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Multi-rate transmissions on spectral amplitude coding optical code division multiple access system using random diagonal codes

HILAL A. FADHIL*, S.A. ALJUNID, R.B. AHMAD

School of Computer and Communication, University Malaysia Perlis (UniMAP),
Kuala Perlis, 0200, Perlis, Malaysia

*Corresponding author: s0740810145@student.unimap.edu.my

In this paper, we study the use of a new code called random diagonal (RD) code for spectral amplitude coding (SAC) optical code division multiple access (OCDMA) networks, using fiber Bragg-grating (FBG). FBG consists of a fiber segment whose index of reflection varies periodically along its length. RD code is constructed using a code level and data level, one of the important properties of this code is that the cross correlation at the data level is always zero, which means that phase intensity induced phase (PIIN) is reduced. We find the performance of the RD code to be better than those of the modified frequency hopping (MFH) and Hadamard codes. It has been observed from simulation and theoretical results that considering the bit error rate (BER), the RD code performs significantly better than other codes. The ability of RD codes to support simultaneous transmissions at different bit rates is shown through simulated results of the BER and the eye patterns.10 Gbps and 2.5 Gbps data transmissions have been successfully demonstrated together with FBG decoding scheme for canceling the code level from SAC-signal.

Keywords: optical code division multiple access (OCDMA), bit error rate (BER), SNR, phase intensity induced phase (PIIN).

1. Introduction

The success and extensive application of code division multiple access (CDMA) in the wireless area has renewed attention in exploring its application in the optics communication systems. Optical CDMA (OCDMA) has long been the subject of research because of its inherent ability to support asynchronous burst communications. Initially, it was employed for local area [1], then for access network applications [2, 3] and more recently for emerging networks such as generalized multiprotocol label switching [4]. The assumption of large code space does not always hold in practice, especially for the spectral-phase-encoded OCDMA [5, 6]. Because of optical hardware limitations and the code orthogonality required for low multiple access interferences, feasible spectral-phase-encoding solutions are limited to several well-known code families that contain relatively small number of codes. The spectral-phase-encoded OCDMA network exploits relatively simple all-optical pulse shaping to achieve optical encoding and decoding. In this scheme, the entire pulse spectrum is divided into different spectral components called "chips". The number of "chips" is chosen to be the length of the selected code. Across the spectrum, the phase is altered in each chip according to the phase code. The code set size is dependent on the code length. For the OCDMA scheme to be more realistic, it is desired to devise an optical code that can accommodate a larger number of simultaneous users with a low error probability for a given code length. A good set of codes is to obtain the maximum number of codes with maximum weight and minimum length with the best possible autocorrelation and cross-correlation properties [7]. To establish the OCDMA, we have to overcome the code orthogonality problem. Many researchers have proposed several codes such as prime code, optical orthogonal code, and so on. In this paper, we focus on random diagonal (RD) codes. In Section 2.1, we introduce the RD code construction, showing how the code has been developed theoretically, and discuss its properties. In Section 2.2, we focus on the proposed system scheme and design steps, and finally, drow conclusions is in Section 3.

2. RD code development

2.1. Construction of RD code

An (N, W, λ) RD code is a family of (0, 1) sequences of length N and weight W, and λ is the in-phase cross-correlation which satisfies the following two properties: *i*) zero cross-correlation will minimize λ and reduce phase induced intensity noise (PIIN); *ii*) no cross-correlation in data level. The design of this new code can be preformed by dividing the code sequence into two groups, that is, a code level (segment) and data level (segment).

Step 1, data segment: let the elements in this group contain only one "1" to keep zero cross-correlation at data level ($\lambda = 0$), which property is represented by the matrix $(K \times K)$, where K represents the number of users, these matrices have binary coefficient and a basic zero cross code ($W = 1$) is defined as $[Y_1]$, for example, three users ($K = 3$), $y(K \times K)$ can be expressed as

$$[Y_1] = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

where $[Y_1]$ consists of $(K \times K)$ identity matrices. Note that for the above expression the cross-correlation between any two rows is always zero.

