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Enhanced Performance of Bit Error Rate by Utilizing Sequential Algorithm *(SeQ)* Code in Optical CDMA Network Systems

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Abstract

This paper presents a new class of Sequential Algorithm (*SeQ*) code for Optical Division Multiple Access (OCDMA) system with flexible cross-correlation. This *SeQ* code has advantages due to flexible cross correlation property of any number of users, weights, and effectively suppressed the impact of phase-induced intensity noise (PIIN) and multiple-access interference (MAI) cancellation properties. In contrary to the existing codes, *SeQ* code provides much better performance of Bit Error Rate (BER) for many users. At the typical error rate of optical communication system BER= 10^{-9}, this paper demonstrate that *SeQ* code can accommodate 190 numbers of simultaneous users compared with DCS (W=4) and MFH (W=4) and capability enhanced performance BER about 111% and 850% in comparison with DCS (W=4), and MFH (W=4) codes. In addition, *SeQ* code has revealed this code can enhance the OCDMA system due *SeQ* code can yield good BER performance for weight equal to 10 and the long of code length are 1300 compared with W=2, W=4, W=6, and W=8. Thus, the results obtained in this paper as an evidence that *SeQ* code was truly performed better than existing codes and applicable to enhance OCDMA system network for future generation usage.

Keywords: Optical Division Multiple Access (OCDMA); Sequential Algorithm (SeQ) Code; Bit Error Rate (BER); Code Length;

INTRODUCTION

Optical code-division multiple access (OCDMA) is field that combines the large bandwidth of the fiber medium with the flexibility of the CDMA technique to achieve high-speed connectivity. CDMA was originally investigated in the context of radio frequency communications systems and the first applied to the optical domain in the mid-1980s [1]. Each users of OCDMA system has a unique signature sequence. The encoder of each transmitter represents each 1 bit by sending the signature sequence, instead, 0 bit is not encoded cause represented using an all-zero sequence. The bandwidth of the data stream is increased, since each bit represented by a pattern of lit and unlit chips [2]. Besides that, in OCDMA, an optical code represents as user address and it signs each transmitted data bit [3]. Recently, OCDMA was implemented in the local area for applications in access network such as Fiber-To-The-Home (FTTH). In OCDMA coding systems, the system performance can be degraded by improperly code designed and the highest number of simultaneous users and presence of MAI [4]. The conventional optical local access networks typically use wavelength-division multiplexing (WDM) and time-division multiplexing (TDM) techniques which required wavelength and time domain processing [5]. The success commercial wireless CDMA (Code Division Multiple Access) networks, optical CDMA (OCDMA) networks envisaged to provide flexible bandwidth access to many subscribers by optical encoded transmissions [6]. MAI is interference that occurred during transmission, which will limit the effective error probability by presence of noise in the overall system. PIIN are related to MAI due to overlapping spectra from different users [7]. Hence, the OCDMA coding system should have an efficient address code sequence with flexible cross-correlation. Inappropriate cross-correlation among the address sequences will cause PIIN between codes sequences increased. Inappropriate cross correlation among of interfering users and cannot be improved by increasing the transmitted power. One of the effective solutions for alleviating the PIIN is decreasing the number of interferences between the signals of different users [8].

There have several codes have been proposed in OCDMA systems such as Dynamic Cyclic Shift (DCS), Modified Quadratic Congruence (MQC), Modified Double Weight (MDW), Modified Frequency Hopping (MFH), Hadamard code and etc. However, this codes have several limitations such as the code too long, the construction is complicated, poor cross correlation, fixed an even natural number for code and the longer code length had limited the flexibility of the codes since it will require wide bandwidth source.

In this paper, a new proposed code called Sequential Algorithm (*SeQ*) code has been developed. This proposed code has been assumed that the in phase cross correlation value can be flexible which ensures that each codeword can be easily distinguished from every other address sequence. This *SeQ* code has been constructed with simple Tridiagonal Matrix Code property and any given number of users and weights. The performance of *SeQ* code significantly enhanced with the existing code such as Dynamic Cyclic Shift (DCS) and Modified Double Weight (MFH) in term of the cardinality and the capability to accommodate the high number of weights.

