Suppression of Noise Based on Recursive Combinatorial Code in Optical CDMA Direct Detection Architecture

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Abstract—**This paper assesses the performance of a newly developed code in the spectral amplitude coding known as the Recursive Combinatorial (RC) code to suppress noise in the Optical Code Division Multiple Access (OCDMA) network. The code construction is shown and performance analysis is compared with other codes. Due to the low number of overlapping bits of the code's property, the Multiple Access Interference (MAI) is successfully suppressed. The feasibility of this code to use direct detection technique at the receiver results in the suppression of Phase Induced Intensity Noise (PIIN). Results indicate that noise reduction using this code is better compared to other codes, with lower effective power needed for an acceptable Bit Error Rates (BER) of 10^{-9}. The shot noise is also shown to be lower using this code compared to other codes.**

Index Terms—**recursive combinatorial, optical code division multiple access, phase induced intensity noise, direct detection, multiple access interference**

I. Introduction

The out coming of optical communication has long been an attractive solution for network providers to support end users with sufficient bandwidth allocation for their communication needs. Optical Code Division Multiple Access (OCDMA) has grown to be an access scheme that reflects numerous interests from its ability to provide asynchronous secured transmission for multiple users, simultaneously [1]-[3].

One important element in OCDMA lies in the code design. It is desirable to develop codes that exhibits low cross correlation [4] to ensure the Multiple Access Interference (MAI) could be reduced.

Some other essential elements of desirable code designs are shorter code length, flexibility of choosing the parameters, and ease of code constructions.

To meet these requirements, many codes were developed, for example Random Diagonal (RD) code [5], Enhanced Double Weight (EDW) [6], Modified Quadratic Congruence [3], Modified Frequency Hopping code (MFH) [7], Modified Double Weight, MDW [8], and etc. Yet, these codes still endures some constraints, such as long code length structures in the Optical Orthogonal Code (OOC) and complicated code constructions such in the MQC and MFH. MQC and MFH codes also only exist for limited prime number p and q only. MDW code has small cross correlation but can only accommodate for even number of weights only, thus not very flexible. Following the same note, EDW also suffers from limitation only for odd number of weights only. RD, on the other hand, successfully introduced codes with shorter code length, but the tradeoff is the larger cross correlation in its code segments, which is a huge disadvantage. In order to reduce the limitations bounded by other existing codes, Recursive Combinatorial (RC) [9] code is introduced. This code construction is relatively easy, the cross correlation is ≤1 and it is flexible for any weights and number of users. Hence, in this work, the construction of this code and its performance on reducing the noise in OCDMA network is evaluated.

The arrangement of this paper is as follow; after introduction in Section 1, the RC code structure is briefly described in Section 2. The performance analysis of the RC code is presented in Section 3, while results and discussion are concisely discussed in Section 4. Section 5 represents the conclusion drawn to the work.

II. RC Code Structure

In SAC OCDMA, a code can be represented as (N, W, λ_c), where N denotes the length of the code, the code weight is represented as W and the overlapping bits is represented by λ_c. The property of RC code is (N, W, 1) and the construction of the code is based on the following processes:

Step 1: The RC code can be characterized based on a $K\times N$ matrix. The number of users is defined by the K rows, while the number of code length is represented by N columns. A basic RC code is given by a 2×3 matrix, as shown below:

$$RC_{basic}=\begin{bmatrix}1 & 1 & 0\\ 0 & 1 & 1\end{bmatrix} \tag{1}$$

Manuscript received September 11, 2015; revised November 30, 2015.

doi: 10.18178/ijsps.4.5.394-398

The chip combination of RC code is based on a sequence of 1-2-1 in the three basic columns. This is to ensure that the cross correlation will uniformly equals to one, in other words the overlapping between bits in any two rows is one.

Step 2: To add the number of code weight, from the initial weight 2 (W=2), a *(W-2)* identity matrix with size $\boldsymbol{n}\times\boldsymbol{n}$ (where n = K); i.e. $\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$ is added at the end of the basic code matrix columns, as illustrated below:

$[RC_{\text{new weight}}]$ = consist of 2 parts, i.e. $\langle Y_1|Y_2\rangle$, where $[Y_1]$ = basic matrix of RC code $=\begin{bmatrix}1 & 1 & 0\\0 & 1 & 1\end{bmatrix}$ and $[Y_2]$ = (W-2) times of identity matrix $\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$.

