Three Dimensional Encoding for Incoherent Optical CDMA System using Spectral/Spatial half zero Cross Correlation Code

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***Abstract* -** In this study, a novelty spectral/temporal/spatial code structure for incoherent optical code division multiple access systems based on the process of spectral amplitude coding (SAC-OCDMA) called three-dimensional half spectral/ spatial zero cross-correlation (3D-HSSZCC). Its creation uses two sequences spectral/temporal (2D-S/T) and one sequence spatial (1D-S) by extending the 1D-ZCC code. Further, the suggested 3D-HSSZCC encoding is characterized by a high data rate, high cardinality, high security, low power consumption, and zero cross-correlation (ZCC) property. Furthermore, the analytical simulation displays that the code has better efficacy in comparison with the codes that have the same three-dimensional encoding such as perfect difference (3D-PD), hybrid perfect difference/multi-diagonal (3D-PD/MD), dynamic cyclic shift/multi-diagonal (3D-DCS/ MD), and same code in the one-dimensional (1D-ZCC) and two-dimensional (2D-HSSZCC) encoding respectively in terms of probability of error (BER) in accordance to the measure of concurrent users, operative power and bit rate, where it is can progress the capacity of the system up to 3.67, 3.2, 2.9, 2.46, and 4.75 times, and improves the data rate by 7.57, 6.28, 5.25, 28.61 and 4.43 times respectively compared to mentioned codes above.

***Keywords* –** HSSZCC, SAC-OCDMA, spatial, spectral, temporal.

I. INTRODUCTION

Nowadays, multiple access systems (OCDMA) have turned into a favorable solution for optical multiplexing networks thanks to their various benefits such as high-security level, ease of users management, and high capacity of multiplexing [1]. Furthermore, can be presented into two classes, coherent OCDMA when the encoding scheme used bipolar bits (-1,+1), and incoherent OCDMA where the encoding scheme is performed using unipolar bits (0, +1). Lately, many researchers are interested in incoherent OCDMA systems due to their simple architecture, simple network access, and the low power consumption [2], [3]-[4]. However, these optical access systems are influenced by the high influence of phase-induced intensity noise (PIIN) that has become as main feature that is degrading the performances of OCDMA systems [5], further, it's caused by the overlapping between optical codes, where this causes errors in the function of the optical network at the receiver level [6],[7]. Moreover, Spectral amplitude coding (SAC) is a type of encoding technique that use in spectral coding to eliminate the effect of this noise where it allows assigning a unique optical code to each user by dividing the spectral bandwidth into optical sub-bands according to the length of the code sequence [8]. In this state, several signatures have been preferred during the last years [9]-[10]. Despite that, increasing the cardinality makes it possible to raise the digit of optical codes, which conducts an increase in their length, consequently, this feature limits the system and supports less number of users (cardinality).

In order to remove the above problems, two-dimensional encoding (2D) is a solution that entices many researchers because it can progress the one-dimensional system capacity, reduce the spread of spectral code, and minify the outcome of the interference between multiple users (MAI), furthermore, the 2D-OCDMA encoding can be used by using two axes of the following four axes (spectral, spatial, time, and polarization). In this regard, several two-dimensional codes have been expanded [11]-[12].

Nevertheless, increasing the cardinality of the 2D-OCDMA system poses the issue of increasing spatial code length which begins to introduce significant performance degradation, higher power consumption, and increased network complexity.

In view of these reasons, a new three-dimensional spectral/temporal/spatial encoding scheme has been investigated specified under the name of Half Spectral/ Spatial Zero Cross-Correlation (3D-HSSZCC) code characterized by high cardinality, simple design, and the property of ZCC that ignores the fuss of PIIN and solves the troubles of 1D and 2D encoding schemes. Additionally, the proposed code achieves better results in comparison to introduced codes in [13]-[14] through the allowed BER (10^{-9}) value when varying in the effective source power, and data rate.

