Performance of Spectral Amplitude Coding OCDMA Using Multi-identity High Power Code

A. Bouarfa and M. Kandouci

Abstract—**Many codes have been studied and suggested to be implemented in Optical Code Division Multiple Access (OCDMA) using spectral amplitude coding (SAC). In this work A novel code structure is propounded for SAC-OCDMA system and theoretically demonstrates the quality of the proposed code system using direct detection technique in order to reduce Multiple Access Interference (MAI). The new code called multi-identity high-power code (MIHP), with its architecture and facility of construction gives regarding BER an excellent performance. High weight and a shorter length compared to other codes are the technical characteristics of the MIHP code. The result shows that the proposed code outperforms the zero cross-correlation code (ZCC) and multi-diagonal code (MD), it's also found that the system can accommodate 360 simultaneous users for a BER equal to 10-9. We simulate the quality of the propounded system with taking into consideration the entire concrete impacts in the system, such as the non-linear effects, the dispersion and attenuation in optical fiber.**

Index Terms—**MIHP code, ZCC code, SAC-OCDMA, direct detection.**

I. Introduction

In the late 1970's, to raise the robust security of information transmission and in order to resist intended interference and implement low probability of detection spread frequency communication has been used in military communications this technique called CDMA (code division multiple access) [1], [2].

In all types of optical multiple access code division systems (OCDMA), the spectral encoding systems (SAC) have received more attention in recent years as the multiuser interference can be eliminated when a code cross-correlation is used in stationary phase [3]. The elimination of MAI occurs at the receiver which is a function of the detection technique used [4]. In general, there are three detection techniques in SAC-OCDMA systems: complementary detection, AND subtraction detection and direct detection technique [5]. At the reception, the detection technique's selection depends on the code used to get the best system performance.

To establish the SAC-OCDMA, we must solve the problem of the orthogonality. Different codes as premium Code and OOC code have been subject of Many researchers [6]. H. A. Fadhil et al propose the Random Diagonal (RD) code [7], which is constructed by separating the code into two parts: data part and code part, for the SAC-OCDMA using direct detection technique, in data part zero cross correlation is set to '0' which reduce the Phase Intensity Induced Noise (PIIN). The Multi-Diagonal code (MD) with zero cross-correlation, which means that PIIN is suppressed, have been proposed by T. H. Abd *et al.* [8].

In this article, we are interesting to the proposed multi-identity high power codes (MIHP). In Section II we will show how these codes have been developed theoretically and we will discuss their properties. Analysis and interpretation of the system's performance is presented in Section III. Finally, a conclusion of this work is shown in Section IV.

II. MIHP Code Construction

The novel propounded MIHP code is represented in a matrix with a size where (row) represents the user's number and the (column) represents the code length.

- nu $\longrightarrow$ User's number
- k $\longrightarrow$ The k^{th} user
- w $\longrightarrow$ The number of '1' in row
- i $\longrightarrow$ Number of the diagonal

The construction of the matrix:

The construction of the MIHP code is based on a combination of two matrices:

- Multi-identity matrix
- All-Ones matrix

A. Multi-identity Matrix

Before starting we present some notions on linear algebra, the matrix's size of identity matrix is set to (NxN) with unit components in the diagonal and zeros elsewhere. It is noted as $I_N$or simply I. The matrix may be defined as follows:

$$I_1 = [1], I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \dots\dots\dots I_N = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

We note 'i' as the number of the diagonal.

The amount of "1" in each row is equal to one '1' and $\lambda = \sum_{i=1}^{N} x_i y_i$ which represents the cross correlation equal to '0'. A matrix called multi-identity matrix (MI) represent the property mentioned above.

