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Performance Analysis of Optical Zero Cross Correlation in OCDMA System

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Abstract: We propose a new code structure for Spectral-Amplitude Coding Optical Code Division Multiple Access (OCDMA) systems with zero cross-correlation and theoretically demonstrate the performance of this code by using a direct decoding technique. The proposed code can be adapted to any weight and user by using transformation and mapping techniques, respectively. The direct decoding technique is exploited since there is no overlapping occurrence in the code construction. The code performance shows that it outperforms the existing SAC OCDMA codes such as Hadamard, Modified Frequency Hopping (MFH) and Modified Double-Weight (MDW). The system can accommodate 120 simultaneous users for a bit error rate of 10^{-9}.

Key words: Zero Cross-correlation (ZCC) code, Phase Induced Intensity Noise (PIIN), Multiple Access Interference (MAI), Bit Error Rate (BER), code weight, direct decoding

INTRODUCTION

A multiple access communication system is a communication system where a number of users share a common transmission medium to transmit messages to a number of destinations. One of the key issues that must be resolved in moving from a single user communication system to a multi-user communication system is how we can efficiently divide the available transmission medium among all users. Optical Code Division Multiple Access (OCDMA) has been recognized as one of the most important technologies for supporting many users in shared media simultaneously and in some cases can increase the transmission capacity of an optical fiber.

OCDMA allows multiple users to utilize the same overlapping spectrum through the use of orthogonal codes that obviate interference between simultaneous users on the channel. One of the crucial issues in OCDMA is to devise a coding system which can suppress the effects of co-channel interference, in so doing yield a better system performance.

The performance of uni-polar codes (Djardjevic and Vasic, 2003a) is determined by the bandwidth efficiency occupied by the codes, closely related to the error probability performance of the code in multiple user transmission as well as the size of the code set which is dependent on the code length. The goal is to design an optical code that can accommodate a larger number of asynchronous, simultaneous users with a low error probability for a given code length.

The effective Signal-to-Noise Ratio (SNR) in OCDMA systems is limited by the interference resulting from the other users transmitting at the same time on a common channel, known as Multiple Access Interference (MAI); MAI is a major source of noise in OCDMA systems (Aljunid *et al*., 2004). Thus, a proper design of the code sequences is important to mitigate the deleterious effect of MAI. There are also intrinsic noise sources arising from the physical effects of the system design itself, such as Relative Intensity Noise (RIN), phase induced intensity noise (PIIN), thermal noise and shot noise (Salehi, 1989). PIIN is closely related to the MAI due to the overlapping of the spectra from the different users (Aljunid *et al*., 2004).

The key to an effective OCDMA system is efficient address codes with zero cross-correlation properties (Andrew and Sargent, 2000). This property not only ensures that each code sequence can be easily distinguished from the other code sequences, but also suppresses any limitations owing to MAI and PIIN. The

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main goal of this study is to develop a new optical CDMA code family to improve the performance of optical network. This study proposes a new Optical Spectrum CDMA code family, Zero Cross Correlation (ZCC) that can be used in Optical Spectrum CDMA (OSCDMA) systems.

CONSTRUCTION OF ZCC CODE

The ZCC code family is an evolution from the modified double weight codes (MDW) which eliminate chip (high bit) overlaps in the sequences. The proposed ZCC code is represented in a matrix of K X C where K (row) represents the number of users and C (column) represents the minimum code length. The matrix contains the binary coefficients. A basic ZCC code (for weight = 1) is shown in Eq. 1.

$$\begin{matrix} & 1 & 1 \\ & \downarrow & \downarrow \\ Z_1 = & \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \end{matrix} \quad (1)$$

Notice that Z_1 has no overlap of 1 for both users. In order to increase the number of users and codes, a mapping technique is used as below;

$$Z_2 = \begin{bmatrix} 0 & Z_1 \\ Z_1 & 0 \end{bmatrix} = \begin{array}{cc|cc} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ \hline 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array} \quad (2)$$

$$Z_3 = \begin{bmatrix} 0 & Z_2 \\ Z_2 & 0 \end{bmatrix} = \begin{array}{cccc|cccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{array} \quad (3)$$

From the mapping, it is noted that as K is increased, the code length C also increases. The basic matrix is mirrored diagonally to increase K. The relationships between the mapping process M, K and C is given by:

$$K = 2^M \quad (4)$$

and

$$C = 2^M \quad (5)$$

thus

$$C = K \quad (6)$$

Note that C also represents the spectral or the chip position in a code sequence.