DESIGN *SEQ* CODE

A. SeQ Code Construction

A set of codes K for the user is binary [0, 1] sequences of length N, code- weight W (the number of *"1"* in each code word) and the maximum cross-correlation, λ_c. The optimum code set is one having any desired cross-correlation properties to support the maximum number of users with shortest code length. The least for the short haul optical networking to ensured guaranteed quality of services with low error probabilities for giving number of users K [9].

Step 1: A set of K, length of code N and code-weight W for K users. This set of codes is then represented by a KxN matrix A_K^w where the elements a_{ij} of A_K^w is binary [0,1] known as **Tridiagonal Code Matrix** can be written as:

$$A_K^W = \{a_{ij} = '0' \, or \, '1', i = 1,2,..K, j = 1,2,...N\} \quad (1)$$

K codes, represented by the K rows of the code matrix are unique and independent of each other, A_K^w should have rank K. Moreover, for A_K^w to have rank K,

$$N > K \quad (2)$$

Step 2: The KxN optical code matrix A_K^w as defined by (2). The code-weight of each of the K codes is assumed to be W. The tridiagonal code matrix A_K^w is given by (3) and the rows A_1, A_2, A_K represent the K code words [10].

$$A_K^w = \begin{bmatrix} a_{11} & b_{12} & c_{13} & 0 & \dots & 0 & 0 \\ 0 & d_{14} & a_{21} & b_{22} & \dots & 0 & 0 \\ 0 & 0 & c_{23} & d_{24} & \dots & 0 & 0 \\ \vdots & \ddots & \ddots & \ddots & \dots & 0 & 0 \\ 0 & 0 & 0 & 0 & \dots & c_{i-1} & a_{KN} \end{bmatrix} = \begin{bmatrix} A_1 \\ A_2 \\ \vdots \\ A_K \end{bmatrix} \quad (3)$$

where,

$$A_1 = a_{11}, b_{12}, \dots d_{1N}$$
$$A_2 = d_{14}, a_{21}, \dots b_{2N}$$
$$A_3 = c_{23}, d_{24}, \dots a_{3N}$$
$$A_K = 0,0, \dots c_{1-i}, a_{KN}$$

Step 3: The K codes, represented in (3) are to represent a valid set of K code word with in phase cross-correlations λ_c and code-weight W, it must satisfy the following conditions:

1. The elements $\{a_{ij}\}$ of A_K^w must have values *"0"* or *"1"*
a_{ij} = *"0" or "1" for i=1,2,..K, j=1, 2, N* (4)

2. The code-weight W of each code word should be equal to W where,

$$\sum_{j=1}^{N} a_{ij} = W, \ i = 1,2...K \quad (5)$$

3. There should not exceed between any of the K, code words (K rows of the matrix A_K^w) and code-weight W in phase cross-correlation, λ_c. That is [11],

$$A_i A_i^T = \begin{cases} \leq \lambda_c \, for \, i \neq j \\ = W \, for \, i = j \end{cases} \quad (6)$$

4. Eq. (6), it is seen that the $W = A_i A_i^T$ is the in- phase auto-correlation function of codes. $A_i A_j^T$ is the out of phase correlation between the i^{th} and the j^{th} codes. It follows that $A_i A_i^T$ should be greater than $A_i A_j^T$. In other words,

$$w \geq \lambda_c \quad (7)$$

5. All K rows of A_K^w should be linearly independent because each codeword must be uniquely different from other words. That is to say the rank of the matrix A_K^w should be K. One of the matrices that satisfies the four conditions above, is the KxN Matrix A_K^w whose i^{th} row is given by,

$$A_i = \overbrace{11..1}^{w} \ \overbrace{0 \dots 0}^{r(K-i)} \quad (8)$$

where,

$$r = W - \lambda_c$$
$$i = \text{Sequences number of rows}$$

The length N of the codes which is the length of the rows of the matrix A_K^w is given by,

$$N = WK - \lambda_C(K-1) \quad (9)$$

Step 4: On the basis of the above discussions, the construction of an optical code having a value of K, code-weight W, λ_c consists of the following steps:

1).For a given number of users K, and code-weight W, forms a set of flexible in phase cross-correlation code with a minimum length as given by (8).

2) The length N of code matrix has defined by the (9).

3).The K rows of the code matrix that give the K optical CDMA codes having flexible in phase cross correlation, code-weight W and shortest code length.

