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SPECTRAL AMPLITUDE CODING OCDMA SYSTEMS USING ENHANCED DOUBLE WEIGHT CODE

F.N. HASOON[1*], S.A. ALJUNID[2], M.K. ABDULLAH[3], S. SHAARI[4]

[1]Faculty of Information Science & Technology,
Multimedia University (Melaka Campus),
Jalan Ayer Keroh Lama, 75450 Bukit Beruang, Melaka, MALAYSIA
* Corresponding Author: feras.n. hasoon@mmu.edu.my

[2]School of Computer and Communication Engineering
Northern Malaysia University College of Engineering
Block A, Kompleks Pusat Pengajian KUKUM,
Jalan Kangar-Arau, 02600 Jejawi, Perlis, MALAYSIA

[3]Photonic Laboratory, Department of Computer System and Communication,
Faculty of Engineering, University Putra Malaysia,
43400 UPM, Serdang, MALAYSIA

[4]Photonics Technology Laboratory (PTL), Institute of Micro Engineering and Nanoelectronics (IMEN), Universiti Kebangsaan Malaysia,
43600 UKM, Bangi, Selangor, MALAYSIA

Abstract

A new code structure for spectral amplitude coding optical code division multiple access systems based on double weight (DW) code families is proposed. The DW has a fixed weight of two. Enhanced double-weight (EDW) code is another variation of a DW code family that can has a variable weight greater than one. The EDW code possesses ideal cross-correlation properties and exists for every natural number *n*. A much better performance can be provided by using the EDW code compared to the existing code such as Hadamard and Modified Frequency-Hopping (MFH) codes. It has been observed that theoretical analysis and simulation for EDW is much better performance compared to Hadamard and Modified Frequency-Hopping (MFH) codes.

Keywords: Optical spectrum code division multiple access (OSCDMA), Cross correlation, double weight (DW), Enhanced double weight (EDW).

1. Introduction

Optical code-division multiple-access (CDMA) systems are getting more and more attractive in the field of all-optical communications as multiple users can access the network asynchronously and simultaneously with high level of

Nomenclatures

B	Noise equivalent electrical bandwidth of the receiver (MHz)
i	Sequence numbers
K	Number of user
M	Hadamard Matrix sequence
N	Code length
n	Integer number
p	Prime number (for Prime Code)
q	Prime number (for MFH code)
W	Code weight
Z	Elements in Hadamard Matrix
Greek Symbols	
Δv	Spectral Width (nm)
λ	Cross- correlation
λ_a	Auto- correlation
λ_c	Cross- correlation

security [1 & 2]. Optical Spectrum Code-Division Multiple-Access (OSCDMA) is a multiplexing technique adapted from the successful implementation in wireless networks. In OSCDMA systems, each user is assigned with a sequence code the serves as its address. A CDMA user modulates its code (or address) with each data bit and asynchronously initiates transmission. Hence, this modifies its spectrum appearance, in a way recognizable only by the intended receiver. Otherwise, only noise-like bursts are observed [3]. The advantages of OSCDMA technique over other multiplexing techniques such as time division multiple access and frequency division multiple access are numerous [4 & 5].

Many codes have been proposed for OSCDMA such as optical orthogonal codes (OOCs), Prime codes, and Modified Frequency-Hopping (MFH) codes. An optical orthogonal code was first introduced by Salehi [6]. An $(N,W,\lambda_a,\lambda_c)$ optical orthogonal code is a set of (0,1) sequences of length N and weight W (the number of ones in every codeword). The OOC codes have been designed following requirement for $\lambda_a = \lambda_c \leq 1$. There are several mathematical or geometrical ways to design such codes [7- 9]. However, the main restriction is that they are very sparse codes and they need to very long code sequences in order to accommodate even a moderate number of subscribers. The number of sequences in a family of OOC codes is also very limited. It has been calculated that for 6000 chip code period with eight 1's in the code there are only 100 OOC sequences [10].

The use of Prime Codes in Optical CDMA networks was first reported in [11]. An experimental set-up using this type of codes was implemented in [12] and results were obtained for a fiber-optic local area network with 5 users. In fact the set of Prime codes were the first optical codes proposed for an optical CDMA communication system [11]. The Prime codes are derived from prime sequences of length *P* obtained from a Galois field GF(*P*), where *P* is a prime number. The code size and weight is equal to *P* and the code length is P^2. Because of this, the number of available addresses is again equal to the generating prime number which is quite small. The autocorrelation peak of Prime codes is obviously *P*, while the cross correlation is always less than two. The performance of these codes depends upon the correlation properties. It is same like OOC codes, Prime code need very long code sequences in order to accommodate even a moderate number of subscribers. However, a major problem associated with prime codes is that their code weight *W* is always fixed to the number of codeword and must be a prime number *P*. To accommodate more users in an OCDMA system, a larger *P* is required, so is the code weight *W*. Since all-optical CDMA encoders and decoders for Prime codes use a parallel configuration the resulting optical power losses and complexity of an encoder or decoder would be high if *W* becomes large.