Therefore, for $N = 4$and $i = 4$ the multi identity matrix is represented as follows:

Step 1: an identity matrix$I_{4\times4}$ is generated:

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$$I_4 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Step2: we create the matrix MI as follows in this case we have 4 identity matrices:

$$\mathrm{MI} = \begin{bmatrix} 1&0&0&0&1&0&0&0&1&0&0&0&1&0&0&0 \\ 0&1&0&0&0&1&0&0&0&1&0&0&0&1&0&0 \\ 0&0&1&0&0&0&1&0&0&0&1&0&0&0&1&0 \\ 0&0&0&1&0&0&0&1&0&0&0&1&0&0&0&1 \end{bmatrix} \quad (3)$$

Note that this matrix keeps the property zero cross correlation between users (rows) [9].

B. All-Ones Matrix

The construction of the second part is made with a very simple way: a matrix which contains ‘1’ must be created, the number of rows still N and the column’s number is equal to w-i.

Example if $w = 4$ and $i = 2$, the number of ‘1’ added is equal to 2.

Therefore, for $nu = 4$, $w = 4$ and $i = 2$ the generated matrix is presented as follows:

$$\mathrm{Ones} = \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{bmatrix} \quad (4)$$

From bases mentioned above (3) and (4), (nu, l) determine the matrices representing our code of size $(nu \times l)$.

The relation between nu, l and w can be written as follows:

$$l = (nu \times i) + (w - i) \quad (5)$$

And the generated code can be constructed by combining the two matrices MI and all-Ones as shown below:

$$\mathrm{MIHP} = [\mathrm{MD}, \mathrm{Ones}] \quad (6)$$

As an example, we can generate the MIHP code who is used in the simulation with a number of users $nu = 3$, $w = 3$ and $i = 1$ which implies that the code length l= 5.

$$\mathrm{MIHP} = \begin{bmatrix} 1 & 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix} \quad (7)$$

From the matrix (7) the wavelength assignment to the MIHP code for each user (see Fig. 1) is as follows:

$$\mathrm{codeword} = \begin{cases} \mathrm{user1} = \lambda_1, \lambda_4, \lambda_5 \\ \mathrm{user2} = \lambda_2, \lambda_4, \lambda_5 \\ \mathrm{user3} = \lambda_3, \lambda_4, \lambda_5 \end{cases} \quad (8)$$

The MIHP code has a greater flexibility, in the choice of parameters k and w, with an easy conception in order to provide a great number of users.

the main point of the MIHP code is that it provides better performance than the other codes systems in terms of the length of the code for the same number of users un = 30, as indicated in the Table I.

A very short length of code limit the flexibility addressing codes, while the long code length is regarded as a disadvantage in the implementation. Our proposed MIHP code exists for the length of the code of practice that is neither too short nor too long.

TABLE I: COMPARISON BETWEEN THE LENGTHS OF THE DIFFERENT CODES

code	N °of users k	Weight w	Code length l
OOC	30	4	364
MFH	30	7	42
MD	30	3	33
RD	30	3	90
ZCC	30	3	91
MIHP	30	3	32

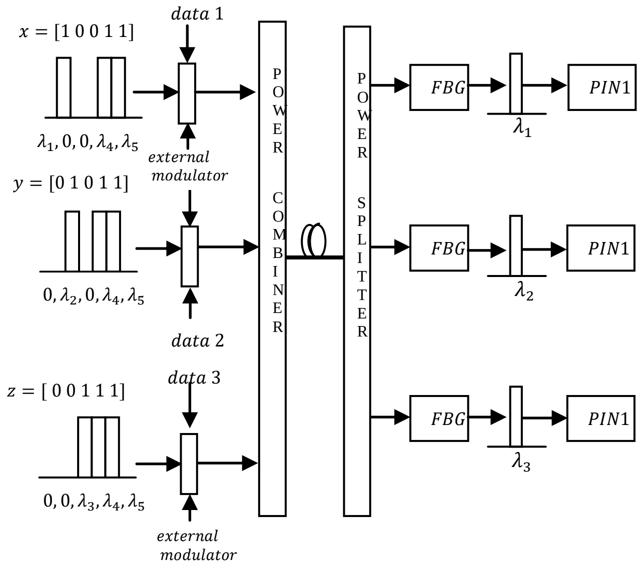

Fig. 1. Theproposed SAC-OCDMA system using MIHP code.