B. Noises Performance Analysis

The Signal Noise Ratio (SNR) is defined as the average signal to noise power, $SNR = \left[I^2 / \sigma^2 \right]$, where σ^2 is the average power of noise which is given by,

$$\sigma^2 = \langle i_{shot}^2 \rangle + \langle i_{PIIN}^2 \rangle + \langle i_{thermal}^2 \rangle \quad (10)$$

Eq. (10) can be expressed as,

$$\sigma^2 = 2eBI + I^2 B \tau_C + \frac{4K_b T_n B}{R_L} \quad (11)$$

where e is the electron charge, I is the average photocurrent, I^2 is the power spectral density for I, B is the noise equivalent of electrical bandwidth, K_b is the Boltzmann constant, T_n is the absolute receiver noise temperature and R_L is the receiver load resistor. Eq (11) it has been assumed that the optical bandwidth is much larger than the maximum electrical bandwidth. The coherence source time τ_c is given as,

$$\tau_c = \frac{\int_0^\infty G^2(v)dv}{\int_0^\infty G(v)dv} \quad (12)$$

where, $G(v)$ denotes as the single sideband source power of spectral density (PSD). Noticed, the effect of receiver's dark current has been neglected in this proposed system analysis. The broadband pulse coming thru to the FBG as an incoherent light field is mixed and incident upon a photo detector output.

The proposed system was analyzed with transmitter and receiver. That are important for mathematical preliminaries simplicity. Since, to analyze the proposed system. The following assumptions below:

- Each unpolarized source PSD and its spectrum are flat over the system bandwidth of *$[V_o \pm (v/2)]$* with amplitude $P_{sr}/\Delta v$, v_o is the central optical frequency and Δv is the optical source bandwidth expressed in Hertz.
- Each user has equal power at receiver
- Each nit stream for each user is synchronized.
- Each power spectral component has an identical spectral width.

Based on the above assumptions, the proposed system can easily analyze using the Gaussian approximation. The PSD of the received optical signals can written as;

$$G(v) = \frac{P_{sr}}{\Delta v} \sum_{K=1}^{K} d_K \sum_{j=1}^{j} \sum_{i=1}^{K} X_{ij} Y_{ij} [\Pi(i)], \tag{13}$$

Where, P_{sr} is the received power from a single source, Δv can be assumed as perfect rectangular unit step function. Fig. 1 showed the bandwidth.

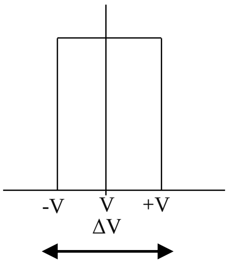

Figure 1. Bandwidth of ΔV

Where, the {0,1} is an element of unit step function given as follows;

$$\left.\begin{matrix} 1, for \quad v \geq 0 \\ 0, for \quad v < 0 \end{matrix}\right\} \in \prod(i) \tag{14}$$

Eq. (13) is the total incident power PSD at the input of PIN *1* and PIN *2* and can be written as;

$$\int_0^\infty G_1(v)dv = \frac{P_{sr}}{\Delta V} \sum_{i=j,i\neq j} dK \sum_{j=1}^{j} \sum_{i=1}^{K} X_{ij}\, Y_{ij} \left\{u\left[\frac{\Delta v}{N}\right]\right\} dv \tag{15}$$

$$= \frac{P_{sr}W}{N} + \frac{P_{sr}}{N} \sum_{i=j,i\neq j} dK$$

$$\int_0^\infty G_2(v)dv = \frac{P_{sr}}{\Delta v} \sum_{i=j,i\neq j} dK \sum_{j=1}^{j} \sum_{i=1}^{K} X_{ij} \bullet Y_{ij}(Y_{ij}) \left\{u\left[\frac{\Delta v}{N}\right]\right\} dv \tag{16}$$

$$= \frac{P_{sr}}{N} + \frac{P_{sr}}{N} \sum_{i=j,i\neq j} dK$$

PSD spectrum will be calculated and the photodiode current *I* and can be written as follows;

$$I = \mathcal{R} \int_0^\infty G(v)\, dv \tag{17}$$

$\mathcal{R}$ represents as the responsively of the photo-detectors. Consequently, from (13) the photo current *I* can be expressed as;

$$I = \Re\left[\frac{P_{sr}[W]}{N}\right] \tag{18}$$

The power of *Shot* noise can be written by subtracting (15) and (16), respectively as;

$$\langle i_{Shot}^2 \rangle = 2eB\mathcal{R}\left[\frac{P_{sr}}{N}\right][W+3] \tag{19}$$

