New Zero Cross-Correlation Codes Based on Zech Method's for OCDMA Systems

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Highlights
• This paper focuses on the suppression of MAI and PIIN effects in optical CDMA systems.
• A new code construction method is proposed for zero cross-correlation.
• A significant performance improvement was obtained.

Abstract

A new structure code for Spectral Amplitude Coding Optical Code Division Multiple Access (SAC–OCDMA) system with zero cross-correlation (ZCC) is presented in this paper. The principle idea of this method is based on the use of Zech logarithms in the construction of the code sequences to ensure orthogonality and compare their performances with previously reported codes. The maximum cross-correlation of this code is zero signifying that Multi-Access Interference (MAI) and Phase-Induced intensity noise (PIIN) effects are eliminated thus the system performances are improved. The BER simulation results against the total number of active users show a significant improvement in the performance of the proposed code over preceding reported codes. The system can accommodate more than 90 simultaneous users compared to other codes at a bit error rate of 10^{-9}. Furthermore, the construction method offers good flexibility in the choice of the number of users, the weight, and the code length.

1. INTRODUCTION

Optical code-division multiple accesses (OCDMA) is one of the most promising technologies to solve the problem of traffic growth and multiple user access on the internet. In this multiplexing technique, each user in the transmitter communication channel is allocated a unique distinguishable optical code [1,2]. This technique has many advantages besides the Wavelength Division Multiplexing (OTDMA) and Time Division Multiplexing (WDM) such as higher security, flexibility**,** and simplicity of the network control [3-5]. However, the performance of the technique OCDMA is mainly dependent on a specifically codes used for encoding. A proper choice of code family and code length is of great importance dictated by different design considerations at the transmitter as well as at the receiver.

The performance of the OCDMA system is limited by shot noise, beat noise, thermal noise, a dark current, and a phase-induced intensity noise (PIIN) [6,7]. The most important noise is the so-called Multi-Access Interference (MAI) originating from the cross**-**correlation existing among multiple active users on a common channel [8-10]. As the number of active users increases, the BER performance degrades due to an increase in MAI. Therefore, the MAI and PIIN effects can be reduced effectively using low cross**-**correlation codes; which increases the SAC-OCDMA system performance. Thus, the design of the code sequence according to cross-correlation is the important property for reducing the MAI contribution to the total optical received power [2, 11]. High auto-correlation and zero cross-correlation properties are required in the design of ZCC code to improve the system performance.

In the literature, various code schemes have been proposed to overcome the MAI problem among multiple users for the SAC-OCDMA systems, such as M-sequence codes [12], optical orthogonal codes [13-16], prime codes [17], double weight codes [18-20], and random diagonal (RD) codes [21]. The construction of the code is limited by the code length parameters, as is the case for the modified quadratic congruence [22,23] and Dynamic Cyclic shift codes [1]. For the case of prime codes [13,24] and random codes [21], cross-correlation increases with the weight number while the code length is large for KS and EDW codes. As a result, code design cannot be used for any number of simultaneous users or high data rates in the SAC-OCDMA systems.

In this paper, we proposed a new construction method of Zero Cross-Correlation ZCC codes for OCDMA systems. The newly proposed method allows the number of users, weight, and code length to be chosen independently. The code cardinality is increased and the cross-correlation is equal to zero. The rest of the paper is organized as follows: we will first describe mathematically the construction method for the proposed ZCC code. Then, we will introduce the code comparison with others codes from the references to prove the efficiency of our proposed code. Next, we validate the performance of the proposed ZCC code by using simulations under Optisystem software. Finally, a conclusion is given to summarize our work.