III. MIHP CODE CONSTRUCTION SYSTEM PERFORMANCE ANALYSIS

A. Analysis with Gaussian Approach

Three quality criteria are used to measure the performance of the SAC-OCDMA system [10]:

- Bit error rate
- The Q factor
- The eye diagram

To simplify our analysis, Gaussian approximation is used for calculation of BER [10]-[12].

Thermal noise, shot noise and phase-induced intensity noise (PIIN) were taken into account for analyzing bit error rate, the setup of the proposed MIHP system using spectral direct detection technique with three users exploits fiber Bragg-grating (FBG) as shown in Fig. 1.

To analyze the system we assume that [10]:

- The light source is unpolarized, the spectrum is flat over the bandwidth $\left[v_0 - \frac{\Delta v}{2}, v_0 + \frac{\Delta v}{2}\right]$.
- The same reception power for different users.
- The binary sequences must be synchronized for each user.

- Each power spectral component has identical spectral width.

The SNR of an electrical signal is defined as the average signal power to noise power can be expressed as:

$$\mathrm{SNR} = \frac{i_k^2}{\sigma^2} \quad (10)$$

For the proposed system analysis phase intensity induced noise PIIN, which is suppressed by our decoding technique, as well as shot noise (σ_{sh}) and thermal noise (σ_{th}) in photodiode are considered. The variance of noise source is given by:

$$\sigma^2 = \sigma_{sh} + \mathrm{PIIN} + \sigma_{th} \quad (11)$$

Which also can be written as:

$$\sigma^2 = 2eIB + \mathrm{PIIN} + \frac{4K_BT_nB}{R_L} \quad (12)$$

where

e	Electron's charge
B	Noise equivalent Electrical bandwidth of the receiver
K_B	Boltzmann Constant
T_n	Receiver noise temperature
R_L	Receiver load resistor
I	Average photocurrent

Let $C_k(i)$ denote the i^{th} element of the k^{th} MIHP code sequence. According to the properties of our code we can write:

$$\sum_{i=1}^{L} C_k(i).C_l(i) = \begin{cases} w & \text{for } k = l \\ w-1 & \text{for } k \neq l \end{cases} \quad (13)$$

B. Direct Detection Technique

By using a direct detection technique in The implementation of the proposed code system, MIHP code will behave similarly as a code with zero cross-correlation, this is due to the technique of detection, where FBG will filter only one wavelength of the desired signal in each branch (in our case λ_1 for the first branch, λ_2 for the second and λ_3 for the third branch) as shown in Fig. 1.

Subsequently, at the receiver, MAI and induced phase intensity noise (PIIN) is suppressed, which implies that the system performance is improved. This leads to the follows resulting:

$$\sum_{i=1}^{L} C_k(i).C_l(i) = \begin{cases} 1 & \text{for } k = l \\ 0 & \text{for } k \neq l \end{cases} \quad (14)$$

$r(v)$ is the power spectral density (PSD) of the received optical signals and can be written as [13]:

$$r(v) = \frac{P_{sr}}{\Delta v}\sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_k(i).\Pi(i) \quad (15)$$

where P_{sr} is the effective power of a broadband source at the receiver, d_k is the data bit of the kth user that carries the value of either "1" or "0".

And $\Pi(i)$ is given by:

$$\Pi(i) = \left\{ \begin{matrix} u\left[v - v_0 - \frac{\Delta v}{2L}(-L+2i-2)\right] - \\ u\left[v - v_0 - \frac{\Delta v}{2L}(-L+2i)\right] \end{matrix} \right\} \quad (16)$$

where $u(v)$ is the unit step function written as follows:

$$u(v) = \begin{cases} 0 & v < 0 \\ 1 & v \geq 0 \end{cases} \quad (17)$$

The photocurrent i_k at the receiver is defined by:

$$i_k = R\int_0^{+\infty} G(v)dv \quad (18)$$

where R is the responsivity of the photodetectors given by $R = (\eta.e)/(h.v_c)$ [14]. Here, η is the quantum efficiency, e is the electron's charge, h is the Planck's constant, and v_c is the central frequency of the original broadband optical pulse.