The rest of this study is ordered as follows, the proposed three-dimensional code texture is displayed in section two, the numerical study is described in section three, section four depicts the outcomes of the suggested system, and finally, a conclusion is presented in section five.

II. CODE BUILDING

The 3D-HSSZCC code design is created by employing the three following series, spectral/temporal sequences from 2D-HSSZCC and spatial sequence from 1D-ZCC code. Where the above three components are denoted by X, Y, and Z respectively. Each sequence is characterized by the weight of sequence (W) and the number of subscribers (K). Further, their sizes are $A = K_1 \times W_1$, $B = K_2 \times W_2$, and $C = K_3 \times W_3$. Moreover, the code length and the cardinality of the 3D-HSSZCC code are respectively $K = K_1 \times K_2 \times K_3$ and $L = A \times B \times C$. Hence, the construction of optical HSSZCC signature is detailed in [15]-[14]

The design of the 3D-HSSZCC code is given as [3]:

$$A_{x,y,z} = X_x^T Y_y Z_z \tag{1}$$

Here X_x^T refers to x^{th} spread code of X, Y_y refers to y^{th} spread code of Y, and Z_z is z^{th} spread sequence of Z, where x = 1, 2, 3, … , K_1, y = 1, 2, 3, … , K_2 and z = 1, 2, 3, … , K_3.

In view of explaining the property of the 3D-HSSZCC, the eight matrices $A^{(d)} = A^{(0)}, A^{(1)}, \dots A^{(7)}$ are expressed as [3]:

$$A^{(d)} = \begin{cases} A^{(0)} = X^T Y\, Z \\ A^{(1)} = X^T \overline{Y}\, Z \\ A^{(2)} = \overline{X}^T Y\, Z \\ A^{(3)} = \overline{X}^T \overline{Y}\, Z \end{cases} \begin{cases} A^{(4)} = X^T Y\, \overline{Z} \\ A^{(5)} = X^T \overline{Y}\, \overline{Z} \\ A^{(6)} = \overline{X}^T Y\, \overline{Z} \\ A^{(7)} = \overline{X}^T \overline{Y}\, \overline{Z} \end{cases} \tag{2}$$

Here X^T is inverse "line/column" of the matrix X. $\overline{X}$, $\overline{Y}$, and $\overline{Z}$ are the supplements of the spreading codes of X, Y, and Z respectively.

Hence, the cross correlation property $R^{(d)}$ of 3D-HSSZCC code between $A^{(d)}$ and $A_{x,y,z}$ is given as:

$$R^{(d)}(x,y,z) = \sum_{x=0}^{A-1} \sum_{y=0}^{B-1} \sum_{z=0}^{C-1} a^{(d)}{}_{x,y,z}\, b_{x,y,z} \tag{3}$$

Consequently, the 3D-HSSZCC property is given as:

$$R^{(0)}(g,h,l) = \begin{cases} W_1.W_2.W_3 & if\ x=0\cap y=0\cap z=0 \\ 0 & else \end{cases} \quad (4)$$

$$R^{(4)}(g,h,l) = \begin{cases} W_1.W_2.W_3 & if\ x=0\cap y=0\cap z\neq 0 \\ 0 & else \end{cases} \quad (5)$$

Hence, the details of the 3D-HSSZCC code property are elucidated in Table I. it contains eight cases divided into two cases, the first case from $R^{(0)}$ to $R^{(3)}$ for $z=0$ and the second case from $R^{(4)}$ to $R^{(7)}$ for $z\neq 0$.

TABLE 1. Cross Correlation Values Of 3D-HSSZCC Code.