2. CONSTRUCTION METHOD OF ZCC CODE

In this technique, A ZCC code sequence S_i can be constructed as follows: Let α be a root of a mth degree primitive polynomial $f(x) \in GF(p)[x]$. All nonzero elements of $GF[p^m]$ are successive powers of α and the multiplicative order of α is $ord[\alpha] = p^m - 1$, such that: $\alpha \in GF[p^m] = \{1, \alpha, \alpha^2, \dots, \alpha^{p^m-2}\}$, where $q = p^m$ with p a prime and m an integer. The Zech logarithm is used in the finite field $GF[q]$ with nonzero element β defined by $\beta = \gamma^i$ and $0 \le i \le q - 2$ as shown in Equations (1) and (2) [25]:

$$\text{for } i \le j, \quad \begin{cases} \gamma^i + \gamma^j = \gamma^i \gamma^{j-i} = \gamma^k \\ \text{where } k \equiv i + z_{j-i} \ (mod \ q - 1), \end{cases} \tag{1}$$

For each element z_j know as Zech's logarithm, we calculate:

$$\gamma^{z_j} = 1 + \gamma^j. \tag{2}$$

We suppose that γ^i and γ^j and also their sum is both non zero. Then, we compute the Zech logarithm to the base $\gamma = \alpha$. For the singular point when the result value is undetermined, we suppose that z_j is null ($z_j = 0$). The polynomial representation for a finite field $GF[p^m]$ can be defined with coefficients in the finite field $GF(p)$. Clearly $GF[p^m]$ can thus be interpreted as a vector space over $GF(p)$. The set $\{1, \alpha, \dots, \alpha^{m-1}\}$ can be used as a basis for the vector space. Based on these assumptions, we can determine the number of user's as:

$$K \le \left\lfloor \frac{q-1}{w} \right\rfloor, \tag{3}$$

where $(q - 1)$ denotes the ZCC code length and w its weight. When the elements z_j are determined, the set of $(q - 1)$ elements are partitioned onto K sub-sets. Each constructed sub-set has w elements corresponding to a specific user. The ZCC sequence is constructed as:

$$S_i = \begin{cases} \left(z_0, z_1, \dots, z_{(i*w+k)}, \dots, z_{(i+1)*w-1}\right) \\ 0 \le i \le K - 1 \ and \ 0 \le k \le w - 1. \end{cases} \tag{4}$$

Finally, the ith binary code of the ZCC code with length $(q - 1)$ is deduced by replacing each number element from the ZCC sequence with ''1''. The resulting $(K \times (q - 1))$ matrix of the ZCC code is given as follows:

$$C_{ZCC} = \begin{bmatrix} c_{0,0} & \cdots & c_{0,(q-1)} \\ \vdots & \ddots & \vdots \\ c_{(K-1),0} & \cdots & c_{(K-1),q-1} \end{bmatrix}_{(K \times (q-1))}.$$

(5)

An example of ZCC code matrix with $q = 8$, $w = 2$ and $K = \left\lfloor \frac{8-1}{2} \right\rfloor = 3$ is derived below:

Let $\alpha \in GF(2^3) \equiv GF(2)$ be a root of a primitive polynomial: $f(x) = x^3 + x + 1$. Since α is a root of $f(x)$, then $\alpha^3 + \alpha + 1 = 0$ which is equivalent to $\alpha^3 = \alpha + 1$ in the $GF(2)$ finite field. So, we can obtain all the polynomial representations of γ^i with $(\gamma = \alpha)$ as follows: $1, \alpha, \alpha^2, \alpha + 1, \alpha + \alpha^2, \alpha^2 + \alpha + 1$ and $\alpha^2 + 1$. Table 1 shows all the elements of the Galois field $GF(2^3)$ generated by the polynomial $f(x) = x^3 + x + 1$. Examples of the product and sum of two elements in this field are calculated as follows:

$\alpha^3 = \alpha + 1$,
$\alpha^4 = \alpha^3 . \alpha = \alpha (\alpha + 1) = \alpha^2 + \alpha$,
$\alpha^5 = \alpha^4 . \alpha = \alpha (\alpha^2 + \alpha) = \alpha^3 + \alpha^2 = \alpha^2 + \alpha + 1$, $\alpha^6 = \alpha^5 . \alpha = \alpha (\alpha^2 + \alpha + 1) = \alpha^3 + \alpha^2 + \alpha = \alpha + 1 + \alpha^2 + \alpha = \alpha^2 + 1$.