For example, to increase from weight 2 to weight 3, it is necessary to add *(3-2)* identity matrix at the end of the basic RC matrix as shown:

$$RC_{w=3}=\left[\begin{array}{ccc:cc}1 & 1 & 0 & 1 & 0\\0 & 1 & 1 & 0 & 1\end{array}\right]$$

here, the $K\times N$ matrix becomes 2×5. One weight increase in the code will mean that the column matrix will be increased by two columns. For K = 2 and W = 4, the K×N matrix will become 2×7. In general, when K, which is the number of user equals to two, the lowest code length, N, necessitated for a specific weight is:

$$N = 2W-1 \tag{2}$$

To increase the number of users, K for the same weight, a mapping technique is applied where the basic code $Y_{[M=0]}$ is mapped diagonally to achieve $Y_{[M=1]}$ as shown below:

$$Y_{[M=1]}=\left|\begin{array}{ccc:ccc}1 & 1 & 0 & 0 & 0 & 0\\0 & 1 & 1 & 0 & 0 & 0\\ \hdashline 0 & 0 & 0 & 1 & 1 & 0\\0 & 0 & 0 & 0 & 1 & 1\end{array}\right|$$

where M is the mapping sector denoted as:

$$M=\begin{cases}0 & ;\text{when } 1<K<2\\ Q & ;\text{ when } K \text{ is odd}\\ Q-1 & ;\text{ when } K \text{ is even}\end{cases} \tag{3}$$

Q represents the quotient of K/2. Every mapping will add up another two rows; while the number of columns will also be increased by $N_{initial}=N_{[M=0]}$. For example, $Y_{[M=0]}$ = 2×3 and, $Y_{[M=1]}$ = 4×6 and $Y_{[M=2]}$ = 6×9 matrices. The number of rows, K, the number of columns, N, and the mapping process is related by the following relation:

$$K=2\times 2^M \tag{4}$$

$$N = N_{[M=0]}+M\times N_{[M=0]} \tag{5}$$

It is necessary to emphasize that the code lengths, N will increase following the increase of number of users, K. The two parameters are connected by the following relation:

$$N=\begin{cases}\frac{3}{2}K\,; & \text{when } K \text{ is even}\\ \frac{3K}{2}+\frac{1}{2}\,; & \text{when } K \text{ is odd}\end{cases} \tag{6}$$

A generalized equation that can be used for the even and odd numbers of K in (6) can be expressed as:

$$N\;=\;\frac{3K}{2}+\frac{1}{2}\left[sin(\frac{K\pi}{2})\right]^2 \tag{7}$$

Equation (7) above is only valid when code weight is equal to two (W=2). It is essential to notice that every mapping sector(M) only consists of two users (K), where the cross correlation, λ_c=1 only exist for the code sequences in the same mapping sector, while for code sequences that belongs to different mapping sector, the cross correlation is always zero. This is one key features of the RC code advantage compared to other SAC OCDMA codes family, where the cross correlation is a major limitation. Using the mapping technique, code increases, the code length will also increase. In general, weights are being remained unchanged while as users given any number of users, K and code weight, W, with cross correlation, λ_c=1, the parameters can be connected as below:

$$N=\frac{3K}{2}+\frac{1}{2}\left[sin\left(\frac{k\pi}{2}\right)\right]^2+(W-2)\left[K+(sin\left(\frac{K\pi}{2}\right))^2\right] \tag{8}$$