A modified Frequency Hopping (MFH) [13] is a family of frequency-hopping (FH) code with ideal cross-correlation presented in [13] is constructed based on prime power. Thus, a family of modified FH (MFH) code results having of code length $N= q^2 + q$, code weight $W = q + 1$ and cross-correlation $\lambda_c = 1$. MFH have the ideal cross correlation properties and shorter code length but their codes constructions are complicated.

Hadamard codes have many uses in digital signal processing and Code Division Multiple Access (CDMA) communication systems [13 & 14]. A *Z*-element Hadamard code is a row from Z x *Z* orthogonal Hadamard matrix, which has (-1,1) valued binary entries. The Z x *Z* Hadamard matrix, H_M where $Z = 2^M$ is generated by the core matrix

$$\mathrm{H}_{M=1} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \tag{1}$$

Hadamard code supports 2^M -1 number of users and for example, if only 20 users are required, *M* will have to be at least equivalent to 5 which supports up to 31 users, thus rendering 11 codes as unused. It is clear that Hadamard code is not efficient code because the sequence cannot be constructed exactly according to the number of users. Hadamard code has increasing value of cross-correlation as the number of user increases. And it also requires more number of filters for each code as the number of user increases.

This paper will discuss the EDW code performance in comparison with Hadamard and MFH codes. This is achieved mainly through software simulations and theoretical analysis. Hadamard and Modified Frequency Hopping (MFH) codes are chosen for the comparison with our proposed codes. The choice is made because

Hadamard is originally the basic and widely familiar code, while MFH is one of the latest codes in the literature whose performance has been shown to surpass that of others. Thus, it is only relevant to compare any new codes to the best and widely used exactingly. The simulated results are more comprehensive and closer to the real environment, taking into accounts the dispersions (chromatic and polarization mode) and the non-linear effects. The set-up parameters' values adopted are based on the typical values in real environment. It is found that EDW codes can support data transmissions at up to 10Gbps with a better performance than that of the other two codes. Theoretical analysis has been show that such a code structure can effectively suppress intensity noise and hence improves the bit error rate (BER) performance

2. Code Design

Ref. [7] defined $\lambda = \sum_{i=1}^{N} x_i y_i$ as the cross-correlation of two different code sequences $X = (x_1, x_2, \ldots, x_N)$ and $Y = (y_1, y_2, \ldots, y_N)$. A code with length *N*, weight *W* and λ can be denoted by (N, W, λ). *W* and λ are two most important parameters as they directly affect the overall system signal-to-noise ratio (SNR) as shown by

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

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 EDW code the cross correlation is ideal and λ is always equal to one.

2.1 DW code construction

Ref. [15] described the construction of DW code using the following steps:

Step 1:
The DW code can be represented by using the *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:

$$H_1 = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 0 \end{bmatrix} \tag{3}$$

Notice that 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:-

$$H_2 = \left|\begin{array}{ccc|ccc} 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ \hline 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 \end{array}\right| = \begin{vmatrix} 0 & H_1 \\ H_1 & 0 \end{vmatrix} \tag{4}$$

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 Eq (5)

$$N = \frac{3K}{2} + \frac{1}{2}\left[\sin\left(\frac{K\pi}{2}\right)\right]^2 \tag{5}$$

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.

2.2 EDW code construction

EDW is the enhanced version of DW code. The EDW code weight can be any odd number that is greater than one. In this paper, the EDW with the weight of three is used as an example. EDW code can be constructed using the following steps:

Step 1:
EDW code can be represented by using a *K x N* matrix. In EDW codes structures, the matrix K rows and N columns represent the number of users and the minimum code length respectively. A basic EDW code is given by a 3 x 6 matrix, as shown below:

$$H_o = \left|\begin{array}{cc|cc|cc} 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \end{array}\right| \tag{6}$$

Notice that similar structure of the basic DW code 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.

Step 2:
From the basic matrix, a larger number of K can be achieved by using a mapping technique as shown in Eq. (7).

$$H_1 = \left| \begin{array}{cccccc|cccccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ \hline 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \right| = \left| \begin{array}{cc} 0 & H_o \\ H_o & 0 \end{array} \right| \quad (7)$$

An EDW code with weight of 3 denoted by (N, 3, 1) for any given code length N, can be related to the number of user K through

$$N = 2K + \frac{4}{3}\left[\sin(\frac{K\pi}{3})\right]^2 \frac{8}{3}\left[\sin(\frac{(K+1)\pi}{3})\right]^2 + \frac{4}{3}\left[\sin(\frac{(K+2)\pi}{3})\right]^2 \quad (8)$$

3. Code Evaluation and Comparison

For comparison, the properties of EDW, MFH, and Hadamard codes are listed in Table 1. The table shows that EDW 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.