Case 1	$R^{(0)}(x,y,z)$	$R^{(1)}(x,y,z)$	$R^{(2)}(x,y,z)$	$R^{(3)}(x,y,z)$
$x=0\cap y=0\cap z=0$	$W_1.W_2.W_3$	0	0	0
$x=0\cap y\neq 0\cap z=0$	0	$W_1.W_2.W_3$	0	0
$x\neq 0\cap y=0\cap z=0$	0	0	$W_1.W_2.W_3$	0
$x\neq 0\cap y\neq 0\cap z=0$	0	0	0	$W_1.W_2.W_3$
Others	0	0	0	0
Case 2	$R^{(4)}(x,y,z)$	$R^{(5)}(x,y,z)$	$R^{(6)}(x,y,z)$	$R^{(7)}(x,y,z)$
Others	0	0	0	0
$x=0\cap y=0\cap z\neq 0$	$W_1.W_2.W_3$	0	0	0
$x=0\cap y\neq 0\cap z\neq 0$	0	$W_1.W_2.W_3$	0	0
$x\neq 0\cap y=0\cap z\neq 0$	0	0	$W_1.W_2.W_3$	0
$x\neq 0\cap y\neq 0\cap z\neq 0$	0	0	0	$W_1.W_2.W_3$

III. NUMERICAL MODEL

The effectiveness of the suggested code is evaluated by measuring the values of BER and the ratio between the signal power and the overall noise (SNR) at the receiver against the variation of the capacity of users, data rate, as well as power consumption, thus, to simplify the numerical analysis and perceive the expressions of these metrics, four hypotheses are reviewed and considered [3]:

1) An unpolarized optical source and its spectrum is uniform during the optical range $[v_0-\Delta v/2\ , v_0+\Delta v/2\ ]$, v_0 is the main frequency and Δv is optical bandwidth.
2) All encoder/decoder instruments for all users have the same spectral width.
3) The spectral devices of every subscriber have the same power.
4) The stream of data of every subscriber at the receiver has coincided.

Accordingly, in the receiver, the power spectral density (PSD) is given as:

$$r(v) = \frac{P_{sr}}{W_2W_3\Delta v}\sum_{k=1}^{K} d_k \sum_{x=0}^{A-1}\sum_{y=0}^{B-1}\sum_{z=0}^{C-1} a_{x,y,z}\, rect(v,x) \quad (6)$$

Where P_{sr},and Δv, are represents the effective source power, range of the light, W_2, W_3 are indicated as the weight of Y and Z respectively, d_k is the binary sequence of k^{th} subscriber and $rect(v,x)$ given as:

$$rect(v,x) = \left\{u\left[v-v_0-\frac{\Delta v}{2A}(-2A+2x)\right]-\left[v-v_0-\frac{\Delta v}{2A}(-A+2x+2)\right]\right\} = u\left[\frac{\Delta v}{A}\right] \quad (7)$$

In the photodetector (PD), the resulting photocurrent is given by:

$$I = \mathcal{R}\int_0^{+\infty} r(v)dv$$
$$= \mathcal{R}\int_0^{+\infty} \frac{P_{sr}}{W_2W_3\Delta v}\sum_{k=1}^{K} d_k\, R_{x,y,z}^{(d)}\, rect(v,x)dv$$
$$= \frac{\mathcal{R}\, P_{sr}W_1}{A} \quad (8)$$

Where W_1 indicates the code weight of the spectral component, and $\mathcal{R}$ is the sensitivity of PD.

The total variance noise is expressed as:

$$\sigma_{noise}^2 = \frac{4K_bT_nB_r}{R_l} + 2eB_rI + B_rI^2\tau_c \quad (9)$$

Here Boltzmann's constant is referred to as K_b, T_n is the absolute temperature, the electrical bandwidth is referred to as B_r, the load resistance is referred to as R_l, e is the electron's charge, and τ_c indicates coherent time of light incident to the photodiode (PD) and given as [3]:

$$\tau_C = \frac{\int_0^{+\infty} G^2(v)dv}{\left[\int_0^{+\infty} G(v)dv\right]^2} \quad (10)$$