Step 2, code segment: the representation of this matrix can be expressed for $W = 4$ as follows:

$$[Y_2] = \left[\begin{array}{cc:ccc} 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 1 & 1 & 0 \end{array}\right]$$

where $[Y_2]$ consists of two parts: a weight matrix part and a basic matrix part; the basic part $[B]$ can be expressed as

$$[B] = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}$$

and the weight part $[M] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$ which is responsible for increasing number of weights. Let $i = (W - 3)$ and $M_i = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{bmatrix}$, where i represents the number of M_i matrix on $[M]$, as given by

$$[M] = \langle M_1 | M_2 | M_3 \ldots M_i \rangle \tag{1}$$

For example, if $W = 5$, from Eq. (1) $i = 2$, so that $[M] = \langle M_1 | M_2 \rangle$

$$[M] = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 \end{bmatrix}$$

Notice that in order to increase the number of users simultaneously with the increase of code word length we can just repeat each row on both matrices $[M]$ and $[B]$; for the K-th user matrices $[M]$ and $[B]$ can be expressed as

$$[M](j) = \begin{bmatrix} 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ 1 & 0 \\ 0 & 1 \\ \vdots & \vdots \\ \vdots & \vdots \\ a_{j1} & a_{j2} \end{bmatrix}, \qquad [B](j) = \begin{bmatrix} 0 & 1 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 0 \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ a_{j1} & a_{j2} & a_{j3} \end{bmatrix}$$

where j represents the value for the K-th user ($j = 1, 2\ldots K$), and the value of a_j is either zero or one. The weights for the code part for both matrices $[M]$, $[B]$ are equal to $W - 1$, so the total combination of code is represented by $(K \times N)$ where $K = 3$, $N = 8$, as given by $[Z_1]$, $[Z_1] = [Y_1 | Y_2]$

$$[Z_1] = \left[\begin{array}{ccc:ccccc} 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 & 1 \\ 1 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{array}\right]$$

Table. Comparison between RD, MFH, OOC, Hadamard, and Prime codes for the same number of users $K = 30$.

Code	Weight W	Code length N
OCC	4	364
Prime	31	961
Hadamard	16	32
MFH	7	42
RD	3	33

From the above basic matrix Z_1, the number of users K and the code length N, is given by $(K \times N)$ matrix. Notice that the code weight of each row is equal to 4, and the relation between N and K for this case can be expressed as

$$N = K + 5 \tag{2}$$

As a result, we can find that for $W = 5$, 6, and 7, the code word length N can be expressed as $K + 7$, $K + 9$ and $K + 11$, respectively. As a result, the general equation describing the number of users K, code length N and code weight W is given by

$$N = K + 2W - 3 \tag{3}$$

Many codes have been proposed for OCDMA systems, such as optical orthogonal code (OOC), modified frequency-hopping (MFH) codes, and Hadamard code, but the key point of RD code is that the RD code offers better performance than other codes in terms of the code length N for the same number of users $K = 30$, as shown in the Table. A short code length limits the addressing flexibility of the codes, while a long code length is considered disadvantageous in implementation, since either a very wide bandwidth source or a very narrow filter bandwidth are required. The RD codes are neither too short nor too long.

2.2. Performance analysis

Figure 1 shows a setup for the proof-of-principle simulation for the scheme proposed. The performances of RD, MFH, and Hadamard codes are simulated by using the simulation software OptiSystem Version 6.0. A simple schematic block diagram consists of two users, as illustrated in Fig. 1. Each chip has a spectral width of 0.8 nm. The tests were carried out at a rate of 10 Gb/s for a 20-km distance with the ITU-T G.652 standard single-mode optical fiber. The attenuation α (*i.e.*, 0.25 dB/km), dispersion (*i.e.*, 18 ps/nm km), and nonlinear effects were activated and specified according to the typical industrial values to simulate real environment as close as possible. The performances of the system were characterized by referring to the bit-error rate (BER). As shown in Fig. 1, after transmission, we used a fibre Bragg grating (FBG) spectral phase decoder operating at the data level. The signals were decoded