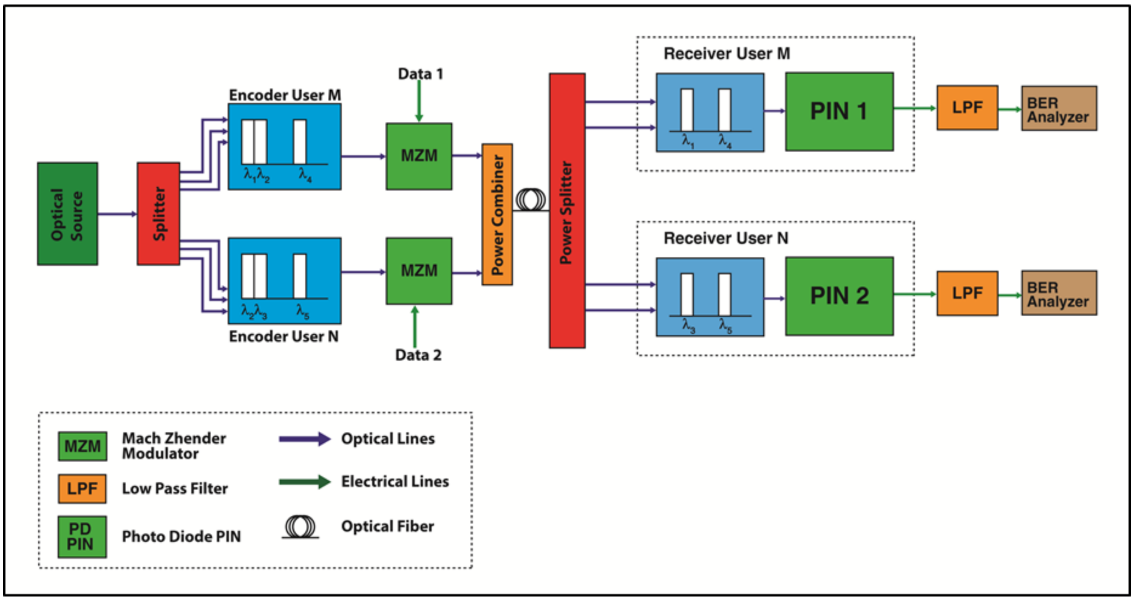

Figure 1. Simulation setup illustration of direct detection OCDMA network based on RC code

III. Performance Analysis of RC Code

In this section, the performance of OCDMA network architecture based on RC code is derived theoretically taking into account the relevant noises presented at the photo detector in the receiver. In this work, this code is proposed to be used in a direct detection scheme system, thus the mathematical analysis will only consider the shot noise and thermal noise. The effect of PIIN is negligible in the setup since the overlapping chips are not considered to be detected at the photo detectors, thus eliminating the effect of PIIN. In addition, the dark current of the receiver is neglected since its value is very low in comparison to the thermal and shot noise [3], [9]. To analyze the OCDMA system performance based on this code, some few assumptions are being made [3], [10]:

(1) Each light source spectra is ideally unpolarized and its spectrum is flat over the bandwidth $\left[v-\Delta v/2, v_0+\Delta v/2\right]$ where v_0 is the optical center frequency and Δv is the optical source bandwidth in Hertz

(2) Each power spectral component has identical spectral width.

(3) Every user occupies the same power at the receiver.

(4) The bit stream of each user is synchronized.

It is then essential to define the code properties of this code by considering the cross correlation and the auto correlation function of the code based on direct detection technique. Let $C_m(i)$ denotes the ***i***th element of the *M*th RC code sequence. Fig. 1 demonstrates the system setup for a direct detection OCDMA network based on RC code. The code properties based on the direct detection technique can therefore be written as:

$$\sum_{i=1}^{L} C_m(i)C_n(i) = \begin{cases} W, m=n \\ 1, m \neq n \end{cases} \tag{9}$$

where C_m and C_n are the RC code sequences, W is the code weight and L denotes the code length. Only the non-overlapping bits are decoded and detected by the photo detector at the receiver. Thus, the total incident power during one period at the input of photo can be given as:

$$\int_0^\infty G_{dd}(v)dv = \int_0^\infty \frac{P_{sr}}{\Delta v}\sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_m(i)C_n(i)u\left[\frac{\Delta v}{L}\right]dv \tag{10}$$

$$= \frac{P_{sr}}{\Delta v}\left[\frac{\Delta v}{L}\right]\sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_m(i)C_n(i) \tag{11}$$

$$= \frac{P_{sr}}{L}(W-1) \tag{12}$$

where P_{sr} represents the broadband source's effective power at the receiver with bandwidth of Δv.

The photodiode current, I expressed as:

$$I = I_{dd} = \Re\int_0^\infty G_{dd}(v)dv \tag{13}$$

which denotes the desired user's signal.

Substituting (10) in (13), the equation becomes:

$$I_{dd} = \Re\frac{P_{sr}}{L}(W-1) \tag{14}$$

In (14), the term of (W-1) demonstrate that at the received signal power, the PSD of the overlapped chips (cross correlation) are subtracted, which means that only the PSD of the non-overlapping chips are filtered and detected at the photodiode.