The PIIN noise will dominate the broadband sources. Hence, with PSD from each user is the same; from that we calculate the receiver PIIN noise directly from the total PSD of each photodiode. By using (19) the PIIN noise at the receiver output is given by;

$$\langle i_{PIIN}^2 \rangle = B(I_1^2 \tau_{c1} + I_1^2 \tau_{c2}) = I^2 * \tau_C * B \tag{20}$$

Where, I_1 and I_2 are the average photodiode currents, τ_{c1} and τ_{c2} are the coherence times of light incident on each photodiode. By using (13), (15), (16) and (20), the variance of the *PIIN* noise at the receiver can be expressed as;

$$\langle i_{PIIN}^2 \rangle = \frac{B\mathcal{R}^2 P_{sr}^2 KW}{N^2 \Delta_V}[3W+1] \tag{21}$$

Since, from (3) until (7), shown the properties of *SeQ* code are unique and independent of each other, (21) is also independent of the active users' data, consequently, proposed coding system does not depend on the timing of transitions in the data and it applied to the asynchronous system. *Thermal* noise is given as;

$$\langle i_{Thermal}^2 \rangle = \frac{4K_b T_n B}{R_L} \tag{22}$$

Eqs (18), (19), and (21), the SNR for the proposed *SeQ* code in the OCDMA coding system is defined by;

$$SNR = \frac{\left[\frac{\Re P_{sr} W}{N}\right]^2}{\left[\frac{2eB\Re P_{sr}}{N}\right][3W+1] + B\Re\left[\frac{P_{sr}^2 KW}{N^2 \Delta V}\right][3W+1] + \frac{4K_b T_n B}{R_L}} \tag{23}$$

Since, there is no pulses are sent for the data bit *'0'* an assuming that the noise distribution is Gaussian, thus, the corresponding BER can be obtained as follows;

$$BER = \frac{1}{2} efrc\left(\sqrt{\frac{SNR}{8}}\right) \tag{24}$$

Finally, (23) and (24) will be used for the numerical calculation for an evaluation of the proposed *SeQ* code OCDMA coding system. The performance of the *SeQ* code has been compared numerically with the existing OCDMA codes such as DCS and MFH code. The numerical parameters used are shown in Table 1.

TABLE 1. Typical parameters for theoretical mathematical calculations.

Parameter	Value
Electron's charge	e = 1.60217646 × 10^{-19} coulombs
PD quantum	η = 0.75
Electrical bandwidth	B = 80 MHz
Boltzmann constant	K_b = 1.38 ×10^{-23} W/K/Hz
Receiver noise	T_n = 300K
Receiver load resistor	R_L = 1030 Ω
Data transmission rate	R_b = 155 Mbps
Broadband line width	Δλ = 3.75 THz

PERFORMANCE ANALYSIS RESULT AND DISCUSSION

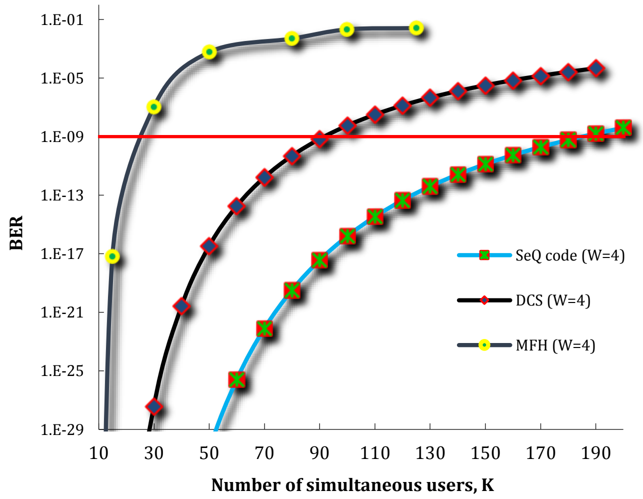

Figure 2. Performance BER versus Numbers of Simultaneous Users of *SeQ* code (W=4), DCS (W=4) and MFH (W=4).