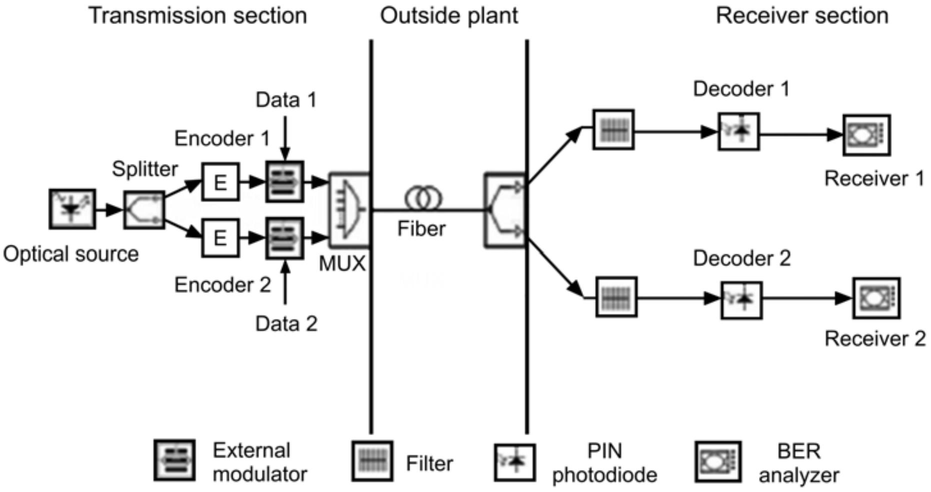

Fig. 1. Simulation setup of the proposed encoding/decoding scheme.

by a photodetector (PD) followed by a 0.75 GHz low-pass-filter (LPF) and error detector. The transmitted power used was 0 dBm out of the broadband source. The noise generated at the receivers was set to be random and totally uncorrelated. The dark current value was 5 nA, and the thermal noise coefficient was 1.8×10^{-23} W/Hz for each of the photodetectors. The eye pattern diagrams for RD, Hadamard and MFH codes are shown in Fig. 2. The eye diagrams of Fig. 2 clearly show that the RD code system gives better performance, having a larger eye opening. The eye pattern diagrams for Channel 1 (10 Gbps) and Channel 3 (2.5 Gbps) are shown in Figs. 2**c** and 2**d**, respectively, for RD code. Figure 2 also clearly shows the cross-talks experienced by Hadamard and MFH codes [8]. The vertical distance between the top of the eye opening and maximum signal level gives the degree of distortion. The more the eye closes, the more difficult it is to distinguish between 1 s and 0 s in the signal. The height of the eye opening at the specified sampling time shows the noise margin or immunity to noise [9, 10].

The system's SNR and the corresponding BER for RD code are given by:

$$\mathrm{SNR} = \frac{\left(\dfrac{2\Re P_{sr} W}{N}\right)^2}{\dfrac{2eBWP_{sr}\Re}{N} + \dfrac{B\Re^2 P_{sr} WK}{2N^2\Delta V}(K-1+W) + \dfrac{4K_B T_n B}{R_L}} \tag{4}$$

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\sqrt{\frac{\mathrm{SNR}}{8}} \tag{5}$$