Table 1. *The Galois field $GF(2^3)$ generated by $f(x) = x^3 + x + 1$*

i	0	1	2	3	4	5	6
γ^i	1	α	α^2	$\alpha + 1$	$\alpha^2 + \alpha$	$\alpha^2 + \alpha + 1$	$\alpha^2 + 1$

Then, the Zech logarithm's to the base $\gamma = \alpha$ are the z_j elements: 0, 3, 6, 1, 5, 4 and 2. The z_j elements are partitioned referring to the number of users and weight leading to the ZCC sequences shown in Table 2. The undetermined value for j=0 is set equal to zero ($z_j = 0$).

Table 2. *Zech logarithm to the base $\gamma = \alpha$*

j	0	1	2	3	4	5	6
z_j	0	3	6	1	5	4	2

Finally, the pairs (0, 3), (6, 1), (5, 4) corresponding to the weight code of each user obtained from Equation (3) are replaced by the ''1' in their positions as is shown in Table 3. The length of the final sequences code corresponds to the product $L = K.w$, where the column with insignificant information is ignored. As we can see, the number of users and weight are too related to the code length. If the number of users increases, the weight code is decreased.

Table 3. *ZCC code obtained with $q = 8$, $K = 3, 2$, and $w = 2$, respectively*

C_{ZCC}	K	Code length L	w	Code matrix
Code ZCC	3	7	2	$\begin{bmatrix} 1\,0\,1\,0\,0\,0 \\ 0\,1\,0\,0\,0\,1 \\ 0\,0\,0\,1\,1\,0 \end{bmatrix}$

For the first code in Table 1, $K > w$. It is possible to further increase the number of users using the matrix mapper below:

$$ZCC(i = 2) = \begin{bmatrix} Zeros(K \times L) & ZCC(1) \\ ZCC(1) & Zeros(K \times L) \end{bmatrix}$$

(6)

$$ZCC(i = 3) = \begin{bmatrix} Zeros(2K \times 2L) & ZCC(2) \\ ZCC(2) & Zeros(2K \times 2L) \end{bmatrix}$$

(7)

where K denotes the number of users, $L = K.w$ is the basic code length, and Zeros(.) denotes a matrix of zeros. $ZCC(1)$ is the basic matrix of the proposed code with the dimension $(K \times L)$. From this mapping, the code length is increasing with the number of users. The number of rows in the newly generated matrix determines the number of users as follows: $K_{Total} = K.2^{i-1}$ and the length code that represents the number of colons in the newly generated matrix is given by: $L_{Total} = L.2^{i-1}$.

3. CODE COMPARISON

In this section, a comparison is given to contrast the performance of the proposed ZCC code method and some other existing optical codes. All the mathematical relationships between parameter codes are shown in Table 4.

Table 4. *Expressions parameters of the proposed code and some other optical codes*

Codes	No. of users	Code length	λ
MDW [26-28]	n	$3K + 8/3 \, [sin(K.\pi/3)]^2$	$\lambda = 1$
OOK [13-16]	ϕ_{OOK}	$\geq w.(w-1)\phi_{OOK}$	$\lambda = 1$
ZCC [29-34]	$2^i.(w+1)$	$2^i.w.(w+1)$	$\lambda = 0$
Hadamard [35-37]	$(2^i - 1)$	2^i	$\lambda = 1$
Proposed ZCC	$K.2^{i-1}$	$L.2^{i-1}$	$\lambda = 0$

From Table 4, we can conclude that our proposed code gives the same minimum cross-correlation value ($\lambda = 0$) as the ZCC code of references [29-34]. The MDW, OOK, and Walsh-Hadamard code have a unit cross-correlation ($\lambda = 1$). Moreover, using the same number of users as is shown in Table 5, we can conclude that the code length of the proposed ZCC code is the lowest than the OOK code and identical to the reported ZCC codes at the same weight value ($w = 4$). The MDW and the Walsh-Hadamard codes provide a low code length compared to the ZCC code but a unit cross-correlation and a high weight code for the case of Walsh-Hadamard code. Consequently, the proposed method gives a good cross-correlation value with more flexibility in the choice of an increase in the number of users and weight. The code length increase with the same factor of proportionality of the number of users but is still too short compared to other optical methods and identical to the reported ZCC codes. The method of construction of the proposed ZCC code is less complicated and can be generated using pre-stored tables. The code length of the proposed method is calculated using Equation (3) for the basic code length of $L = q - 1 \geq K \times W$. Then, for a total number of users, in our case $K_{Total} = 30$, the code length L_{Total} obtained is equal to $L = 120$).