The number of users, K supported by EDW 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 EDW codes, W can be fixed at any odd 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 Eq (1), thus the same quality of service can be provided for all users.

EDW code has better SNR than MFH and Hadamard. This is evident from the fact that EDW 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 one, the SNR is smaller than that of EDW. MFH needs a higher number of Q or W to increase SNR.

Table 1.Comparison between EDW, MFH and Hadamard Codes

Code	Existence	No of user (*K*)	Weight (*W*)	Cross correlation (λ)	SNR
EDW (W=3)	n	$K = n$	$W = 3$	$\lambda = 1$	$\frac{8\Delta v}{Bn(n+2)}$
MFH	q	$K = q^2$	$W = q+1$	$\lambda = 1$	$\frac{2q\Delta v}{BK(K/2+q-1)}$
Hadamard $(M \geq 2)$	M	$K = 2^M - 1$	$W = 2^{M-1}$	$\lambda = 2^{M-2}$	$\frac{4\Delta v}{B(2^M-1)^2}$

Figure 1 shows the bit-error rate (BER) versus with number of users when different codes are used. In this figure we have been used the following parameters: Δv = 0.8nm, B=311MHz (for bit rate 622Mbps) at the operation wavelength of 1550nm. It clearly shows that the EDW code can support more users compared with Hadamard and MFH codes.

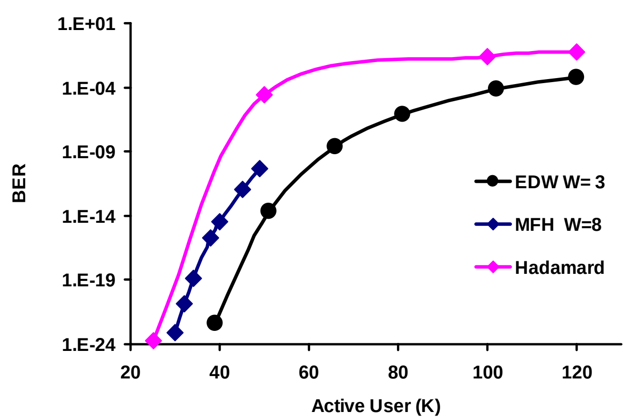

Fig. 1. BER versus number of users for EDW, MFH and Hadamard codes

4. Performance Analysis

The performance of EDW, MFH and Hadamard codes was simulated by using commercial simulation software, OptiSystem Version 4.0. A simple schematic block diagram consisting of 2 users is illustrated in Fig. 2 as an example (the study is carried out for three users).

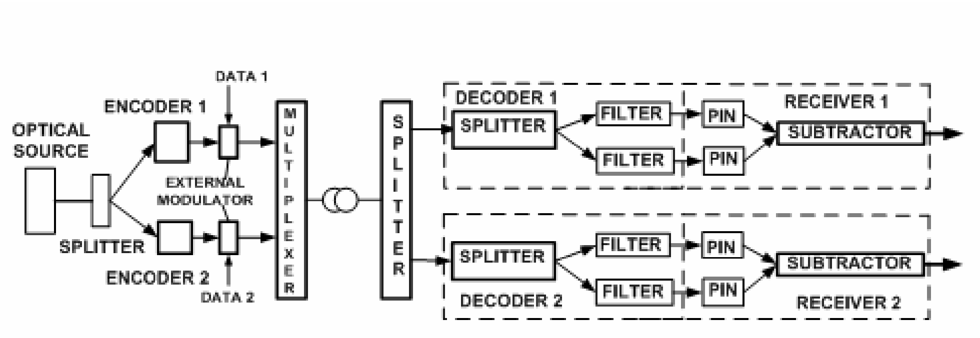

Fig. 2. The system architecture of the OCDM network

The fiber length is varied from 10km to 50km. At the receiver side, the incoming signal is split 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 used to subtract the overlapping data from the wanted one. The performance of the system is characterized by referring to the bit error rate and the eye patterns.

The fiber used has the parameters' values taken from data which are based on the G.652 Non Dispersion Shifted Fiber (NDSF) standard. This includes the attenuation, group delay, group velocity dispersion, dispersion slope and effective index of refraction, which are all wavelength dependent. The nonlinear effects such as Four Wave Mixing and Self Phase Modulation are also activated. At 1550nm wavelength, the attenuation coefficient is 0.25dB/km, chromatic dispersion coefficient is 18ps/nm-km and polarization mode dispersion coefficient is 5ps/√km. The transmit power used is 0dBm out of the broadband source. The noises generated at the receivers are set to be random and totally uncorrelated. The dark current value is 5nA and the thermal noise coefficient is $1.8\text{x}10^{-23}$ W/Hz for each of the photo-detectors. The eye pattern diagrams for EDW, MFH and Hadamard codes are shown in Figs. 3(a), 3(b), and 3(c) respectively.