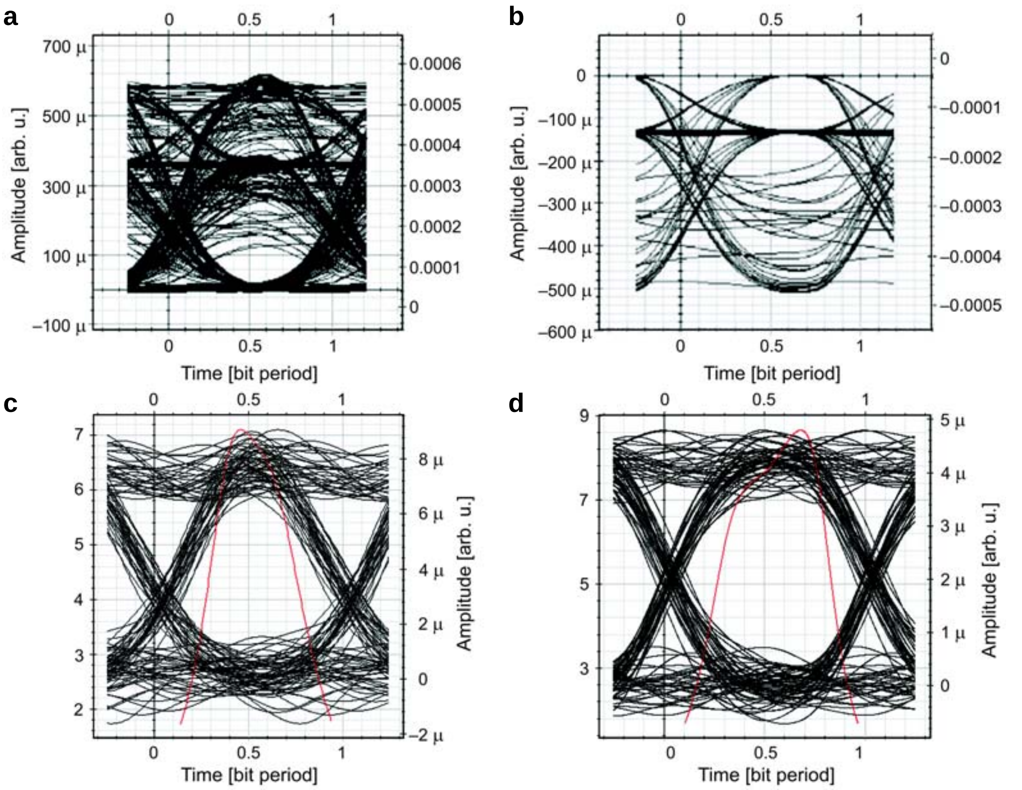

Fig. 2. Eye diagram of one of the Hadamard channels at 10 Gb/s after 10 km (**a**), and one of the MFH channels, at 10 Gb/s after 10 km (**b**), RD channel 1 at 10 Gb/s with BER of 6.4×10^{-13} at a 20 km transmission (**c**), RD channel at 2.5 Gb/s with BER of 2.4×10^{-18} after a 30 km transmission (**d**).

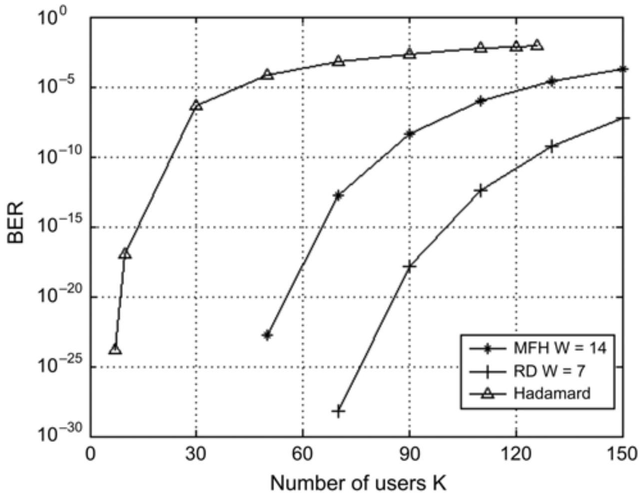

Fig. 3. BER against the number of users for RD, Hadamard, and MFH codes when P_{sr} = 0 dBm.

Figure 3 shows the relation between the number of users and the BER, for RD, MFH, and Hadamard codes, as plotted for different values of K (number of users). From this figure it is clearly seen that RD code gives a much better performance, *i.e.*, (smaller BER) than MFH code and Hadamrad code schemes. This is evident from the fact that RD code has a zero cross-correlation while Hadamard code has increasing value of cross-correlation as the number of users increases. However, a few code specific parameters are chosen based on the results published for these practical codes [7, 10, 11]. The calculated BER for RD was achieved for $W = 7$, while for MFH and Hadamrad codes, $W = 14$, and $W = 64$, respectively.

3. Conclusions

A simple model using RD code is developed and employed to investigate the effects of SAC-OCDMA for different transmission rates on the OCDMA access links. The SAC-OCDMA is distinct because its requirement as to the light source is not strict and its encoder/decoder using FBGs is simple to be implemented. It has been shown that the RD code performs better than the system encoder with MFH and Hadamard, and the advantages of the proposed code are: shorter code length, no cross-correlation in data level (zero cross-correlation will minimize λ and reduce PIIN), data level can be replaced with any type of codes, more overlapping chips will result in crosstalk, flexibility in choosing parameters N, K unlike with other codes, such as MFH and Hadamard, and finally, RD code can support different transmission rates. The simulated result of one of the three RD coded carriers running at 10 Gb/s and 2.5 Gb/s over a communication-standard fiber shows a good quality transmission.

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