Table 5. *The proposed code in comparison with some other optical codes for $K_{Tot} = 30$ users*

Codes	No. of users	Code length	Weight
MDW [26-28]	30	90	$w = 4$
OOK [13-16]	30	364	$w = 4$
ZCC [29-34]	30	120	$w = 4$
Hadamard [9-35]	30	32	$w = 16$
Proposed ZCC	30	120	$w = 4$

4. PERFORMANCE ANALYSIS AND SIMULATION RESULTS

The performance of the proposed ZCC code for OCDMA systems using direct detection is simulated in OptiSystem 7.0. In this simulation, a conventional signal mode fiber with attenuation of $0.2 \, dB/km$ is used. The chromatic dispersion parameter is $16.75 \, ps/nm/\, km$ and the polarization mode dispersion (PMD) coefficient is equal to $0.5 \, ps/sqrt(k)$. The wavelengths used are in the range of $1478.8 \, nm$ to $1485.2 \, nm$. Each chip has a spectral width of 0.8 nm. The performance of the system was characterized by referring to the BER and the eye patterns.

Figure 1 shows the eye diagram and BER values of the proposed ZCC code in the OCDMA system. The number of users was chosen to be equal to three and the code weight value $W = 4$ at a data rate of $1\ GHz$ through a fiber distance length of $25\ Km$.
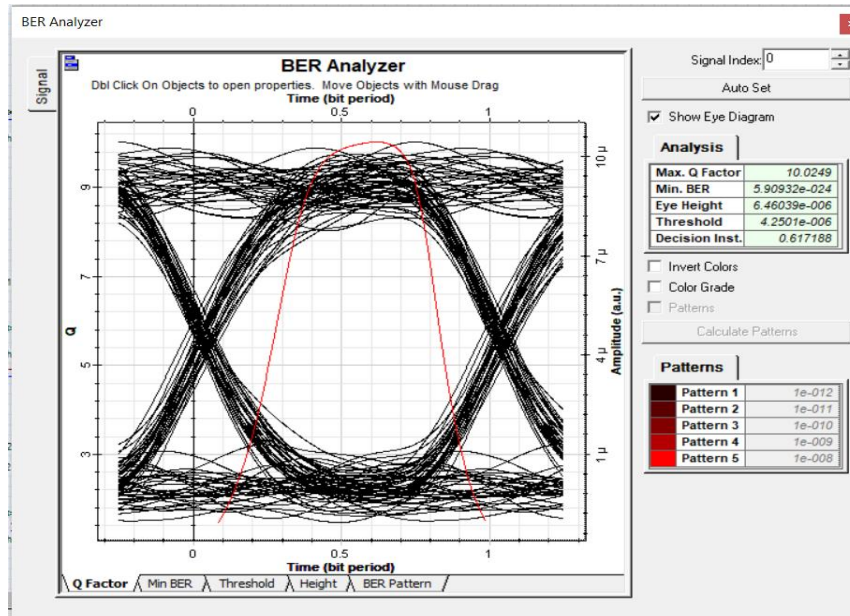
Figure 1. Eye diagram of the proposed Zech's ZCC code at 1GHz user's data rate, three users, and code weight 4

From Figure 1, the eye diagram clearly illustrates that the proposed Zech's ZCC code system gives good BER for optical applications. The more the eye closes, the more difficult it is to distinguish between ones and zeros in the signal. The height of the eye-opening at the specified sampling time shows the noise margin or immunity to noise. The BER value of 5.9×10^{-24} was obtained which is much higher than the basic required (10^{-9}) value for system performance. The corresponding fill factor (Q) is $10\ (> 6)$. Thus, the BER is less than 10^{-9} or ($Q > 6$) can also be obtained with more than three users or data rates less than 1GHz.