The integration of the power spectral density at the photo-detector of the l^{th} receiver during one period can be written:

$$\int_0^{+\infty} r(v)dv = \frac{P_{sr}}{\Delta v}\sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_k(i).C_l(i)\int_0^{+\infty}\Pi(i)\, dv \quad (19)$$

The above equation can be simplified as follows:

$$\int_0^{+\infty} r(v)dv = \frac{P_{sr}}{\Delta v}\sum_{k=1}^{K} d_k \sum_{i=1}^{L} C_k(i).C_l(i).\frac{\Delta v}{L} \quad (20)$$

$$\int_0^{+\infty} r(v)dv = \frac{P_{sr}}{L}\sum_{k=1}^{K} d_k \sum_{\substack{i=1\\k=l}}^{L} C_k(i).C_l(i) + \frac{P_{sr}}{L}\sum_{k=1}^{K} d_k \sum_{\substack{i=1\\k\neq l}}^{L} C_k(i).C_l(i) \quad (21)$$

When all users are transmitting bit "1":

$$\sum_{k=1}^{K} d_k = w \quad (22)$$

Consequently, the photocurrent i_k can be expressed as:

$$i_k = R\int_0^{+\infty} r(v)dv = R.\frac{P_{sr}.w}{L} \quad (23)$$

Substituting eq (23) in eq (12), we obtain:

$$\sigma^2 = \frac{2eBRP_{sr}w}{L} + \frac{4K_BT_nB}{R_L} \quad (24)$$

Note the probability of sending bit "1" at any time for each user is $1/2$, thus the equation (24) becomes:

$$\sigma^2 = \frac{eBRP_{sr}w}{L} + \frac{4K_BT_nB}{R_L} \quad (25)$$

Finally, we can calculate the average signal to noise ratio (SNR) according to the properties of MIHP code is calculated as follows:

$$\mathrm{SNR}=\frac{\left(\frac{\mathrm{RP_{sr}w}}{\mathrm{L}}\right)^2}{\frac{\mathrm{eBRP_{sr}w}}{\mathrm{L}}+\frac{4\mathrm{K_BT_nB}}{\mathrm{R_L}}} \tag{26}$$

The bit error rate, using the Gaussian approximation, can be calculated by the following equation:

$$\mathrm{BER}=\frac{1}{2}\mathrm{erfc}\sqrt{\frac{\mathrm{SNR}}{8}} \tag{27}$$

C. Mathematical Analysis

The performance of MIHP code system has been compared mathematically with the recent codes, such as Multi-Diagonal (MD) and ZCC based on BIBD in [15].

Using BER equation, the parameters used in our numerical calculation [16] are listed in Table II.

TABLE II: TYPICAL PARAMETERS USED IN THE ANALYSIS

η	Photo-detector quantum efficiency	0.6
$\mathbf{P_{sr}}$	the effective power	-10dBm
$\mathbf{v_c}$	Operating wavelength	1550 nm
B	Electrical bandwidth	311 MHz
$\mathbf{R_b}$	Data bit rate	622 Mbps
$\mathbf{T_n}$	Receiver noise temperature	300 K
$\mathbf{R_L}$	Receiver load resistor	1030 Ω
e	Electron charge	1.6×10−19 C
h	Planck's constant	6.66 ×10−34 Js
$\mathbf{K_B}$	Bolzmann's const	1.38×10−23 J/K

Fig. 2 depicts the relation between BER and the number of active users k of MIHP code (w=4) with various SAC-OCDMA codes such as MD code (w=4) and ZCC code (w=4) for the effective receiver power $P_{sr}=-10$ dBm. We can notice that the system BER degrades as the number of active users increased.