Additionally, phase-induced intensity noise (PIIN) photocurrent is given as:

$$\sigma_{PIIN}^2 = B_r\mathcal{R}^2\left[\int_0^{+\infty} \frac{P_{sr}}{W_2W_3\Delta v}\sum_{k=1}^{K} d_k \sum_{x=0}^{A-1}\sum_{y=0}^{B-1}\sum_{z=0}^{C-1} a_{x,y,z}\, rect(v,x)\, dv\right]^2$$

$$= \frac{B_r\mathcal{R}^2 {P_{sr}}^2 {W_1}^2}{\Delta v\ A} = \frac{AB_r}{\Delta v}\left[\frac{\mathcal{R}P_{sr}W_1}{A}\right]^2 = \frac{AB_rI^2}{\Delta v} \quad (11)$$

The Shot noise is given as:

$$\sigma_{shot}^2 = 2eB_rI = 2eB_r\left[\frac{\mathcal{R}P_{sr}W_1}{A}\right] \quad (12)$$

Consequently, the total variance noise of (9) becomes as:

$$\sigma_{noise}^2 = \frac{4K_bT_nB_r}{R_l} + 2eB_r\left[\frac{\mathcal{R}P_{sr}W_1}{A}\right] + \frac{B_r\mathcal{R}^2 {P_{sr}}^2 {W_1}^2}{\Delta v\ A} \quad (13)$$

According to the equations obtained above, the expression of SNR becomes as:

$$SNR = \frac{I^2}{\langle\, \sigma_{noise}^2 \,\rangle}$$

$$= \frac{\left(\frac{\mathcal{R}P_{sr}W_1}{A}\right)^2}{\frac{4K_bT_nB_r}{R_l} + 2eB_r\left[\frac{\mathcal{R}P_{sr}W_1}{A}\right] + \frac{B_r\mathcal{R}^2 {P_{sr}}^2 {W_1}^2}{\Delta v\ A}} \quad (14)$$

In addition, bits '1' and '0' have the same probability (P=0.5), So that, SNR expression becomes as:

$$SNR = \frac{I^2}{\langle\, \sigma_{noise}^2 \,\rangle}$$

$$= \frac{\left(\frac{\mathcal{R}P_{sr}W_1}{A}\right)^2}{\frac{4K_bT_nB_r}{R_l} + eB_r\left[\frac{\mathcal{R}P_{sr}W_1}{A}\right] + \frac{B_r\mathcal{R}^2 {P_{sr}}^2 {W_1}^2}{2\Delta v\ A}} \quad (15)$$

Based on the approximation of Gauss, the probability of error (BER) is acquired from the SNR and given as [3]:

$$BER = \frac{1}{2} \times erfc\sqrt{SNR/8} \quad (16)$$

$$BER = \frac{1}{2} \times erfc\sqrt{\left[\frac{\left(\frac{\mathcal{R}P_{sr}W_1}{A}\right)^2}{\frac{4K_bT_nB_r}{R_l} + eB_r\left[\frac{\mathcal{R}P_{sr}W_1}{A}\right] + \frac{B_r\mathcal{R}^2 {P_{sr}}^2 {W_1}^2}{2\Delta v\ A}}\right]/8} \quad (17)$$

IV. NUMERICAL RESULTS

To explore the performance of the suggested 3D-HSSZCC system, our code is tested with already systems developed and published in [13]-[14], where the comparison is presented using the above equations in terms of BER as a function of cardinality, effective power, and bit rate. Moreover, Table II lists the parameters used in the numerical calculation under MATLAB software.

TABLE 2. PARAMETERS USED FOR NUMERICAL CALCULATION.