The Bit Error Rate (BER) expression can be estimated, from Signal to Noise Ratio (SNR), using Gaussian approximation as [6,9]:

$$BER = \frac{1}{2}\sqrt{\frac{SNR}{8}}. \tag{8}$$

For the direct detection SAC-OCDMA systems, the SNR expression is given by [37]:

$$SNR = \frac{\left(\frac{\mathcal{R}\ P_{sr}\ W}{L}\right)^2}{2\ e\ B\ \mathcal{R}\ P_{sr}(W/L) + (4\frac{K_b\ T_n\ B}{R_L})} \tag{9}$$

where $\mathcal{R}$: Responsivity of the photodiode, B: Electrical equivalent noise bandwidth receiver, K_b: Boltzmann constant, R_L: Resistance load, T_b: Temperature of noise at the receiver, P_{rc}: Effective power at the receiver and e: Charge of Electron.

Performance comparison between MDW, Hadamard, ZCC and our proposed ZCC codes using direct detection is illustrated in Figure 2. The BER is evaluated taking into account thermal and shot noises only. BER against the total number of active users is simulated by Matlab software. Following Table 6 illustrates the parameters used in our analysis.

Table 6. *Table of parameters*

$\mathcal{R}$	The responsivity of the photodiode	1
B	Electrical equivalent noise bandwidth of the receiver	$311\ MHz$
K_b	Constant Boltzmann	$\lambda = 0$
R_L	Resistance load	$1030\ \Omega$
T_b	The temperature of noise at the receiver	$300\ K$
P_{rc}	Effective power at the receiver	$-10\ dBm$
e	Charge of Electron	$1.6\ 10^{-19}C$

As we can conclude from Figure 2, our proposed ZCC construction method code gives a high performance as the reported ZCC codes than the other methods MDW and Hadamard. More than 90 users can be supported with our method with approximately a BER of 9×10^{-10}. The results are a consequence of the code cross-correlation properties that eliminate the effect of multiple access interference (MAI) and phase-induced intensity noise (PIIN) which have an important impact on the degradation of the system performance.

Figure 3 shows the BER and the Fill Factor (Q) for three users against the fiber length at different data rates, 1 GHz, 1.5 GHz, and 2 GHz, respectively. As we can see, the average BER value increases with the increase of the transmission length. Moreover, at system performance BER 10^{-9}, the maximum transmission distance to be reached for the proposed scheme without amplification is approximately about 40 Km at 1 GHz data rate.

For the user's data rate of 1.5 GHz, the maximum fiber distance is about 37 Km with a Fill Factor Q value of 6 and a corresponding BER value of 9.38×10^{-10}. The maximum distance to be attained can be further reduced when the user data bit is increased. This later is about 33 Km for a user data bit of 2 GHz corresponding to a BER value of 3.16×10^{-9}. This reduction in performance is caused by the higher optical attenuation in the longer fiber span.

As a result, the performance of the system is best with high BER values when the distance or user data rate used is well chosen. Using Equation (10) below, we can find the maximum fiber distance given as [38]:

$$P_{imax}(dB) = \alpha \times L + P_r(dB), \tag{10}$$

where, P_{imax} is the maximum input power, α is the attenuation, L is the transmission distance and P_r is the minimum receiver power. For the OCDMA system, a typical dynamic range of the receiver is between -7 dBm and -28 dBm [38].