Fig. 2 shows performances of BER of *SeQ* code (W=4), DCS (W=4) and MFH (W=4). The performance of BER analyzed from (24) at 155 Mbps bit rate and effective power -10 dBm. From the plots, BER becomes increasingly degraded as the number of simultaneous users increased. At the error floor threshold BER = 10^{-9}, *SeQ* code (W=4) shows the good performance in comparison with DCS (W=4), MFH (W=4). Fig 2 shows, the *SeQ* code (W=4) can accommodate 190 numbers of simultaneous of users in comparison with DCS (W=4) and MFH (W=4) are 90 and 20 numbers of simultaneous users only. At BER=10^{-9} error floor, the *SeQ* code has cardinality improvement about 111% and 850% of DCS (W=4) and MFH (W=4) codes. Hence, *SeQ* code presents excellent performance due to the arrangement of the code algorithm and in-phase cross-correlation cause the *SeQ* code curve is the nearest to the error floor which is BER=10^{-9}. Thus, this result revealed that *SeQ* code can enhance the performance of the OCDMA system better than others existing codes.

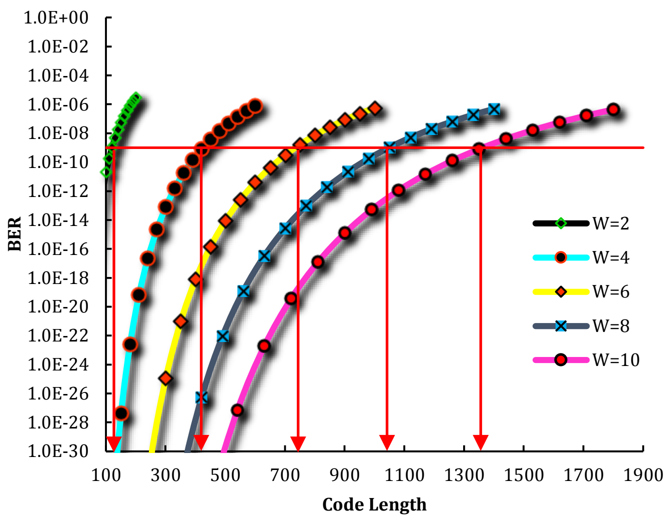

Figure 3. Relation between Performance of BER versus Code Length *SeQ* code for W=2, W=4, W=6, W=8 and W=10.

Fig. 3 illustrates the relation between performances BER to the code length for W=2, W=4, W=6, W=8 and W=10 of *SeQ* code. These BER performance has been analyzed at 155 Mbps and effective power at -10 dBm, respectively. From the plot, clearly showed the BER increasingly degrade as the weight and length of the code increase. Each curves represent for different of weight, where the curve of W=10 is the excellent performance in comparison with W=2, W=4, W=6 and W=8. It can be seen that, at the error floor threshold BER= 10^{-9}, the long of code length of W=2, W=4, W=6, W=8 and W=10 are 110, 450, 730, 1080 and 1350, respectively. When fixed the code length equal to 200 the *BER* performance for W=2, W=4, W=6, W=8 and W=10 are 10^{-6}, 10^{-20}, 10^{-39}, 10^{-57} and 10^{-91}.This performance shows, *SeQ* code can implement highest weight (W=10) and long of code length for OCDMA system. Fig. 3 revealed that the longer code length without increasing the code weight will need more space for bandwidth. Nevertheless, the *SeQ* code with the higher code weight, obviously can enhance the system performance of BER due to weight is proportional with the effective optical power received.

CONCLUSION

The algorithm of the *SeQ* code develop to enhance the impact of correlation that has been presented in OCDMA system. The *SeQ* code had shown excellent performance indicated that *SeQ* OCDMA coding system can accommodate a highest numbers of simultaneous users which is 190 number of users at the error floor BER= 10^{-9}. This *SeQ* code can accommodate the highest users at low performances of BER compared with the DCS and MFH code. While the BER performance against code length, BER increasingly degrade as the code length increase. At BER= 10^{-9}, *SeQ* code can support high of weight (W=10) and long of code length is 1350 due to weight is proportional with the effective optical power received. From the results, this *SeQ* code will give an opportunity in OCDMA system for better quality of service in optical access for future generation's usage.

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