For the noise variances, σ^2, the PIIN is disregarded since the overlapping bits are not taken into account at receivers employing the direct detection technique. Hence, the noise variance is only deemed to thermal and shot noise. The noise variance equation can thus be written as:

$$\sigma^2 = \left\langle I_{shot}^2 \right\rangle + \left\langle I_{thermal}^2 \right\rangle \tag{15}$$

I_{shot} is given by [11]:

$$\left\langle I_{shot}^2 \right\rangle = 2eBI_{dd} \tag{16}$$

Substituting I_{dd} in (16), assuming all users transmitting bit "1", we get:

$$\left\langle I_{shot}^2 \right\rangle = 2eB\frac{\Re P_{sr}(W-1)}{L} \tag{17}$$

The thermal noise is given as [12]:

$$\left\langle I_{thermal}^2 \right\rangle = \frac{4K_BT_NB}{R_L} \tag{18}$$

where K_B, T_N, B, and R_L is the Boltzmann constant, absolute receiver noise temperature, noise–equivalent electrical bandwidth of the receiver and receiver load resistor respectively.

The total noise here can then be expressed as:

$$\left\langle \sigma^2 \right\rangle = \left\langle I_{shot}^2 \right\rangle + \left\langle I_{thermal}^2 \right\rangle$$

$$\left\langle \sigma^2 \right\rangle = eB\frac{\Re P_{sr}(W-1)}{L} + \frac{4K_BT_NB}{R_L}$$

The SNR of the OCDMA using RC code can be written as:

$$SNR = \frac{\left(I_{dd}\right)^2}{\left\langle \sigma \right\rangle^2}$$

$$SNR = \frac{\dfrac{\Re^2 P_{SR}^2 (W-1)^2}{L^2}}{\dfrac{2eB\Re P_{SR}(W-1)}{L} + \dfrac{4K_BT_nB}{R_L}} \tag{19}$$

Finally, the bit error rates, BER can be denoted as [3]:

$$BER = \frac{1}{2}erfc\left(\sqrt{\frac{SNR}{8}}\right) \tag{20}$$

IV. Results and Discussion

Fig. 2 shows the performance comparison of the RC code weight three (3) and ten (10) with the MQC code weight eight (8) and MFH code weight ten (10). It is obvious that the power required at the photo detector for the RC code is much lower compared to the other two codes, although the RC code weight is smaller. For acceptable BER of 10^{-9}, the effective power for the RC code weight 3 is -23.5dBm, while for MFH it is -21dBm and -22dBm for MQC. When RC code weight is increased to ten (10), the effective power required also decreased to -24dBm. Hence, a lower effective power is required at the photo detector using the RC code for the same system performance. Although the code weight is lesser than the MQC and MFH code, the RC code still outperformed those codes in term of effective power. The reason is that MAI is eliminated using this code, hence effective power for signals to be transmitted would be lesser.