The ZCC code has flexibility in code weight w. In order to increase w, some code transformations steps need to be followed Djarjevic and Vasic (2003b). As mentioned before, the basic matrix of ZCC code has a w of 1; to increase w to 2, the general form of transformation is given by:

$$Z_w = \begin{array}{c|c} A & B \\ \hline C & D \end{array} \quad (7)$$

Where:

A = Consist of [1, w (w-1)] matrix of zeros,

B = Consist of w times replication of the matrix $\sum_{j=1}^{w} j$ [0 1],

C = Consist of the duplication of the matrix from w-1,

D = Consist of the diagonal pattern of [m×n] with alternate column of zeros matrix [m×n].

For example, the transformation code from w = 1 → w = 2→w = 3 is shown as;

$$Z_{w=1} = \begin{array}{c|c} 0 & 1 \\ \hline 1 & 0 \end{array}$$

$$\begin{matrix} & A & B \\ & \downarrow & \downarrow \\ Z_{w=2} = & \begin{array}{cc|cccc} 0 & 0 & 0 & 1 & 0 & 1 \\ \hline 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 \end{array} \\ & \uparrow & \uparrow \\ & C & D \end{matrix}$$

$$\begin{matrix} & A & B \\ & \downarrow & \downarrow \\ Z_{w=3} = & \begin{array}{cccccc|cccccc} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 \\ \hline 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{array} \\ & \uparrow & \uparrow \\ & C & D \end{matrix}$$

The relationship between the number of user K_B, weight w and basic code length C_B is given by;

$$K_B = w+1 \quad (8)$$

$$C_B = w(w+1) \quad (9)$$

$$ZCC_{i,j} = \begin{cases} 1 \quad \text{if} & \begin{cases} j = (n_1 - 1) + \left\lfloor \frac{(2n_1 + 1)}{2} \right\rfloor + \sum_{m=0}^{i \bmod k_{B1} - 2} (2w - 2m) & \text{for} \quad n_1 = \{1, 2, .., w - (i-1)\} \\ j = 2(i-1) + \sum_{m=1}^{\lfloor n_2 - 1 \rfloor} (2w - 2m) & \text{for} \quad n_2 = \{1, 2, ..., (i-1)\} \end{cases} \\ 0 \quad \text{otherwise} \end{cases} \qquad (10)$$

Where, w is the weight of the code with zero cross correlation value. This transformation technique was written in MATLAB program for the ease of generating the code corresponds to the K th user.

Code comparison: A comparison has been undertaken to contrast the performance of ZCC codes and existing optical codes such as such as Optical Orthogonal Codes (OOC), modified double weight (MDW) and modified frequency-hopping (MFH) codes (Aljunid *et al.*, 2004). All the mathematical relationships between C and w are shown for the above codes (Table 1).

Many codes have been proposed for the SAC OCDMA systems however, these codes suffer from various limitations; code constructions are complex (e.g., OOC and MFH codes), the cross-correlation are not ideal or the code length is too long (e.g., OOC) (Table 2). In ZCC, a lengthy code sequence is considered as the downside of the code since the longer the length the wider the source bandwidth requirement. Conversely, if the bandwidth of the broadband source is limited, one will require a narrow bandwidth filter to accommodate the chips in the code sequences. The longer code length will also increase the number of filters needed for the encoder and decoder.

Performance analysis: A basic block diagram of an OCDMA system employing the direct decoding technique is shown in Fig. 1.

Table 1: The relationship between code length and weight for a number of OCDMA codes

Codes	No. of users (K)	Code length	Weight	Cross-correlation
MFH	$K = Q^2$	$N = Q^2+Q$	$W = Q+1$	$\lambda = 1$
MDW (W = 4)	$K = n$	$N = 3n + \frac{8}{3}\left[\sin\left(\frac{n\pi}{3}\right)\right]^2$	$W = 4$	$\lambda = 1$
Hadamard d(M≥2)	$K = 2^M-1$	$N = 2^M$	$W = 2^{M-1}$	$\lambda = 1^{M-3}$
Optical ZCC	$K = 2^M$	$C = 2^M$	$W = 2^{M-1}$	$\lambda = 0$

Table 2: Comparison between OOC, Hadamard, MDW code, MFH and ZCC code

Codes	No of user (K)	Weight (w)	Code length (C)
OOC	30	4	364
Hadamard	30	16	32
MDW code	30	4	90
MFH	30	7	42
ZCC code	30	4	120

