =2 = DW= $\begin{bmatrix} 011 \\ 110 \end{bmatrix}$
4. D is a matrix ***n*** x ***n*** consisting of basic matrix of [X_3], D= $\begin{bmatrix} 000110 \\ 110000 \end{bmatrix}$

The basic MDW code denoted by (9, 4, 1) is shown below:-

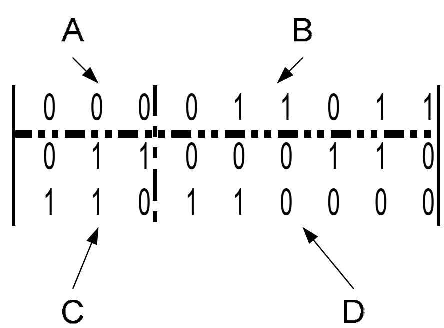

Fig. 3: The basic MDW code with code length 9, weight 4 and an ideal in-phase cross correlation

Notice that similar structure of the basic DW code, H_1 is still maintained with a slight modification, whereby the double weight pairs are maintained in a way to allow only two overlapping chips in every column. Thus, the 1, 2, 1 chips combination is maintained for every three columns as in the basic DW code. This is important to maintain λ =1.

The same mapping technique as for DW code is used to increase number of user. The example shows that we can increase number of user from 4 to 6 while the weight is still fixed at 4. An MDW code with weight of 4 denoted by (***N**, 4, 1*) for any given code length ***N***, can be related to the number of user ***K*** through:

$$N = 3K + \frac{8}{3}\left[\sin(\frac{K\pi}{3})\right]^2 \tag{7}$$

Some MDW code sequences are listed in Table 3.

Table 3: Example of DW Code sequences

Kth	C_9	C_8	C_7	C_6	C_5	C_4	C_3	C_2	C_1
1	**0**	**0**	**0**	**0**	**1**	**1**	**0**	**1**	**1**
2	**0**	**1**	**1**	**0**	**0**	**0**	**1**	**1**	**0**
3	**1**	**1**	**0**	**1**	**1**	**0**	**0**	**0**	**0**

The total spectral width Δv of DW and MDW systems is governed by the code length, ***N***. Assuming that the chips are ideally rectangular shape, the relationship can be written as:

$$\Delta v = \Delta F N \tag{8}$$

where ΔF is the chip width. Equation (8) is always valid for DW and MDW code systems because for ***K*** number of users multiplexed into a common fiber, the whole code length ***N*** is spectrally covered as evident from Tables 1 and 2.

3.0 CODE EVALUATION AND COMPARISON

For comparison, the properties of MDW, MFH and Hadamard codes are listed in Table 4. The table shows that MDW codes exist for any natural number, ***n*** while Hadamard codes exist only for the matrix sequence ***M,*** where ***M*** must at least be equivalent to 2. On the other hand, MFH codes exist for prime number ***Q*** only.

Table 4: Comparison between MDW, MFH and Hadamard Codes

CODE	Existence	No. of User (K)	Code Length (N)	Weight (W)	Cross-correlation λ	SNR
MFH	Q	$K = Q^2$	$N = Q^2 + Q$	$W = Q + 1$	$\lambda = 1$	$\frac{2Q\Delta v}{BK(K/2+Q-1)}$
MDW (W=4)	n	$K = n$	$N = 3n + \frac{8}{3}\left[sin(\frac{n\pi}{3}\right]^2$	$W = 4$	$\lambda = 1$	$\frac{12\,\Delta v}{Bn\,(n+4)}$
Hadamard (M ≥ 2	M	$K = 2^M - 1$	$N = 2^M$	$W = 2^{M-1}$	$\lambda = 2^{M-2}$	$\frac{4\Delta v}{B(2^M-1)^2}$

The number of users, ***K*** supported by MDW code is equivalent to ***n***. On the other hand for Hadamard and MFH codes, the number of user supported depends on ***M*** and ***Q*** respectively which in turn, alters the value of weight, ***W***. This will affect both the design of the encoder /decoder and the SNR of the existing codes in use. In contrast, for MDW codes, ***W*** can be fixed at any even numbers regardless of the number of users. By fixing ***W***, encoder/decoder design and the signal SNR will be maintained and will not be affected by the number of users, as shown by Equation (1), thus the same quality of service can be provided for all users.