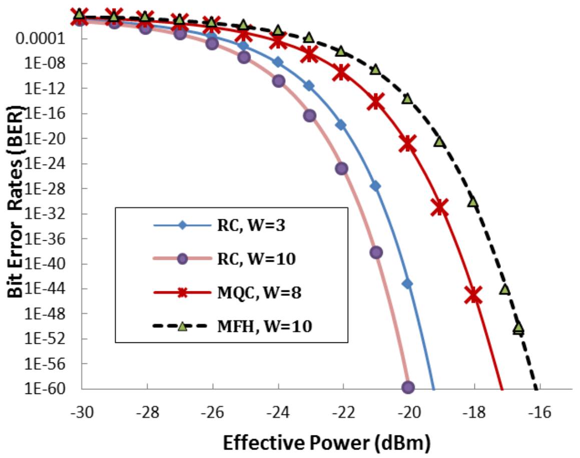

Figure 2. Comparison of effective power transmitted for various codes at 622Mbps

The impact of effective transmitted power (P_{sr}) on shot noise for a fixed number of users, K=12 of the RC code compared with other SAC OCDMA codes is depicted in Fig. 3. A good OCDMA system should have the effective transmitted power as low as possible. Here, the electrical bandwidth, B is fixed to 311MHz, while the effective transmitted power varies from -30dBm to 0dBm. In this figure, the curves indicate that the shot noise increases linearly with P_{sr} for all codes. However, the RC code is shown to produce the lowest value of shot noise power compared to the other SAC OCDMA codes. For example, at a P_{sr} of -10dBm, the shot noise power produced using the RC code is 5.33×10^{-16}W, while the shot noise produced by the MQC weight 6 is 3.48×10^{-15}W and the MFH weight 10 is 1.33×10^{-15}W. The higher shot noise power exhibited by the MQC and MFH codes are due to the larger code length used to occupy increasing users. Furthermore, although the MFH code length in this case is 90, which is much larger than the RC code length (L=42), the shot noise of the RC code is still lower than the MFH code. On the other hand, although having the same or smaller code weight than the RC code, RD code, MDW code and EDW code still produce a higher shot noise power of 1.75×10^{-15}W, 8.29×10^{-15}W, and 1.08×10^{-14}W at P_{sr} of 0dBm because they have a shorter code length than the RC code. Thus, this result indicates that the code development of the RC code has successfully minimized the shot noise in the OCDMA system performance.

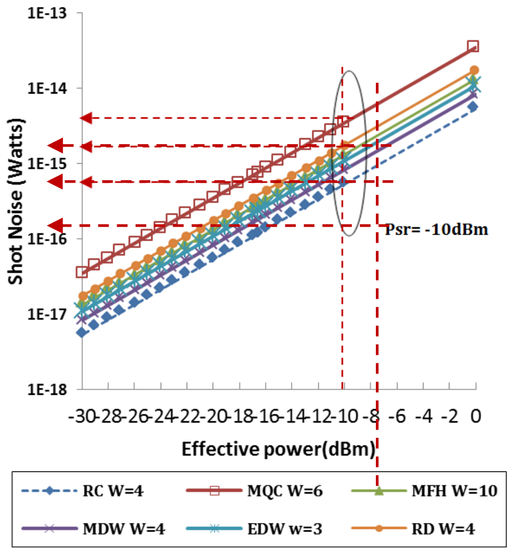

Figure 3. Comparison of shot noise with respect to effective transmitted power (P_{sr}) for different codes at 622Mbps

The BER curves with respect to variation of bit rates are depicted in Fig. 4 for different codes. Here, the received power, P_{sr} is fixed at -10dBm, while the number of users is kept constant of 30 users. From the figure, it is obvious that as the bit rates are increased, the BER performance gradually deteriorates.

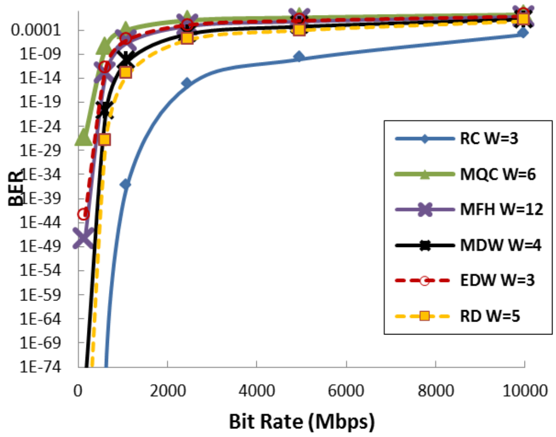

Figure 4. Comparison of shot noise power in term of effective transmitted power for different codes

This is mainly due to as the bit rates get higher the bandwidth becomes larger, thus increasing the noise influencing the performance. Hence, the signal to noise ratio will then decrease and eventually degrades the BER performance. It can be seen that the RC coding system can provide better performance compared to other codes, although using a lower code weight. For example, at a BER of 10^{-9}, the RC code with weight three can achieve a bit rate of 2.5Gbps, while the RD weight of five and MDW weight of four only achieve up to1.1Gbps. Lower bit rates, slightly over than 622Mbps are achieved by MQC code weight 6, MFH code with weight 12 and EDW code with weight 3. This better performance presented by the RC code is contributed from the elimination of PIIN noise and MAI suppression in the RC coding system.

V. Conclusion

This paper successfully demonstrates the design of a new code known as Recursive Combinatorial (RC) code in which the de structure enables suppression of noise in the OCDMA network. Results demonstrated that this code shows better performance compared to other codes such as MQC, RD and EDW code in term of improved effective power and bit rates transferred due to PIIN and MAI noise suppression. Hence, this new code property capability to restrain system performance can be a promising approach for employment in the OCDMA system network.

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