Parameters	Value
Photo detector responsivity ($\mathcal{R}$)	0.75
Data rate (R_b)	1.25 Gb/s
Spectral width of light (Δv)	5 Thz
Receiver Load resistor (R_l)	1030 Ω
Electrical bandwidth (B_r)	$0.5 \times R_b$ GHz
Effective source power (P_{sr})	-10 dBm
Number of users (K)	150
Boltzmann's constant (K_b)	$1.38 \times \mathbf{10^{-23}}$ J/K
Receiver noise Temperature (T_n)	300 k
Electron charge (e)	$1.6 \times \mathbf{10^{-19}}$ c

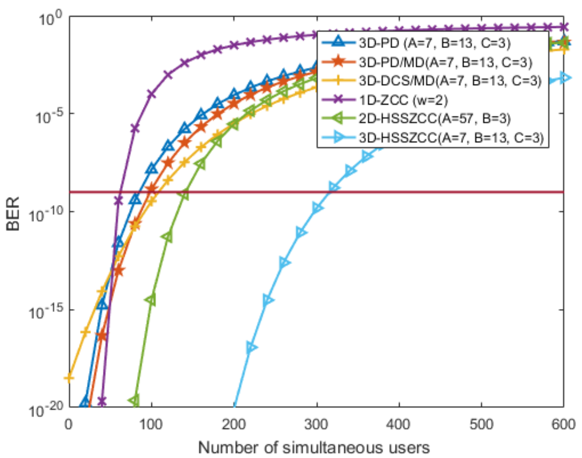

Fig. 1. BER regarding the concurrent subscribers.

Fig. 1 appears the alteration of the BER regarding the available concurrent subscribers when the bit rate is equal to 1.25 Gb/s and the power of the system is equal to -10dBm. Hence, when the length is the same (A=7, B=13, C=3) for all codes, it is seen that our system proves top operative in comparison with other systems. Further, our 3D-HSSZCC code reaches 320 users, whereas the first code 3D-PD reach 87 users, the second code 3D-PD/MD reach 100 users, and the third code 3D-DCS/MD reached 110 users, as well, the same code in the 1D encoding and 2D encoding achieves 70, and 130 users respectively. Consequently, the proposed 3D-HSSZCC code improved the cardinality 3.67 times than the first code, 3.2 and 2.9 times than the second and third codes respectively, furthermore, the moving of 1D and 2D to 3D improves cardinality to 4.75 and 2.46 times.

Fig.2 appears the alteration of BER versus the consumed power when the data stream is equal to 1.25 Gb/s and the available subscribers is fixed at 150. It clary that our code consumes little power in comparison to other codes. At passable BER (10^{-9}), the suggested code consumes a lower power reach of -11dBm, while the 1D-ZCC and 2D-HSSZCC codes can consume power up to -4.8dBm and -8dBm respectively. Otherwise, the first, second, and third codes consume great power compared to our code. As a result, the passage from 1D to 3D can keep power up to -6.2dBm, and the bypassing from 2D to 3D can keep power up to -3dBm.