The table also shows clearly that for the same number of users, MDW codes have better SNR than Hadamard and MFH codes. This is evident from the fact that MDW code has an ideal cross-correlation while Hadamard code has increasing value of cross-correlation as the number of user increase. For MFH codes, although the cross correlation is also fixed at 1 but the SNR is smaller than of MDW. MFH needs higher number of ***Q*** or ***W*** to increase SNR. This is shown in Fig. 4.

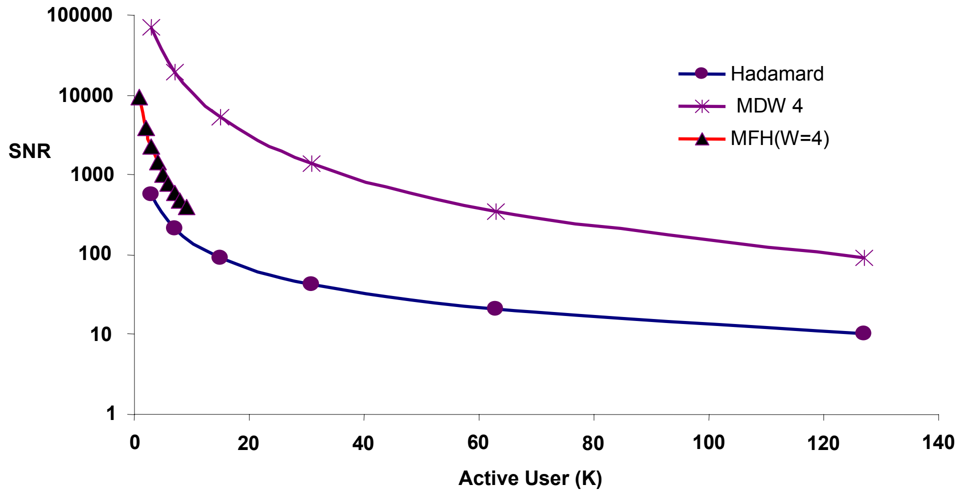

Fig. 4: SNR versus number of users for MDW, MFH and Hadamard code using $\Delta F = 0.8nm$, B = 311MHz at the operating wavelength of 1550nm

4.0 PERFORMANCE ANALYSIS

The performance of MDW, MFH and Hadamard codes was simulated by using commercial simulation software, OptiSystem Version 3.0. A simple schematic block diagram consists of 2 users is illustrated in Fig. 5.

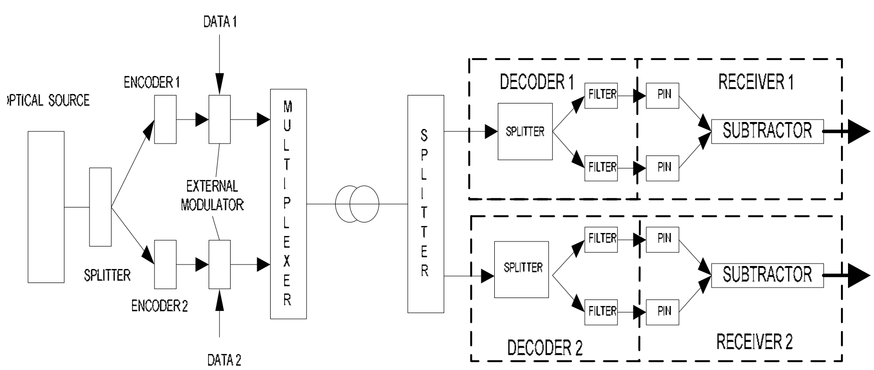

Fig. 5: The system architecture of the optical CDMA network under test

Each chip has a spectral width of 0.7nm. The tests were carried out at the rate of 10Gbps for 70km distance with the ITU-T G.652 standard single mode optical fiber. All the attenuation (i.e. 0.25dB/Km), dispersion (i.e. 18ps/nm-Km) and non-linear effects were activated and specified according to the typical industry values to simulate the real environment as close as possible. The performances of the system were characterised by referring to the bit error rate, BER and the eye patterns.

At the receiver side of the system, the incoming signal splits into two parts, one to the decoder that has an identical filter structure with the encoder and the other to the decoder that has the complementary filter structure. A subtractor is then used to subtract the overlapping data from the intended code. Similar approach has been used in a previous report [7]. The results taken after the subtraction are shown in Fig. 6(a) for MDW code, in Fig. 6(b) for Hadamard code and Fig. 6(c) for MFH code.