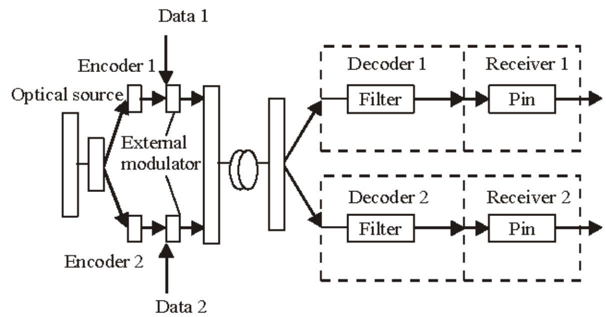

Fig. 1: OCDMA system architecture using the direct decoding technique

In direct decoding, a single input only to the receiver is required compared to the other techniques which required two input branches viz. the first branch represents the decoded code sequence whilst the second represents the complement of the code sequence (Salehi, 1989). Direct decoding will reduce the number of filters required at the receiver (Zou and Gahafouri Shiraz, 2002). Since ZCC is designed with zero cross-correlation, the MAI and PIIN effects are completely eliminated thus improving the BER of the system.

For a multiple number of users, the variance in the power of chips will impair system performance (Salehi, 1989). However, this problem can be eliminated by using ZCC codes. Here, the BER of the system is evaluated taking into consideration shot noise and thermal noise only. It is assumed that the PIIN effects are completely eliminated.

The SNR for direct decoding is expressed by Djardjevic and Vasic (2003b):

$$SNR = \frac{\frac{2\Re^2 P_{sr}^2 W^2}{N^2}}{\frac{P_{sr}\, e\, B\, \Re}{N}\left[(K_B - 1) + W\right] + \frac{4K_h T_n B}{R_L}} \qquad (11)$$

$$BER = \frac{1}{2}\,\mathrm{erfc}\sqrt{\frac{SNR}{8}} \qquad (12)$$

Where:

R = Photodiode responsivity,
P_{sr} = Effective power at receiver,
e = Electron charge,
B = Electrical equivalent noise band-width of the receiver.

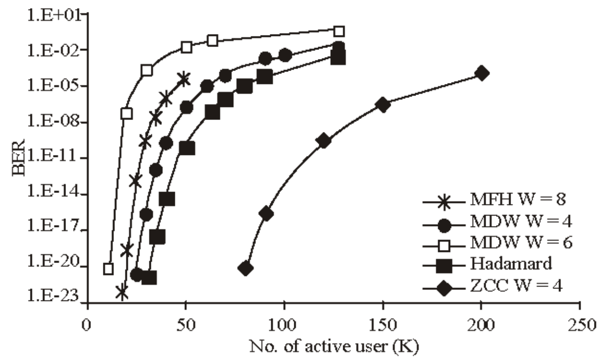

Fig. 2: Performance comparison between Hadamard, MDW, MFH and ZCC codes

k_B = Boltzmann's constant,
T_r = Temperature of receiver noise,
R_L = Load resistance,
w = Weight,
k = No. of user,
C = Code length,
erfc = A complementary error function (Djardjevic and Vasic, 2004a)

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-u^2} du$$

The relationship between number of active user and the system performance BER (Fig. 2), showing that ZCC codes yield the best performance on comparison to Hadamard, MDW and MFH codes. 127 to 109 users can be supported simultaneously at typical bit error rates of 10^{-9} to 10^{-12}. From Eq. 11 and 12, it shows that BER is proportional to the number of users.

This is directly attributed of the superior code cross-correlation property of ZCC codes which maintains that value at zero. ZCC codes can provide a much lower BER than when using MFH and MDW codes, although the code weight for, MFH and MDW codes are higher than ZCC codes. Please note that no BER performance analysis has been undertaken for OOCs due of the length of these code sequences.

CONCLUSION

The performance of the OCDMA systems degrades as the number of simultaneous users' increases, primarily owing to MAI which arises from the incomplete orthogonality of the signature codes.

In this study, a zero cross-correlation code has been constructed through a simple algebraic framework. Analytical results revealed that ZCC codes provide a better BER compared to the OOC, MFH and MDW codes and the results presented are based on the theoretical calculation. In addition the elimination of MAI also has a beneficial impact on the generation of PIIN which in turn eliminates one of the major implementation issues in photonics. ZCC code has shown superior performance compared with other OCDMA codes whereby the total noise level is reduced. The codes lend themselves to the use of a direct decoding, which is reducing the number of filters required at the receiver. The advantages of the proposed code are numerous including easy and efficient code construction, simple encoder-decoder design, existence for every natural number of user and weight, zero cross correlation and high SNR.

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