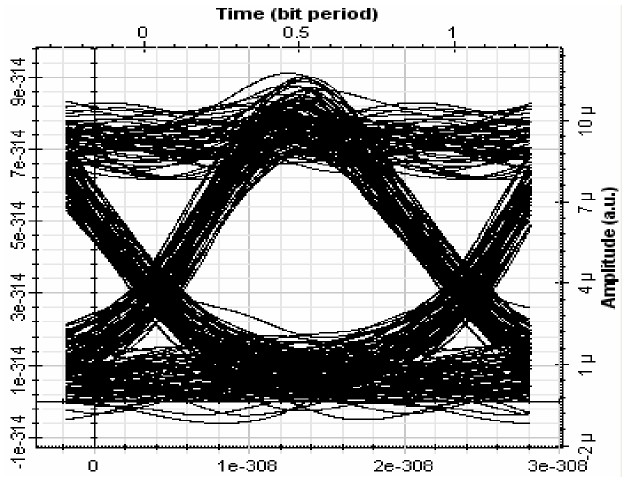

Fig. 3(a). Eye diagram of one of the EDW channels at 10Gbps

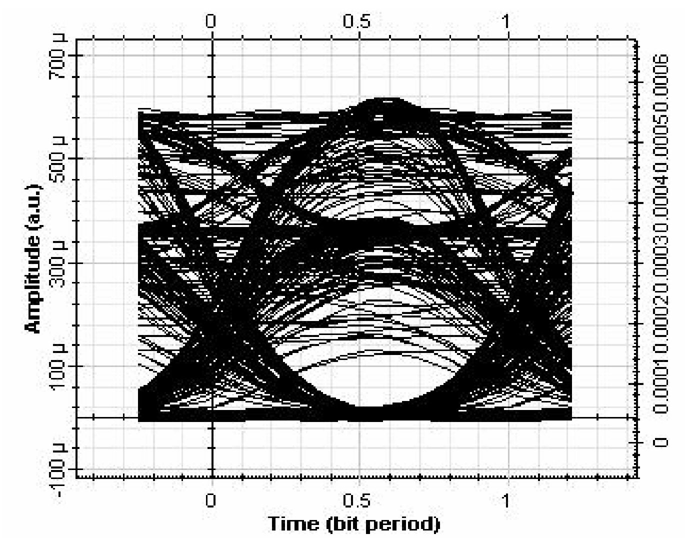

Fig. 3(b). Eye diagram of one of the Hadamard channels at 10Gbps

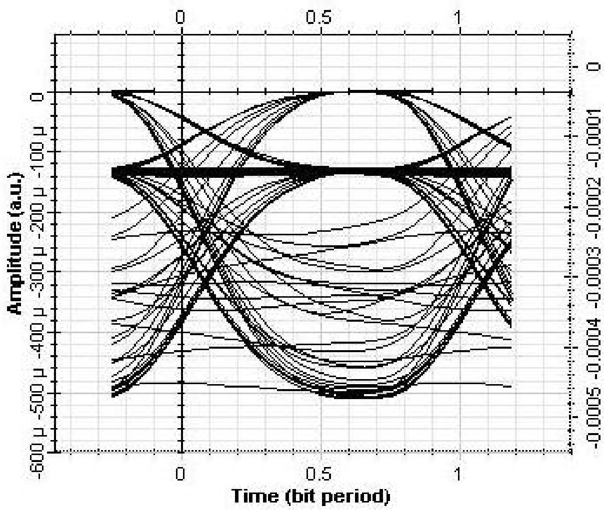

Fig. 3(c). Eye diagram of one of the MFH channels at 10Gbps

The eye patterns shown in Fig. 3 above clearly depict that the EDW code system gave a better performance. The BER for EDW, Hadamard and MFH codes systems were 10^{-12}, 10^{-4} and 10^{-3} respectively. Figures 3(b) and 3(c) also clearly show the cross-talks experienced by Hadamard and MFH codes [16]. The cross-talk is not present in the eye pattern EDW code.

5. Conclusions

It has been shown that the EDW code performs better than the system encoded with MFH and Hadamard codes. The advantages the proposed code are numerous, including easy and efficient code construction, simple encoder/decoder design, existence for every natural number *n*, ideal cross-correlation λ =1, and low BER. From the simulation, the eye pattern of one of the three EDW coded carriers running at 10 Gbps via a communication-standard fiber has achieved BER of 10^{-12}.

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