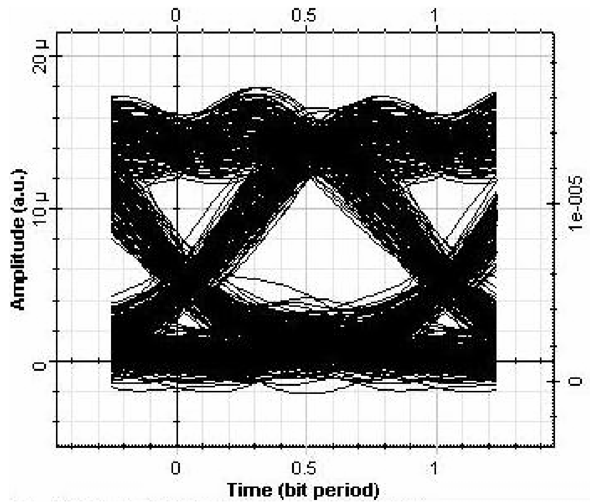

Fig. 6(a): Eye diagram of one of the MDW channels at 10Gbps

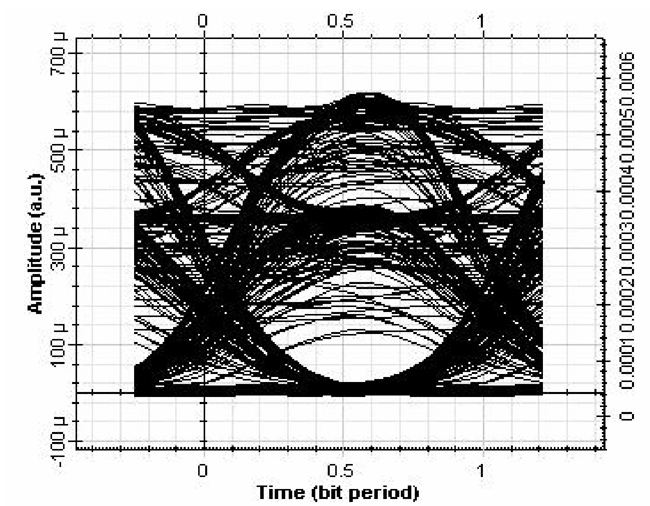

Fig. 6(b): Eye diagram of one of the Hadamard channels at 10Gbps

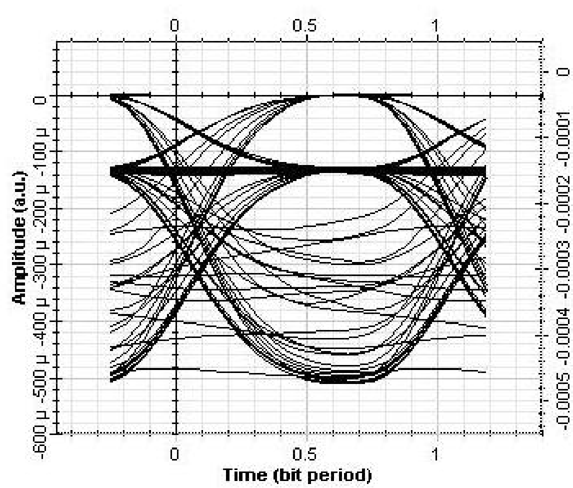

Fig. 6(c): Eye diagram of one of the MFH channels at 10Gbps

The eye patterns shown in Fig. 6 above clearly depict that the MDW code system gave a better performance. The BER for MDW, Hadamard and MFH codes systems were $10^{-12,}$ 10^{-4} and 10^{-3} respectively. Figs. 6(b) and 6(c) also clearly shows the cross-talks experienced by Hadamard and MFH codes [8]. The cross-talk is not present in MDW code. The results are consistent with the calculated SNR for all the codes as shown in Fig. 4. It clearly shows that the MDW code can support more users compared with Hadamard and MFH codes.

5.0 CONCLUSION

A new variation of optical code structure for amplitude-spectral encoding optical CDMA system has been successfully developed. The MDW code has been proven to provide a better performance compared to the systems encoded with Hadamard and MFH codes. This code possess such a numerous advantages including the efficient and easy code construction, simple encoder/decoder design, existence for every natural number *n,* ideal cross-correlation $\lambda = 1$, and high SNR. From the simulation, the eye pattern of one of the four MDW coded carriers running at 10 Gbps via a communication-standard fiber has achieved BER of 10^{-12}.

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