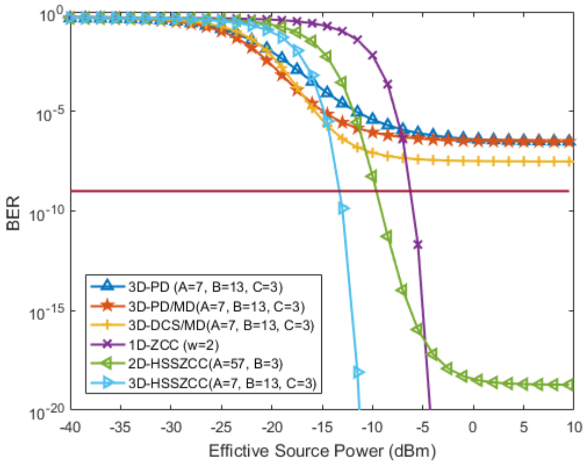

Fig. 2. BER regarding effective source power

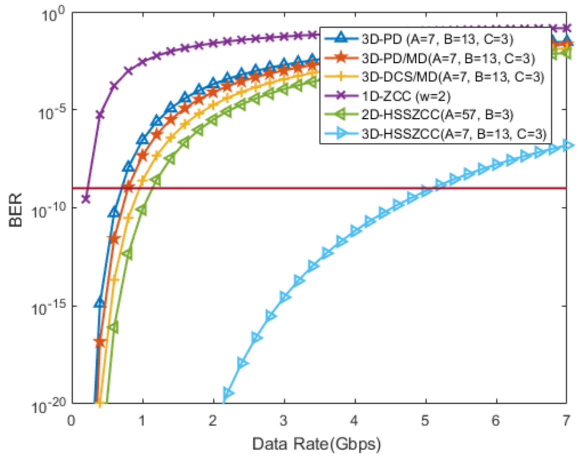

Fig. 3. BER versus data rate.

Fig. 3 explores the alteration of BER regarding the bit rate when the consumed energy is at -10dBm and the available subscribers is fixed at 150. We can observe that the proposed code accommodates a higher data stream in parallel with other codes, where our code accommodates reach 5.15Gb/s data rate, whereas the first code 3D-PD accommodates 0.68 Gb/s, while the second and third codes accommodate 0.82 Gb/s, 0.98 Gb/s respectively. Furthermore, the same code in 2D encoding can accommodate 1.1 Gb/s, thus, the proposed 3D-HSSZCC code improved the data rate by 7.57 times the 3D-PD code, 6.28 times the 3D-PD/MD code, and 5.25 times than the 3D-DCS/MD code respectively; as well as, the transit of 1D and 2D to 3D encrypting enhance the bit rate by 28.61 and 4.43 times respectively.

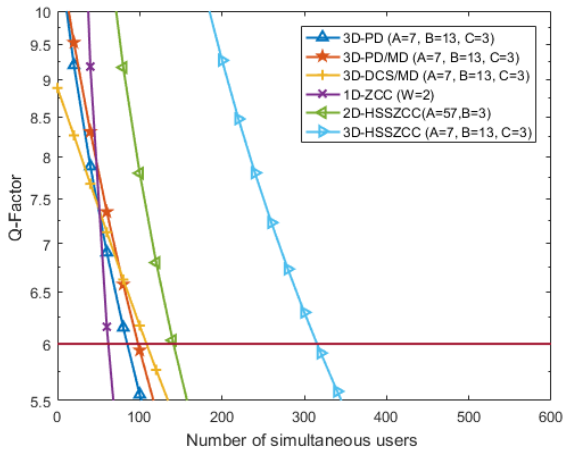

Fig. 4. Q factor regarding the concurrent subscribers

Fig.4 draws the effect of factor Q regarding the available subscribers where the spectral width and bit rate are equal respectively 3.75THz and 1.25Gb/s. it is obvious that our suggested code has a good transmission quality compared to other codes, moreover, at an admitted quality rate of Q=6 in optical requirements, the proposed code offers a high cardinality reaching 320 users, while the other three codes reach 85, 97, and 110 users respectively, moreover, the same code in spectral encoding (1D-ZCC) and spectral/spatial encrypting (2D-HSSZCC) it can favor cardinality up to 61 and 140 users respectively.

V. CONCLUSION

To revoke the impact of one-dimensional encoding and two-dimensional encoding problems in the OCDMA network, we introduced for the first time a novel spectral/temporal/spatial codeword for the incoherent optical CDMA system. The suggested code can completely suppress the effect of interferences between multiple users (MAI) and supports a significant cardinality. It provides a high bit rate compared to those 3D codes that have been compared to it above and is also better than the same code in 1D and 2D domains thanks to its ZCC property that conduct to curb the effect of PIIN noise. Further, we have found that our code demonstrates high multiplexing ability and can totally remove the effect of multi-user interferences (MUI) which allow it accommodates 320 users at a higher bit rate reaching 1.25Gbps as well as minimize the effective power to -11dBm.

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