From the Fig. 2, it is observed that the performance of the system using MIHP code is better compared with the other systems, in Fig. 3 the maximum acceptable BER of 10^{-9} was achieved by the MIHP code with 360 active users compared to MD and ZCC with 90 active users this is due to the reduced length of the proposed code MIHP while maintaining the same weight (w) as mentioned in section 2 and section 3, and also the fact of using the Direct Detection which makes the behavior of the MIHP code similar to a ZCC code. Since the length of (w.k) for MD and [(w.k) +1] for ZCC [14] we note a slight difference in performance system between MD code and ZCC code.

Fig. 4 compares the BER variations against the number of simultaneous users when the received signal power is -10 dBm and -15 dBm.

It is clear from the curves that the SNR performance degrades with increasing number of active users for a given received signal power and the decrease in power causes the degradation of SNR, this is due to the effects of other noise sources such as thermal noise and shot which become stronger when the power received is decreased.

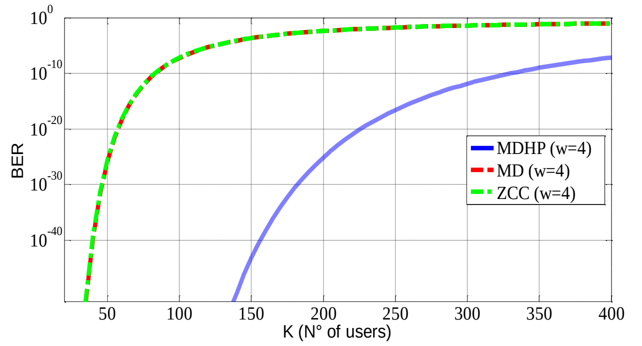

Fig. 2. BER versus the number of active users.

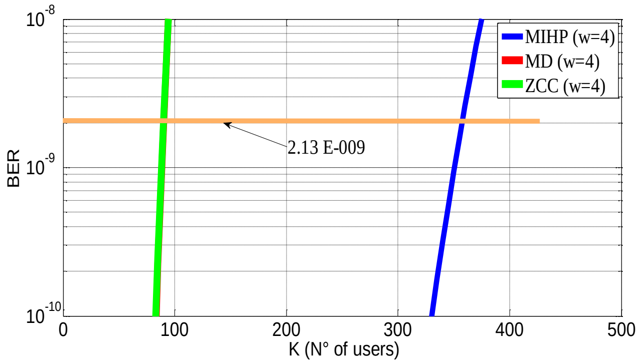

Fig. 3. The number of active users achieved by the MIHP compared to the others codes.

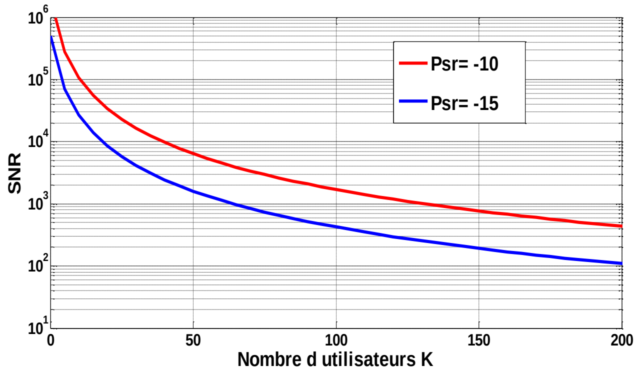

Fig. 4. SNR against The number of active users for different Power received.

IV. CONCLUSION

The OCDMA system performance is degraded when the number of users is important. This is due to the multiple access interference (MAI) which results from incomplete orthogonality.

In this article, the MIHP code was built with simple algebraic. The major contribution of this code is the elimination of the interference MAI, suppression of induced phase intensity noise (PIIN) and the high power of the input signal by increasing the weight without overly increasing the length of the code, it has also been demonstrated that improved performance may be significantly reduced when there's a correlation between codes.

The results demonstrate that the MIHP code is not only efficient for the binary error rate BER versus MD and ZCC, but it allows multiplexing of multiple users.

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