From Figure 3, the performance of the system is best with high BER values when the distance or user data rate used is well chosen.
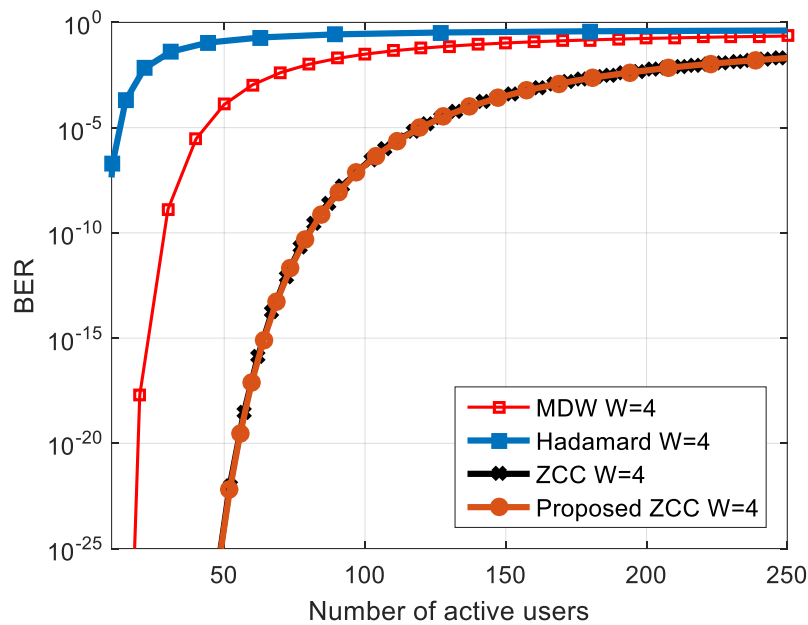
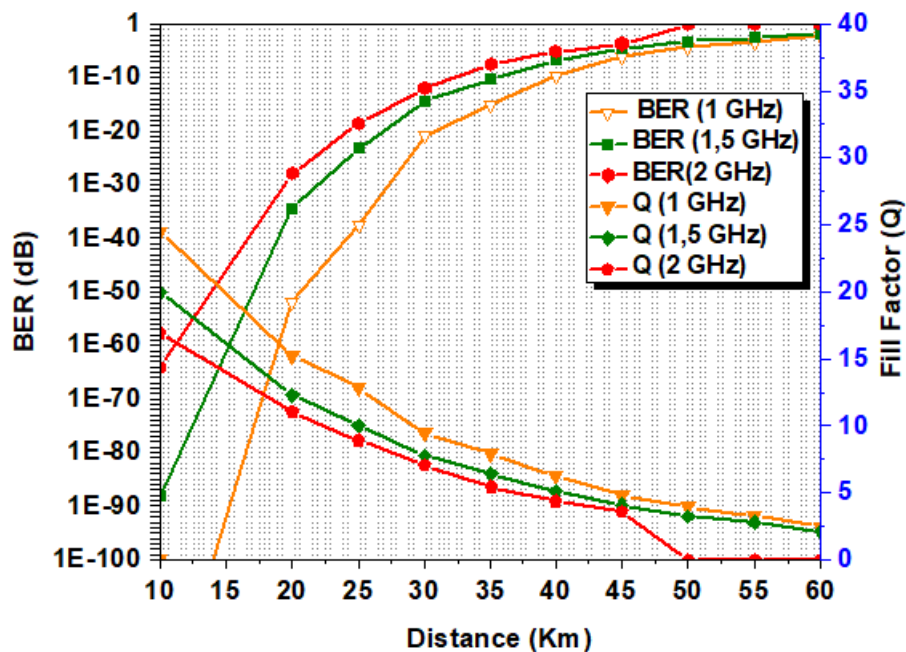*Figure 2. BER vs number of active users with $P_{sr} = -10 \, dBm$*

Figure 3. BER and Fill Factor (Q) versus fiber distance for the proposed Zech's ZCC code at different user's data rates 1GHz, 1.5 GHz, and 2 GHz

5. CONCLUSION

This paper proposes a novel construction method of ZCC code for SAC-OCDMA systems. Minimum cross-correlation is one of the important properties in optical code design. An efficient choice of Zero-Cross Correlation code increases the system performance by suppressing the MAI and PIIN interference effects. The key idea of this method is based on the use of Zech's logarithms in the construction of the ZCC code and compare its performance with previously reported codes. The direct decoding technique is implemented at the receiver, which reduces the number of filters corresponding to one single branch of decoding.

Simulations and theoretical analysis show that our proposed construction code gives a significant improvement in system performances (BER, Q) as compared to other conventional codes with simple construction methods and high transmission quality. The minimum cross-correlation value (zero) not only eliminates efficiently the MAI and PIIN effects but also improves the BER performance of the system. Furthermore, the proposed code can accommodate more active users simultaneously at high data rates and longer distances with much more flexibility in the choice of the number of users, weight, and code length. The design of the code is made simple using a pre-stored table for codes.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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